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16. Abstract

At the heart of all concrete pavement projects is the concrete itself. This manual is intended as both a training tool and a reference to help concrete paving engineers, quality control personnel, specifiers, contractors, suppliers, technicians, and tradespeople bridge the gap between recent research and practice regarding optimizing the performance of concrete for pavements. Specifically, it will help readers do the following:

- Understand concrete pavement construction as a complex, integrated system involving several discrete practices that interrelate and affect one another in various ways.
- Understand and implement technologies, tests, and best practices to identify materials, concrete properties, and construction practices that are known to optimize concrete performance.
- Recognize factors that lead to premature distress in concrete, and learn how to avoid or reduce those factors.
- Quickly access how-to and troubleshooting information.

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Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual

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U.S. Department of Transportation
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The content of this manual reflects the professional expertise of 15 technical authors (see the inside title page). Collectively, they represent the state of the science and art of concrete pavement design, materials, and construction in the United States. They also represent the wide variety of discrete processes and variables that must be integrated in order to optimize the performance of concrete in pavements. The authors helped the project team assemble a resource that helps bridge the gap between recent research and common practice. Thank you, all.

We also gratefully acknowledge the contributions of the project's technical advisory committee. The members of this committee were responsible for the technical direction of the manual. They helped develop the original outline and critically reviewed several hefty drafts. Their feedback and suggestions were invaluable. The committee members were the following:

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Chapter 1

Introduction

This manual provides a ready reference and/or instruction guide for anyone involved in designing or constructing concrete pavements. The emphasis is on the concrete material itself—specifically, on optimizing concrete's performance. To optimize concrete's performance in today's pavement construction environment, everyone in concrete paving projects must understand concrete as the central component of a complex, integrated pavement system.

Readers will find some overlap and repetition of information among the chapters. This is a result of the integrated nature of the various stages and considerations involved in designing and constructing concrete pavement projects.

Purpose of This Manual

The purpose of this manual is to bridge the gap between recent research and common practice related to producing concrete for pavements. The intended audience is agency or industry personnel who are interested in optimizing concrete performance for every paving project. Readers may include

- Engineers.
- Quality control personnel.
- Specifiers.
- Contractors.
- Materials and equipment suppliers.
- Technicians.
- Construction supervisors.
- Tradespeople.

Specifically, this manual will help readers do the following:

- Understand concrete pavements as complex, integrated systems.
- Appreciate that constructing a concrete pavement project is a complex process involving several discrete practices. These practices interrelate and affect one another in various ways.
- Implement technologies, tests, and best practices to identify materials, concrete properties, and construction practices that are known to optimize concrete performance.
- Recognize factors leading to premature distress in concrete, and learn how to avoid or reduce those factors.
- Quickly access how-to and troubleshooting information.

Today's Construction Environment

In the early days of road building, a civil engineer would work on all aspects of a project. This included securing right-of-way, designing the road and selecting materials, and acting as the resident engineer to help the contractor build the project. The engineer knew everything about the project, and this centralized knowledge facilitated project quality.

As the pavement industry has grown and changed, processes previously handled by a single engineer have been split into separate specialties or departments. This is at least partly because the various processes have become more complex. More ingredients (like supplementary cementitious materials and chemical admixtures) have been introduced to the concrete mix. New testing procedures have been developed. Equipment and placement techniques have changed.

In today's complex road-building environment, dividing responsibilities among departments is effective only as long as communication is effective. Too often, however, this is not the case. The materials engineer focuses on materials, the design engineer focuses on design details, the contractor focuses on construction, and rarely do the parties think about or communicate with each other about the effects of their activities on other parties involved in the process.

For example, engineers trying to advance a new design or solve a specific problem may overlook the concrete materials and focus on other pavement details. Likewise, contractors sometimes try to overcome constructability issues associated with a poor concrete mixture by overusing their equipment rather than seeking to correct the mixture.

It is probably impossible to go back to the days when one engineer handled a concrete paving project from beginning to end. Therefore, as the number of variables and specialties continues to increase, all personnel involved in every stage of a project need to understand how their decisions and activities affect, and are affected by, every other stage of the project.

In other words, today's road-building process must be integrated to be cost-effective and reliable.

Principles of Concrete Pavement as an Integrated System

At the heart of all concrete pavement projects is the concrete itself. The concrete affects, and is affected by, every aspect of the project, from design through construction.

The concrete material itself is only one component of a specific pavement system or project. (Other components include, for example, the pavement's structural and functional design, the subgrade/base.)

- The concrete material is arguably the *central* component of the concrete pavement system.

By and large, the performance of a system is judged by the performance of the concrete.

- Concrete's performance is critically affected by many variables throughout the pavement system and throughout the process of building the system. These variables include the sources, quality, and proportions of its ingredients; construction variables like weather, paving equipment, and practices, etc.; and design parameters like design strength and climate factors (figure 1-1).
- Understanding concrete pavements as integrated systems, and pavement construction as an integrated process, will help readers optimize concrete performance.

Optimizing Concrete for Pavements

Optimizing the performance of concrete for pavements involves understanding the variables that affect concrete's performance and the properties of concrete that correspond to performance.

Variables That Affect Concrete Performance

The starting point for achieving a good-quality concrete pavement is to proportion, make, and use a good-quality concrete mixture. The definition of a good-quality concrete mix depends on the specific application. As mentioned above, how well a concrete performs for a specific application is affected by many factors, including the following:

- Structural and functional design of the pavement system. The pavement must carry the design loads without experiencing distresses. It should provide a smooth ride and adequate traction. During its design life, it may have to withstand the rigors of extreme temperature cycles.
- Quality of and variability inherent in concrete's constituent materials. Aggregates, admixtures, cement, and supplementary cementitious materials all vary in their properties to some degree based on their raw materials and manufacturing processes. These variations in materials, and variations in their proportions, affect the degree of uniformity that can be achieved when they are mixed in many separate concrete batches during a project.
- Construction factors, like weather, equipment, and personnel. Environmental variations can significantly affect the properties of plastic and hardening concrete. Pavements are built outside, where weather conditions during concrete placement can be unpredictable and can vary widely from conditions assumed during mix design and materials selection. Site conditions, equipment, and the construction and inspection teams play vital roles in the development of good-quality concrete.

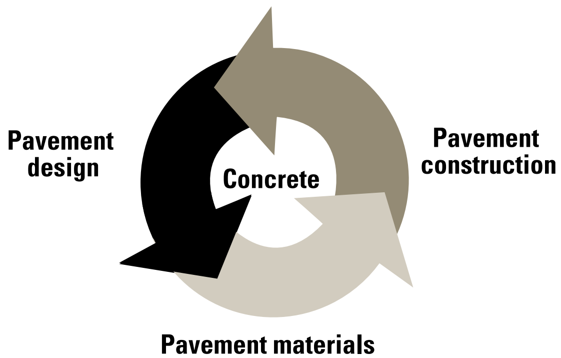

Figure 1-1. Concrete pavement construction is an integrated system, with the concrete material at the center.

Mix Properties That Correspond to Concrete Performance

Several properties of concrete mixtures correlate with concrete performance. A 16-State pooled fund study at Iowa State University, "Materials and Construction Optimization for Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements" (TPF-5[066]), has identified many of these properties, including workability, strength gain, air-void system, permeability, and thermal movement (see all of chapter 5).

During the various stages of a concrete paving project—mix design, pre-construction verification, and construction—these and other properties can be monitored and necessary adjustments can be made to mixture proportions or to construction practices to help ensure the final concrete product performs as designed. Design, verification, and field tests are critical elements of quality assurance and quality control (QA/QC).

In a departure from past practice, laboratory tests of mixture properties, using materials specific to a project, are now often needed before construction starts. Ideally, full-size trial batches should be done before paving is begun to verify laboratory findings and determine if adjustments are needed. This is especially important when using unfamiliar materials.

These tests provide data that serve as a basis for making necessary adjustments in the field. The construction team (agency and contractor) should prepare in advance for situations that may arise during construction, such as changes in materials sources or unexpectedly hot or cold weather. The team should pre-determine how these changes will likely affect the concrete mixture properties, and decide in advance how to compensate for the effects.

For example, will hot weather lead to decreases in air entrainment? How rapidly will a mixture lose workability in hot weather? The project team should have answers to these types of questions well before construction begins so that solutions are at hand if and when conditions change. Trial batching at the plant is essential to verify the laboratory findings.

Organization of This Manual

The manual is organized into 10 chapters, listed at right. Some chapters are more detailed than others. In addition, each chapter and section begin with general information and then become more detailed.

Critical Details: Chapters 3, 4, 5, 6, and 9

The emphasis throughout the manual is on concrete as a material and how its quality (performance) is affected by all aspects of a pavement project. Topics covered in the chapters highlighted in blue at right—3 (Materials), 4 (Hydration), 5 (Properties), 6 (Mix), and 9 (QA/QC)—are central

Chapter 2. Basics of Concrete Pavement Design: how concrete pavement design interacts with materials and construction requirements.

Chapter 3. Fundamentals of Materials Used for Concrete Pavements: the ingredients that we have to work with, and how they influence concrete performance.

Chapter 4. Transformation of Concrete from Plastic to Solid: how cement chemistry and the cement's physical changes during hydration are central to good-quality concrete, and how supplementary cementitious materials and chemical admixtures affect the hydration process.

Chapter 5. Critical Properties of Concrete: fresh and hardened properties of concrete that correlate with concrete performance.

Chapter 6. Development of Concrete Mixtures: how to achieve the required performance with the materials that we have.

Chapter 7. Preparation for Concrete Placement: how the subgrade and base influence the concrete.

Chapter 8. Construction: how construction activities and workmanship influence the concrete, what tools are available, and the current best practices to ensure high-quality pavement.

Chapter 9. Quality and Testing: a brief discussion of quality systems, and descriptions of some test methods that can be used to monitor concrete performance.

Chapter 10. Troubleshooting and Prevention: identifying the problem and the fix when something goes wrong, and preventing recurrence.

to this emphasis, and therefore these chapters are quite detailed.

Complete coverage of the topics in the remaining chapters is beyond the scope of this book. These chapters provide overviews only, but again from the perspective of their relevance for optimizing concrete performance.

Quick References: Chapters 4 and 10

Some sections of the manual are presented as references:

Chapter 10 (Troubleshooting). Field personnel in particular will find chapter 10 useful on site.

Stages of Hydration charts in Chapter 4 (Hydration). Many readers will refer to the Stages of Hydration charts (pages 76–83) again and again. Understanding cement hydration is central to successfully integrating the various stages of concrete pavement projects for optimum concrete performance.

The charts provide a quick reference to help readers understand the relationships among cement chemistry, stages of hydration, the implications of hydration for the construction process, and the effects on hydration when supplementary cementitious materials and mineral admixtures are included in the mixture. In addition, the charts highlight some materials incompatibility issues that can arise.

A full-size Stages of Hydration chart. The chart is included with this manual as a foldout poster.

Subject index. The manual ends with an abbreviated subject index. (See the sidebar below.)

Cross-References and the Subject Index

The topics addressed in this manual are complex. Concrete pavements are complex, integrated systems, and the process of designing and constructing them is a complex, integrated process. Any thorough discussion about optimizing concrete as the central component of pavement systems cannot be presented in a strictly linear manner.

Readers will therefore discover overlap, repetition, and interaction among the chapters.

Here are two examples:

- **Aggregates**. Aggregates compose the largest volume in concrete mixes. Readers will find pertinent information about aggregates in several sections of the manual.
  - Chapter 3 describes the ingredients of concrete mixtures, including aggregates—their role in concrete, and the various types and properties of aggregate that can positively or negatively affect concrete performance.
  - Chapter 6 provides guidelines for proportioning the ingredients, including aggregates, to achieve the desired concrete performance.
  - Chapter 8 describes the importance of managing aggregate stockpiles so as not to tip the moisture balance in the mix.
- **Testing**. As mentioned earlier, testing is critical to an effective QA/QC program to ensure concrete performance. Readers will find information about testing in several sections of the manual.
  - Chapter 3 includes information about testing required or recommended for the ingredients of concrete.
  - Chapter 5 covers tests of concrete properties, both fresh and hardened.
  - Chapter 9 provides suggested procedures for conducting tests identified and conducted in Iowa State's study (TPF-5[066]).

As a result of this kind of overlap of information, important topics are thoroughly cross-referenced throughout the manual.

In addition, a basic index at the back of the manual lists primary topics and the chapters and pages where each is discussed (see page 323).

Chapter 2

Basics of Concrete Pavement Design

To effectively integrate best materials and construction practices, readers need to understand the basics of concrete pavement design. This chapter therefore provides an introduction to design. It identifies general materials and construction issues related to design, as well as some of the latest technological changes that allow the assumed design variables to relate more closely to as-built results.

The chapter begins with brief overviews of the philosophy of integrated pavement design and basic concrete pavement design types. It then discusses the elements of pavement design: first, determining what we want; then, determining the specific site variables that must be accommodated; and, finally, designing pavements that give us what we want in light of the variables. The chapter ends with a brief discussion of concrete overlay designs.

Integrated Pavement Design

Key Points

- The objective of pavement design is to select pavement features, such as slab thickness, joint dimensions, and reinforcement and load transfer requirements, that will economically meet the needs and conditions of a specific paving project.
- Traditionally, concrete pavement design has focused on slab thickness. A more integrated approach to pavement design considers all components of the pavement system that affect performance.
- The *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements* (M-E PDG) (NCHRP 2004) incorporates an integrated approach to slab thickness determination.
- Most concrete pavements constructed today are plain (unreinforced) and jointed. These designs are generally cost-effective and reliable.
- Unjointed, reinforced concrete pavement designs, although more expensive to construct, may be warranted for certain high-traffic routes, such as some urban routes.

Pavement design is the development and selection of slab thickness, joint dimensions, reinforcement and load transfer requirements, and other pavement features. A pavement designer's objective is to select pavement features that will economically meet the specific needs and conditions of a particular project.

Figure 2-1 shows the variety of basic features that must be determined when designing a concrete pavement.

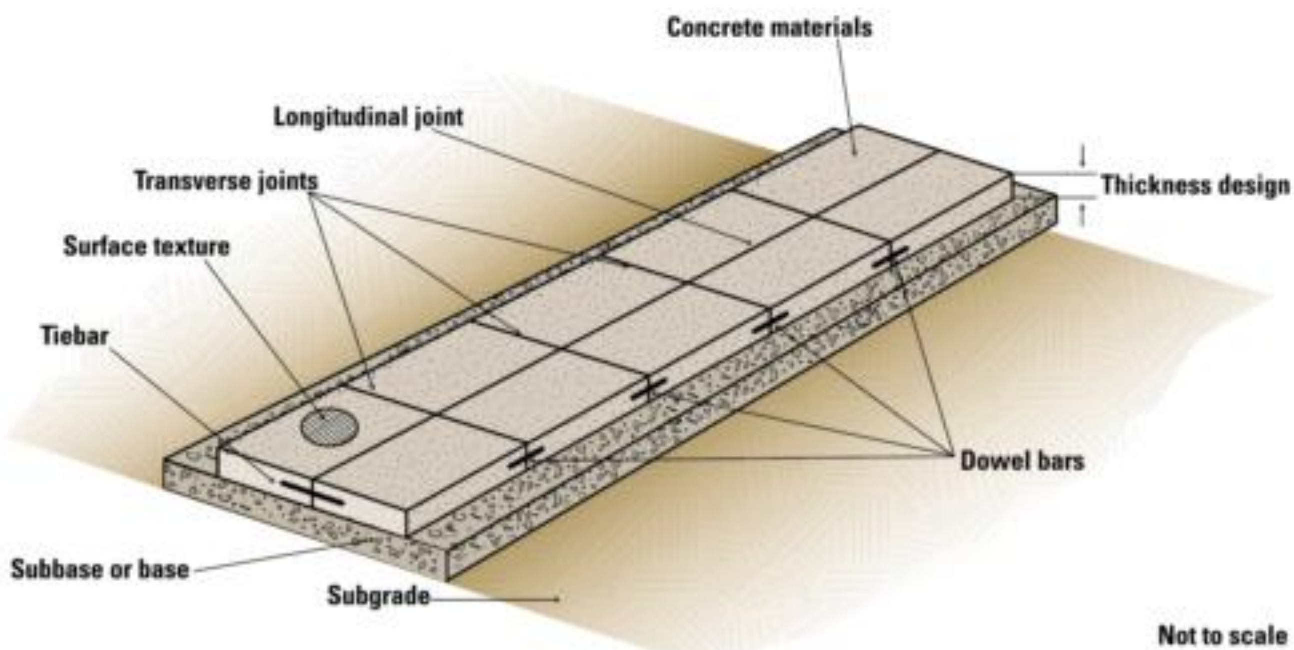

Figure 2-1. Pavement features (ACPA)

2004 Design Guide

During the design process, broad assumptions are often made about materials and construction issues that have a profound impact on the ultimate performance of a specific pavement design, but that are never verified or achieved in the as-built project. It is therefore critical to characterize materials properly through field tests during mix design and verification and through appropriate subgrade and base construction activities. Such tests are important not only to ensure the quality of each material, but also to ensure that the actual concrete and base materials reflect the assumptions made when the pavement was designed.

The focus of concrete pavement design has generally been on determining how thick the slab should be. Today, agencies are adopting a more integrated approach to pavement design. Such an approach simultaneously considers key pavement features as well as durable concrete mixtures, constructability issues, etc. Such an integrated approach is reflected in the long-life pavement concepts that have been adopted by many highway agencies. This integrated approach can also be observed in the thickness determination concepts incorporated into the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements* (M-E PDG) (NCHRP 2004).

More detailed information on concrete pavement design may be found in several sources (Yoder and Witzak 1975; PCA 1984; AASHTO 1993; AASHTO 1998; Smith and Hall 2001; ACI 2002; NCHRP 2004).

Basic Concrete Pavement Types

In pavement construction, three different concrete pavement design types are commonly used: jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP) (figure 2-2).

Each of these design types can provide long-lasting pavements that meet or exceed specific project requirements. Each type is suitable for new construction, reconstruction, and overlays (resurfacing) of existing roads (see more on overlays later in this chapter, Concrete Overlays, page 23).

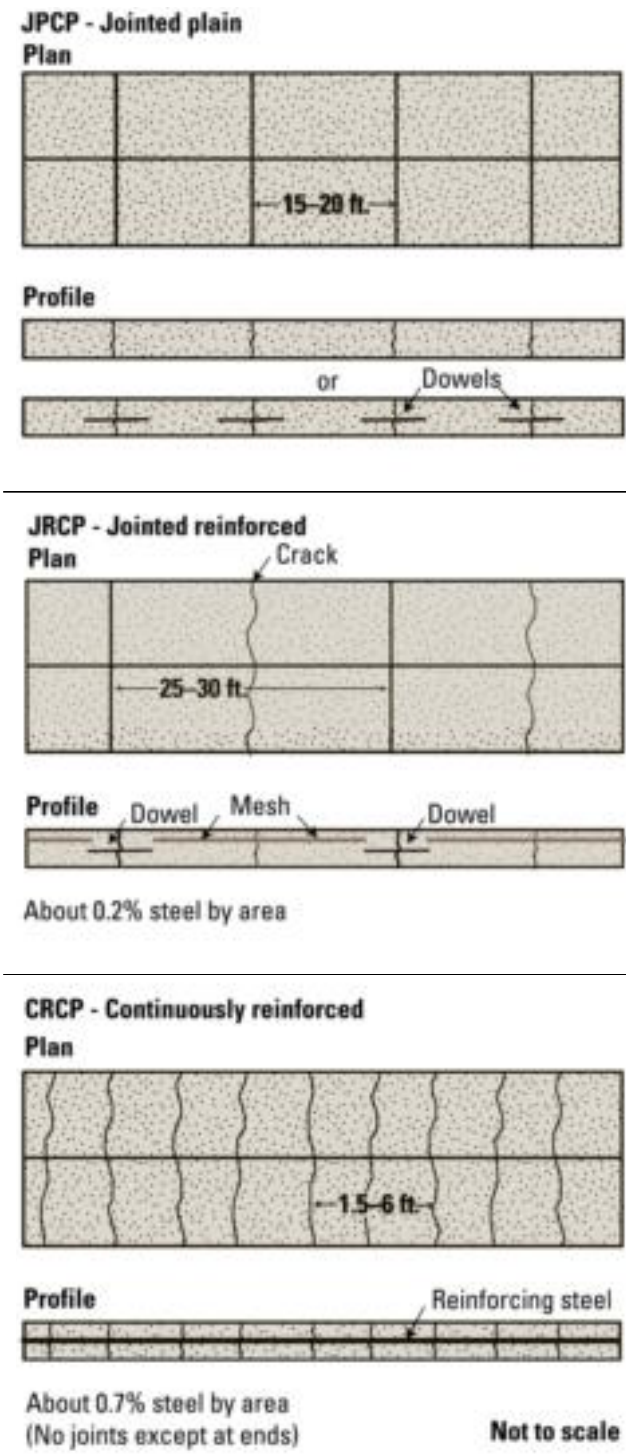

Figure 2-2. Concrete pavement types (ACPA)

JPCP

Because of their cost-effectiveness and reliability, the vast majority of concrete pavements constructed today are JPCP designs. They do not contain reinforcement. They have transverse joints generally spaced less than 5 to 6.5 m (15 to 20 ft) apart. They may contain dowel bars across the transverse joints to transfer traffic loads across slabs and may contain tiebars across longitudinal joints to promote aggregate interlock between slabs.

JRCP

JRCP designs contain both joints and reinforcement (e.g., welded wire fabric, deformed steel bars). Joint spacings are longer (typically about 9 to 12 m [30 to 40 ft]), and dowel bars and tiebars are used at all transverse and longitudinal joints, respectively.

The reinforcement, distributed throughout the slab, composes about 0.15 to 0.25 percent of the cross-sectional area and is designed to hold tightly together any transverse cracks that develop in the slab. It is difficult to ensure that joints are cut where the reinforcement has been discontinued. This pavement type is not as common as it once was on State highways, but it is used to some extent by municipalities.

CRCP

CRCP designs have no transverse joints, but contain a significant amount of longitudinal reinforcement, typically 0.6 to 0.8 percent of the cross-sectional area. Transverse reinforcement is often used. The high content of reinforcement both influences the development of transverse cracks within an acceptable spacing (about 0.9 to 2.5 m [3 to 8 ft] apart) and serves to hold cracks tightly together. Some agencies use CRCP designs for high-traffic, urban routes because of their suitability for high-traffic loads.

Design Considerations: What Do We Want?

Key Points

- For every concrete pavement project, the designer must define certain parameters:
  - Level of structural and functional performance.
  - Target service life, or design life.
  - Levels of various concrete properties—durability, strength, rigidity, shrinkage, etc.—required (or tolerated) to achieve optimum performance for the design life.
- Pavements must perform well structurally (i.e., carry imposed traffic loads) and functionally (i.e., provide a comfortable ride). Performance is generally described in terms of structural and functional distresses.
- Concrete strength has traditionally been the most influential factor in design and is still a primary design input for determining slab thickness.
- Concrete durability is a critical aspect of long-term pavement performance, but it is not a direct input in pavement design procedures. (Concrete durability is governed through appropriate material and construction specifications.)
- Concrete stiffness and dimensional stability (drying shrinkage and thermal movement) influence performance, but have not traditionally been considered in design procedures.

For each specific pavement design, a designer defines the desired pavement performance, service life, and various concrete properties.

Pavement Performance

The goal of all pavement design methods is to provide a pavement that performs well; that is, the goal is to provide a serviceable pavement over the design period for the given traffic and environmental loadings. A pavement's desired performance is generally described in terms of structural and functional performance:

- Structural performance is a pavement's ability to carry the imposed traffic loads.
- Functional performance is a pavement's ability to provide users a comfortable ride for a specified range of speed.

Both structural and functional distresses are considered in assessing overall pavement performance or condition. Even well-designed and well-constructed pavements tend to degrade at an expected rate of deterioration as a function of the imposed loads and/or time. Poorly designed pavements (even if they are well-constructed) will likely experience accelerated deterioration (figure 2-3).

Note that good concrete durability through good mix design and construction practices is necessary

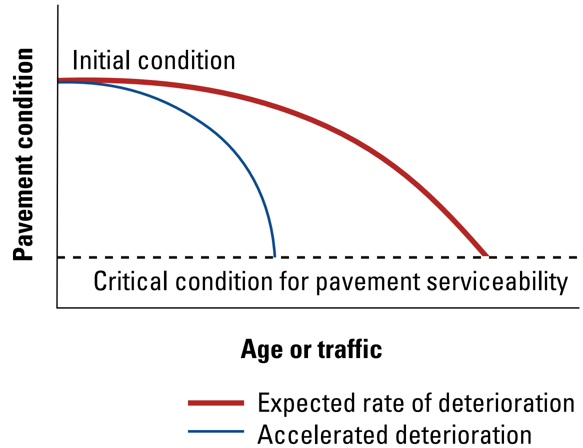

Figure 2-3. Pavement condition as a function of time or traffic (ACPA)

to achieve the initial expected level of pavement performance. Poor mix design and/or construction practices may significantly accelerate functional and/or structural deterioration, leading to premature failure of the pavement.

Structural Performance

Structural performance is the ability of the pavement to support current and future traffic loadings and to withstand environmental influences. Structural performance of concrete pavements is influenced by many factors, including design, materials, and construction. The most influential design-related variables for structural performance at a given level of traffic are slab thickness, reinforcement, concrete strength, elastic modulus (characterization of the concrete's stiffness), and support conditions.

The most prevalent type of structural distress is load-related cracking, which may appear as corner cracks, transverse cracks, or longitudinal cracks.

Corner Cracks. Corner cracks or corner breaks, as shown in figure 2-4, are usually caused by structural failure under loads, particularly when a pavement has aged and repeated loadings create voids under slab corners.

Factors that contribute to corner cracks include excessive corner deflections from heavy loads, inadequate load transfer across the joint, poor support conditions, curling (see Curling and Warping in chapter 5, page 150), insufficient slab thickness, inadequate curing, and/or inadequate concrete strength. It is critical that uniform support be provided to prevent excessive stresses resulting from varying support conditions. In addition, the slab is best able to distribute wheel loads at the center of the slab, rather than at the edges; therefore, longitudinal joints in the wheel track should be avoided. Corner breaks are not common when realistic traffic projections are used in the design and where effective, uniform base support and joint load transfer exist.

Transverse Cracks. Transverse cracking is a common type of structural distress in concrete pavements, but not all transverse cracks (also called mid-panel cracks) are indicative of structural failure. Moreover, many transverse cracks may have little or no impact on long-term performance. In general, cracks that do not separate and fault (i.e., undergo differential vertical movement or displacement) are not typically detrimental to pavement structural performance. The transverse crack shown in figure 2-5 is considered a structural distress because faulting is evident. Such a crack has significant structural implications, since the dynamic loading from a rough pavement reduces structural life.

Transverse cracking can be due to a number of factors, including excessive early-age loading, poor joint load transfer, inadequate or nonuniform base support, excessive slab curling and warping (see Curling and Warping in chapter 5, page 150), insufficient slab thickness, inadequate sawing, and materials deficiencies.

Figure 2-4. Corner cracking in jointed concrete pavement (ACPA)

Figure 2-5. Transverse crack that represents structural distress (ACPA)

Longitudinal Cracks. Longitudinal cracking may or may not be considered a structural distress, depending on whether the crack remains tight and nonworking. Figure 2-6 shows a longitudinal crack typical of poor support conditions. Note that the crack has significant separation and shows differential vertical movement, which indicates a structural distress.

Longitudinal cracking is generally associated with poor or nonuniform support conditions related to frost heave, moisture-induced shrinkage/swelling in the subgrade, or poor soil compaction. Longitudinal cracking may also result from inadequate placement of longitudinal joints, over-reinforcing of longitudinal joints, or too-shallow joint saw cuts.

Shattered Slabs. Shattered slabs are divided into three or more pieces by intersecting cracks (figure 2-7). These working cracks allow for differential settlement of the slab sections at a rapid rate.

This type of distress can be attributed to numerous factors, the most important being too-heavy loads, inadequate slab thickness, and poor support.

Functional Performance

Most often, functional performance is thought to consist of ride quality and surface friction, although other factors such as noise and geometrics may also come into play. Functional distress is generally represented by a degradation of a pavement's driving surface that reduces ride quality.

The functional performance of a concrete pavement is impacted by design, construction practice, concrete materials, and environment. Concrete pavement thickness design methods consider structural performance directly and functional performance only in terms of pavement smoothness and faulting, widening, lane capacity, etc. Additional functional distress types are generally considered through specifications governing items like surface friction characteristics.

Some functional distresses, such as alkali-silica reactivity (ASR) and D-cracking, can arise from materials-related problems (see Aggregate Durability in chapter 3, page 47). The cracking and spalling resulting from these distress types affect ride quality, safety, and the structural capacity of the pavement. However, distresses like ASR and D-cracking are not pavement design issues; they must be addressed through mix design and materials selection and verification (see Adjusting Properties in chapter 6, page 185).

Surface friction is an important functional characteristic of pavements. Friction is not considered a design element per se, but has implications for noise and dry- and wet-weather skid resistance.

The friction necessary for skid resistance increases with increasing roughness (texture). Surface texture can be affected by materials in the concrete mixture. For example, aggregates that polish under traffic eventually result in reduced pavement surface texture (see Abrasion Resistance in chapter 5, page 146). Aggregate specifications targeting a minimum silica content in the fine aggregate portion of the concrete mixture are often used to prevent polishing.

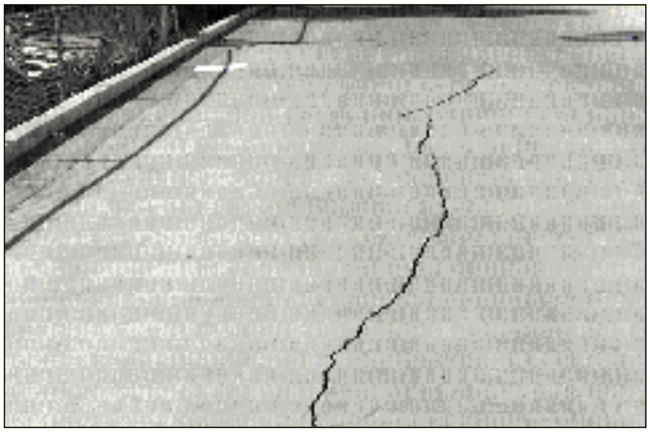

Figure 2-6. Longitudinal crack representing structural distress (ACPA)

Figure 2-7. Shattered slab representing structural distress (ACPA)

Surface texture is also affected by construction practices. Concrete pavement surfaces are generally textured to provide adequate friction and skid resistance. A variety of texturing techniques may be used to promote good friction characteristics (see Texturing in chapter 8, page 221).

Surface texture significantly affects tire-pavement noise. Ride quality is considered a key indicator of functional performance and is affected by both initial construction and the occurrence of distress. Ride quality is generally assumed to equate to pavement smoothness, although this is not always the case.

There are many methods to determine pavement smoothness, ranging from profilographs (appropriate for construction quality control) to noncontact, high-speed inertial profilers (useful for a network-level analysis).

Functional distress is not always distinguishable from structural distress and often may have the same root cause. Structural distress will almost always result in a reduction in functional performance, because structural distresses generally reduce ride quality. Faulting is one example. Faulting results from a combination of inadequate load transfer at the joints,

Surface Texture: Balancing Friction and Noise

Work is ongoing to find the optimum means of achieving satisfactory skid resistance while reducing noise effects at the tire/pavement interface (Rasmussen et al. 2004).

Conventional Texturing Techniques

In general, various tools or materials are dragged across fresh concrete to produce a surface texture. These tools and materials include moistened burlap, brooms, tining rakes, and artificial turf. Another technique is diamond grinding the hardened concrete surface.

Diamond Grinding. Diamond grinding is a process of removing a thin layer of hardened concrete pavement using closely spaced diamond saw blades. Diamond grinding has traditionally been used to restore smoothness to an existing pavement. However, this process has been shown to significantly reduce tire-pavement noise and increase friction; therefore, diamond grinding has become an effective, if somewhat expensive, option for texturing newly placed concrete pavements after a minimum specified curing time.

Drag Textures. Dragging artificial turf or moistened, coarse burlap across the surface of plastic concrete creates a shallow surface texture. This texturing method is inexpensive, results in relatively quiet pavements, and provides sufficient friction characteristics for many roadways, particularly those with speeds less than 72 km/hr (45 mph). Iowa has found that drag textures can provide adequate friction on roadways with higher speeds when the concrete mix includes adequate amounts of durable (e.g., siliceous) sand (Wiegand et al. 2006).

Longitudinal Tining. Longitudinally tined textures are created by moving a tining device (commonly a metal rake controlled by hand or attached to a mechanical device) across the plastic concrete surface in the direction of the pavement. Although skid trailer friction levels of longitudinally tined textures may not be as high as those of transversely tined surfaces (see below), longitudinal tining provides adequate friction on high-speed roadways while sometimes significantly reducing tire-pavement noise.

Variations in the amount of concrete displaced to the surface during tining appear to affect the level of tire-pavement noise. As a result, there are conflicting reports about the effect of tining depth on noise. Further investigation is needed before optimum dimensions can be recommended.

Transverse Tining. Transversely tined textures are created by moving a tining device across the width of the plastic pavement surface. The tines can be uniformly or randomly spaced, or skewed at an angle.

Transverse tining is an inexpensive method for providing durable, high-friction pavement surfaces. The friction qualities are especially evident on wet pavements.

(continued on the following page)

high corner deflections caused by heavy traffic loading, and inadequate or erodible base support conditions.

Joint faulting is shown in figure 2-8. Faulting is also possible where cracks have developed in the pavement, as described earlier. Faulted cracks have the same impact on the functional and structural performance of the pavement as faulted joints.

Figure 2-8. Faulting in jointed concrete pavement (ACPA)

Service Life

Concrete pavements can be designed for virtually any service life, from as little as 10 years to 60 years or more. The primary factors in the design life are

Surface Texture: Balancing Friction and Noise, continued

(continued from previous page)

However, uniform transverse tining has been shown to exhibit undesirable wheel whine noise and should be avoided if possible.

Contrary to earlier studies, recent observations have found that, although randomly spaced and/or skewed transverse tining may reduce the audible whine while providing adequate friction, random and/or skewed transverse tining is not an adequate solution for reducing tire-pavement noise (Wiegand et al. 2006).

If transverse tining is used, it is recommended that a spacing of 12.5 mm (0.5 in.) be used and that care be taken to produce as uniform a texture as possible.

Innovative Techniques

Exposed aggregate pavements and pervious pavements are being investigated for their friction and noise levels.

Exposed Aggregate Pavements. Texture is created on exposed aggregate pavements via a two-layer, “wet on wet” paving process. A thin layer of concrete containing fine siliceous sand and high-quality coarse aggregate is placed over a thicker layer of more modest durability. A set-retarding agent is applied to the newly placed top layer. After 24 hours the surface mortar is brushed or washed away, exposing the durable aggregates.

When designed and constructed properly, these pavements have been reported to improve friction and durability while reducing noise.

In Europe, exposed aggregate pavements are regarded as one of the most advantageous methods for reducing tire-pavement noise while providing adequate friction. Smaller aggregate sizes have been reported to provide larger noise reductions, while aggregates with a high polished stone value increase durability.

In trial projects in North America, however, reported noise levels on exposed aggregate surfaces have not been low. Additional research is ongoing.

Pervious Concrete. Large voids are intentionally built into the mix for pervious, or porous, concrete, allowing water and air to flow through the pavement. The voids tend to absorb tire-pavement noise. The sound absorption levels of pervious concrete pavements have been shown to increase with higher porosity levels and smaller aggregate sizes.

However, European trials have found the acoustical performance and friction characteristics of pervious pavements to be poor, and research continues in this country.

Other Techniques. New technologies, including poroelastic, euphonic, and precast pavements, have demonstrated ability to reduce noise. However, further research must be conducted to predict the noise and friction performance of these construction methods. Contact the National Concrete Pavement Technology Center for information regarding the most recent research (see page iii).

the materials quality and slab thickness. Pavement mixtures with enhanced strength and durability characteristics, combined with enhanced structural design elements, are necessary for long life-spans (FHWA 2002).

Special high-performance concrete mixtures may be specified for long-life pavements. Ideally, such mixtures generally contain high-quality, durable, and well-graded coarse aggregate; a targeted air content (6 to 8 percent entrained, with a spacing factor of <0.20 mm [0.008 in.]) for increased freeze-thaw protection; an appropriate amount of ground, granulated blast-furnace slag or fly ash for reduced permeability; and a water-cementitious materials ratio of 0.40 to 0.43. Another requirement may include a maximum 28-day rapid chloride penetrability (ASTM C 1202) of 1,500 coulombs for concrete permeability. Proper curing is also important. Note that experienced practitioners, using considerable care, may be able to construct long-life pavements with gap-graded aggregate and/or higher water-cementitious materials ratios.

Concrete Properties

Many concrete properties are critical to the performance of concrete pavements over a given design life. Some of these properties are used as inputs to the pavement design process; others are assumed in determining concrete thickness or are not considered in the design process (see chapter 5, Critical Properties of Concrete, page 105).

The most influential concrete properties for concrete performance include strength and stiffness, dimensional stability (drying shrinkage and thermal sensitivity), and durability, which are discussed in the following sections.

Concrete Strength

Concrete strength is a primary thickness design input in all pavement design procedures. Usually, flexural strength (also called the modulus of rupture) is used in concrete pavement design because it characterizes the strength under the type of loading that the pavement will experience in the field (bending) (see Strength and Strength Gain in chapter 5, page 116.)

Flexural strength testing is conducted on a concrete beam under either center-point or third-point loading conditions. The third-point loading configuration, described under ASTM C 78 / AASHTO T 97, is more commonly used in pavement design and provides a more conservative estimate of the flexural strength than the center-point test.

Although flexural strength is specified in design, many State transportation agencies do not mandate the use of beam tests in determining the strength value. Instead, they develop correlations to other tests, such as compressive strength or split tensile strength, which are more convenient and less variable (Kosmatka, Kerkhoff, and Panarese 2002). Each individual concrete mixture has its own correlation of compressive strength to flexural strength. That is, the correlation is mix-specific, can vary from mix to mix, and should be measured in laboratory tests. In general, the correlation can be approximated by the use of either of two equations:

$$MR = a \cdot \sqrt{f_c'} \qquad (2.1)\ \text{(ACPA 2000)}$$

$$MR = b \cdot f_c'^{(2/3)} \qquad (2.2)\ \text{(Raphael 1984)}$$

where,

MR = modulus of rupture (flexural strength), in pounds per square inch (lb/in^2) or megapascal (MPa).

f_c' = compressive strength, lb/in^2 or MPa.

a = coefficient ranging from 7.5 to 10 for lb/in^2, or 0.62 to 0.83 for MPa (coefficient must be determined for specific mixture).

b = 2.3 for lb/in^2, or 0.445 for MPa (exact coefficient must be determined for specific mix).

The more conservative equation should be used, depending on the range of values being used (figure 2-9).

Maturity tests are becoming more common in assessing the in-place strength of concrete for opening the pavement to traffic (ASTM C 1074; ACPA 2003). Maturity testing provides a reliable technique for continuously monitoring concrete strength gain during the first 72 hours. The technology offers several advantages over traditional testing methods. Most important, maturity testing allows pavement owners to open any pavement to traffic as soon as it has attained the necessary strength, without delay, whether or not it is a fast-track project (see Maturity Testing in chapter 5, page 121).

Elastic Modulus

Another concrete property important in pavement design is the elastic modulus, E, which typically ranges from 20 to 40 gigapascal (GPa) (3,000 to 6,000 ksi). The modulus of elasticity, or stiffness, of concrete is a measure of how much the material will deflect under load and strongly influences how the slab distributes loads. The determination of elastic modulus is described in ASTM C 469. However, elastic modulus is often determined from the empirical formula related to compressive strength (ACI 318):

$$E = 57{,}000 \cdot \sqrt{f_c'} \qquad (2.3)$$

$$E = 5{,}000 \cdot \sqrt{f_c'} \qquad (2.4)$$

where,

E = modulus elasticity, lb/in^2 or MPa.

f_c' = compressive strength, lb/in^2 or MPa.

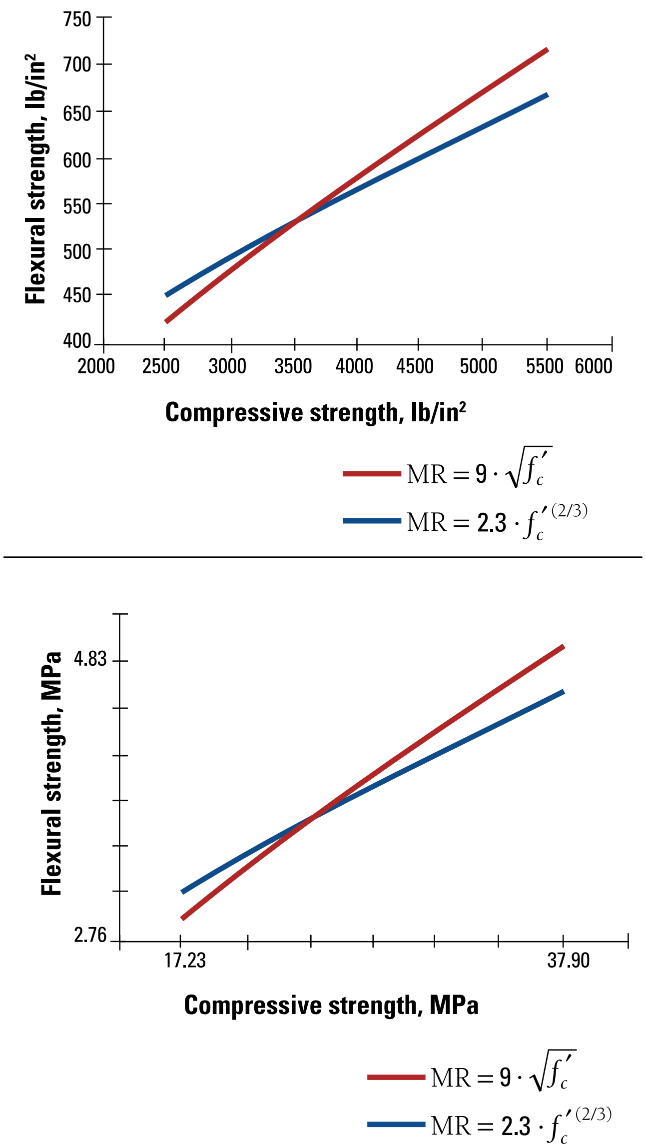

Figure 2-9. Comparison of compressive and flexural strength correlations, based on equations 2.1 and 2.2

Drying Shrinkage and Thermal Expansion/Contraction

Concrete is affected by its drying shrinkage and thermal expansion/contraction properties (see Shrinkage and Temperature Effects in chapter 5, pages 125 and 127, respectively). The effects depend on a number of influential factors, including total water content, types and amounts of cementitious materials, water-cementitious materials ratio, coarse and fine aggregate types and quantities, and curing method.

Slab curling and warping (vertical deflections in the slab due to differential temperatures and moisture contents) are functions of volume changes in the concrete. Excessive curling and warping have a substantial effect on long-term pavement performance in terms of cracking, faulting, and smoothness (see Curling and Warping in chapter 5, page 150).

In the past, concrete volume changes were not a design input. However, volume changes play an important role in the M-E PDG (NCHRP 2004). Accounting for drying shrinkage and thermal expansion/contraction properties in thickness design evaluation leads to better designs that optimize the slab thickness required for the design circumstances.

Joint spacing, another important element of concrete pavement design, should take into account potential volume changes of the concrete from temperature expansion/contraction and curling/warping. Reducing joint spacing typically controls curling and warping. Higher degrees of drying shrinkage and concrete coefficient of thermal expansion can be accommodated without increasing the risk of cracking problems.

Durability

Durable concrete is stable in its environment; that is, it experiences minimum deterioration due to freeze-thaw cycles, adverse chemical reactions between the concrete and its surroundings (for example, deicing chemicals), or internal reactions between the portland cement and aggregates (see the sidebar on Concrete Durability in chapter 5, page 130).

Concrete durability is the most critical aspect of long-term pavement performance. However, durability is not characterized by concrete strength and is not a direct input in design procedures. Instead, durability is assumed in design and governed through appropriate-quality materials and construction specifications. For example, freeze-thaw durability is primarily affected by the environment and the air-void system of the concrete. Alkali-silica reactivity is controlled through specifications by controlling the amount of alkali in the concrete, prohibiting aggregates that have detrimental reactivity, adding an aggregate that limits the expansion of the concrete to an acceptable level, or using an adequate amount of effective pozzolans or ground, granulated blast-furnace slag. D-cracking can be controlled by specifying the quality or maximum size of the coarse aggregate.

However, a pavement designer must be aware of the potential impact of materials selection (made to improve durability) on structural and functional performance. A list of some potential impacts is listed here for illustration:

- Small top-sized coarse aggregates, selected to avoid D-cracking, will likely reduce load transfer at joints.
- Air content targets (for freeze-thaw durability) that exceed six percent will likely decrease the concrete strength achieved at given levels of cement.
- Gravel or relatively hard coarse aggregates produce concrete with a relatively higher elastic modulus (rigidity) than softer aggregates. The elastic modulus affects crack spacing development on CRCP designs and joint spacing requirements on JPCP designs.
- Higher levels of strength used in design may drive increased cement content in the concrete mixture, leading to increased paste content, decreased durability, and a higher risk of cracking.

Relationship of Concrete Durability to Pavement Design

Durability is not a function of concrete strength. Rather, it is an indication of a particular concrete's stability in its environment. Durability is determined by a concrete's susceptibility (preferably, lack of susceptibility) to deterioration due to freeze-thaw cycles, adverse chemical reactions between the concrete and its surroundings (for example, deicing chemicals), or internal reactions between the portland cement and aggregates. Durability also includes the ability of concrete to protect reinforcing steel from corrosion and to resist abrasion.

Concrete durability is not an input in pavement design but is assumed during the pavement design process. Concrete durability is generally the goal of good mix design and materials selection.

Design Considerations: What Site Factors Do We Have to Accommodate?

Key Points

- Concrete pavements need adequate, well-draining, uniform subgrade/base support. Uniformity is especially important.
- Environmental factors can have a significant effect on pavement performance but are not considered in most design procedures. (The design procedure in the NCHRP M-E PDG attempts to incorporate important environmental factors.)
- Traffic data, particularly regarding the anticipated number of trucks and their loadings, are major factors in pavement design.

Factors unique to the location of a particular paving project that significantly affect its design and performance are site factors: subgrade support conditions, environmental forces, and anticipated traffic loadings.

Support

Concrete pavements distribute wheel loads over a large area through the slab. Poor or nonuniform support under the slab, or support degrading with time, causes settlement that leads to cracking and failure. Concrete pavements do not require as much support as other pavement materials, thus reducing the extent of necessary base preparation, but they do require uniform support for good long-term performance.

In concrete pavement design, subgrade support is characterized by the modulus of subgrade reaction (k). The modulus of subgrade reaction can be determined through a plate load test, back-calculation of deflection data, or correlation to other readily determined soil strength parameters.

The support value used in design generally represents a seasonally adjusted average over the design life of the project. It is assumed that the support is nonerodible and relatively constant.

Environmental Factors

Environmental factors like precipitation and temperatures can significantly affect pavement performance.

Generally, pavements exposed to severe climates (e.g., higher rainfall or more freeze-thaw cycling) may not perform as well as pavements in moderate climates. Pavements in similar climatic regions or exposed to similar climatic forces should perform in a similar manner if similar materials, proportions, and construction practices are followed.

Most design procedures, however, do not incorporate environmental factors, or may consider only a few of them indirectly. The M-E PDG (NCHRP 2004) attempts to incorporate some of the important environmental factors into the pavement design process.

Daily and seasonal environmental variations can influence the behavior of concrete pavement in the following ways (Smith and Hall 2001):

- Opening and closing of transverse joints in response to daily and seasonal variation in slab temperature, resulting in fluctuations in joint load transfer capability.
- Upward and downward curling of the slab due to daily cycling of the temperature gradient through the slab thickness (see Curling and Warping in chapter 5, page 150).
- Permanent curling (usually upward), which may occur during construction as high set temperature dissipates.
- Upward warping of the slab due to variation in the moisture gradient through the slab thickness.
- Erosion of base and foundation materials due to inadequate drainage.
- Freeze-thaw weakening of subgrade soils.
- Freeze-thaw damage to some coarse aggregates.
- Corrosion of steel, especially in coastal environments and in areas where deicing salts are used.

Traffic Considerations

Traffic types and loadings anticipated on a roadway over its design life represent a major factor in pavement design. Of particular interest is the number of trucks and their axle loads (axle type, axle weight, number of axles, axle spacing, and load footprint).

Design Procedures: Getting What We Want, Given Site Factors

Key Points

- The design procedure in the NCHRP M-E PDG, which uses mechanistic-empirical design principles, will eventually replace the 1993 AASHTO design procedure.
- Mechanistic-empirical design combines mechanistic principles (stress/strain/deflection analysis and resulting damage accumulation) and empirical data for real-world validation and calibration.
- The validity of any concrete pavement design is only as good as the data used as inputs and the values used for local conditions in the models.
- In a constructability review process, designers partner with construction personnel who have extensive construction knowledge to ensure, early in the design process, that a project is buildable, cost-effective, biddable, and maintainable.

Two important developments are occurring in concrete pavement design: By 2010, the M-E PDG (NCHRP 2004) mechanistic-empirical (M-E) design procedure will likely replace the 1993 AASHTO design procedure. Additionally, many agencies are developing a constructability review process for the early stages of concrete pavement design to help ensure the success of their projects.

Mechanistic-Empirical Design Procedure

Currently, most State agencies are using the 1993 AASHTO design procedure. The 1993 design procedure is an empirical procedure based on the results of the AASHO Road Test conducted near Ottawa, Illinois, from 1958 to 1960.

As of this writing, the M-E PDG, which includes companion software and supporting technical documentation, has been released on a limited basis for industry evaluation. The M-E PDG was developed in an effort to improve the basic pavement design process (NCHRP 2004). It also provides a means to design selective pavement restoration and overlays, integrating materials factors.

The M-E PDG procedure must be locally calibrated so that appropriate values are used for local conditions. Many States are currently beginning calibration efforts by developing the required program inputs. The validity of any concrete pavement design is only as good as the data used as inputs and the values used for local conditions in the models.

M-E design combines mechanistic principles (stress/strain/deflection analysis and resulting damage accumulation) with field verification and calibration. The M-E procedure in the M-E PDG is considered to be a more scientifically based approach than the 1993 AASHTO procedure, incorporating many new aspects of pavement design and performance prediction, and generally results in less conservative designs. Design inputs include elastic modulus, flexural strength (modulus of rupture), and splitting tensile strength.

The M-E approach is radically different from previous design procedures. The M-E procedure is based on the accumulation of incremental damage, in which a load is placed on the pavement at a critical location, the resulting stresses/strains and deflections are calculated, the damage due to the load is assessed, and finally a transfer function is used to estimate the distress resulting from the load. A similar procedure is followed for each load (based on traffic spectra) under the conditions existing in the pavement at the time of load application (considering load transfer, uniformity and level of support, curling and warping, concrete material properties, and so on). The final step is to sum all of the distresses that accumulate in the pavement as a function of time or traffic.

A benefit of M-E analysis is that it predicts specific distress types as a function of time or traffic. Cracking, faulting, and changes in smoothness (based on the International Roughness Index) are estimated.

Threshold values for each distress type are input by the designer based on experience, policy, or risk tolerance.

Constructability Issues

Constructability refers to the feasibility of constructing the proposed pavement design, including the materials, construction, and maintenance aspects. It is the assurance that the pavement design can be capably constructed using available materials and methods and then effectively maintained over its service life.

To help ensure the success of their construction projects, many agencies are exploring development of a constructability review process (CRP). As defined by the AASHTO Subcommittee on Construction, constructability review is "a process that utilizes construction personnel with extensive construction knowledge early in the design stages of projects to ensure that the projects are buildable, while also being cost-effective, biddable, and maintainable" (AASHTO 2000).

Input Parameters for M-E Design

The M-E design procedure (NCHRP 2004) is based on the process of adjusting factors that we can control in order to accommodate factors that we cannot control and to achieve the parameters and performance that we want.

1. What do we want?

All of the following are modeled, based on experience and experimentation, to predict the state of each parameter at the end of the selected design life. The model uses inputs from items 2 and 3 below. If the results are unacceptable, then the parameters that can be changed are adjusted and the model recalculated.

- Acceptable surface roughness at the end of the life.
- Acceptable cracking at the end of the life.
- Acceptable faulting at the end of the life.

2. What do we have to accommodate?

These are parameters that vary from location to location and cannot be changed, but must be accounted for in the modeling.

- Expected traffic loading.
  - Type of traffic (classes).
  - Growth of traffic density with time.
- The climate in which the pavement is built.
- Water table depth.

3. What can we adjust?

These are the parameters that can be adjusted in the design process in order to achieve the properties and performance required in item 1.

- Pavement type (JPCP, JRCP, or CRCP).
- Joint details (load transfer, spacing, sealant).
- Edge support (if any).
- Drainage.
- Layer 1: Concrete properties.
  - Thickness.
  - Strength and modulus of elasticity.
  - Thermal properties (coefficient of thermal expansion, conductivity, heat capacity).
  - Shrinkage.
  - Unit weight.
- Layer 2: Stabilized layer properties.
  - Material type.
  - Thickness.
  - Strength.
  - Thermal properties.
- Layer 3: Crushed stone properties.
  - Strength.
  - Gradation.
- Layer 4: Soil properties .
  - Type (soils classification).
  - Strength.
  - Gradation.

Implementing a CRP is expected to offer the following advantages (AASHTO 2000):

- Enhance early planning.
- Minimize scope changes.
- Reduce design-related change orders.
- Improve contractor productivity.
- Develop construction-friendly specifications.
- Enhance quality.
- Reduce delays.
- Improve public image.
- Promote public/work zone safety.
- Reduce conflicts, disputes, and claims.
- Decrease construction and maintenance costs.

Constructability issues are involved in all aspects of the concrete pavement design and construction process. Furthermore, the issues can range from very general to very detailed. Some constructability issues in the concrete pavement design and construction process at the broadest level include the following:

- Mix design.
- Pavement design.
- Construction.
- Curing and opening to traffic.
- Maintenance.

Mix Design

Are quality materials available for the proposed mix design? Does the proposed mix design provide the required properties (workability, durability, strength) for the proposed application? What special curing requirements may be needed for the mix?

Pavement Design

What design procedure was used in developing the slab thickness design? Was an alternative design procedure used for verification? Have the individual design elements been developed as a part of the entire pavement system? Has an effective jointing plan been developed for intersections or other complex locations?

Construction

Are competent contractors available to do the work? Do the properties of the base and subgrade materials meet the design assumptions? Does the design have any unique construction requirements? What are the duration of construction and the anticipated weather conditions? Is there an extreme weather management plan in place? Are contractors familiar with hot-weather (ACI 305R-99) and cold-weather (ACI 306R-88) concrete construction? Are safeguards in place to prevent rain damage during construction? What curing is required? How will traffic be maintained or controlled during construction?

Curing and Opening to Traffic

What curing is required for the mix design in order to meet opening requirements? What systems are in place to monitor strength gain? What protocols are in place to deal with adverse environmental changes or conditions?

Maintenance

Is the design maintainable? Are there features that may create maintenance problems in the future? Should a longer life design be contemplated to minimize traffic disruptions for future maintenance and rehabilitation activities?

Again, these represent very general items; many more detailed items may be added to the review process. Various levels and frequencies of constructability reviews can be conducted, depending on the scope and complexity of the project. More detailed information on constructability reviews is available from NCHRP (Anderson and Fisher 1997) and AASHTO (2000).

Concrete Overlays

Key Points

- Concrete overlays are used as a rehabilitation technique on existing concrete and asphalt pavements.
- The following types of concrete overlays may be considered: (on existing concrete) bonded concrete overlays and separated concrete overlays, and (on existing asphalt) conventional whitetopping and thin and ultrathin whitetopping.
- If the existing pavement is cracked, the cracks are likely to reflect through the new layer unless a separation layer is provided.
- If the existing pavement is suffering from materials-related distress, in general it should not be overlaid.
- The most important aspect of overlay design is the interface with the existing pavement.

As with conventional concrete pavements, concrete overlays require the use of a durable concrete mixture to produce an effective project. However, a few additional issues need to be considered specific to the design and construction of concrete overlays (see Preparation for Overlays in chapter 7, page 200).

Types of Concrete Overlays

Concrete overlays are being used more often as a rehabilitation technique on existing concrete and existing asphalt pavements. Several types of concrete overlays are available, depending on the type and condition of the existing pavement. Concrete overlays offer many important advantages, including extended service life, increased load-carrying capacity, fast construction times, reduced maintenance requirements, and lower life-cycle costs.

Concrete overlays are classified according to the existing pavement type and the bonding condition between layers, as described below (Smith, Yu, and Peshkin 2002).

Overlays on Concrete Pavements

Concrete overlays on concrete pavements are either bonded or separated.

Bonded Concrete Overlays. A bonded concrete overlay is a thin concrete surface layer (typically 76 to 102 mm [3 to 4 in.] thick) that is bonded to an existing concrete pavement, creating a monolithic structure. Bonded overlays are used to increase the structural capacity of an existing concrete pavement or to improve its overall ride quality.

Bonded overlays should be used only where the underlying pavement is free of structural distress and in relatively good condition, without existing cracks that will reflect through the new layer. To perform well, the joints should be aligned with joints in the support layer, and there should be an adequate bond between the two layers.

Bonding is generally accomplished by milling and then shot-blasting or sand-blasting the existing concrete surface before the overlay is placed.

Separated Concrete Overlays. Separated overlays (sometimes incorrectly called unbonded concrete overlays) contain an interlayer between the existing concrete pavement and the new concrete surface layer. The separation layer is typically one inch of hot mix asphalt. It is placed to ensure independent movement between the two concrete slabs, thereby minimizing the potential for reflection cracking.

The asphalt interlayer bonds to both the original concrete slab and the concrete overlay, adding load carrying capacity but remaining flexible enough to provide required stress relief.

Separated concrete overlays are typically constructed about 150 to 300 mm (6 to 12 in.) thick. Because of the separation layer, they can be placed on concrete pavements in practically any condition. However, overlays on pavements in advanced stages of deterioration or with significant materials-related problems (such as D-cracking or alkali-silica reactivity) should be considered cautiously, because expansive materials-related distresses can cause cracking in the new overlay.

Overlays on Asphalt Pavements (Whitetopping)

Concrete overlays on asphalt pavements include conventional whitetopping and thin or ultrathin whitetopping.

Conventional Whitetopping. Conventional whitetopping is the placement of a concrete overlay on an existing distressed asphalt pavement. This type of overlay is generally designed as a new concrete pavement structure and constructed 150 to 300 mm (6 to 12 in.) thick. In conventional whitetopping, bonding between the concrete overlay and hot mix asphalt pavement is not purposely sought or relied on as part of the design procedure. Such bonding is desirable, however, because it increases the effective thickness through composite action.

Thin and Ultrathin Whitetopping. Thin (TWT) and ultrathin whitetopping (UTW) are rehabilitation processes for existing asphalt pavements, typically on lower volume roadways. These thin treatments have been used most often on State highways and secondary routes.

Thin whitetopping is the placement of a 130- to 200-mm (5- to 8-in.) concrete layer on an asphalt pavement. The existing asphalt pavement may be milled to enhance the bond between the concrete overlay and the asphalt pavement, creating a monolithic structure. Joint spacings between 1.8 and 3.7 m (6 and 12 ft) are typically used.

Ultrathin whitetopping is the placement of a 50- to 100-mm (2- to 4-in.) concrete layer on an existing asphalt pavement. Small square slabs are also used (typically between 1.0 to 1.8 m [3 to 6 ft]). As with thin whitetopping, the existing surface is milled to promote a bond between the two layers and increase load-carrying capacity.

Considerations for Overlays

The most important aspect of overlay design is the interface with the existing pavement.

If the existing concrete pavement is cracked, the cracks are likely to reflect through the new layer unless a separation layer like asphalt is provided.

In separated overlays, using a whitewash layer will help cool the asphalt separation layer and reduce differential thermal stresses in the new concrete layer, but may reduce the bond between the asphalt and the concrete. To cool the asphalt separation layer without reducing the bond between asphalt and concrete, water is sprayed on the asphalt surface, and enough time is allowed for the water to evaporate before the concrete overlay is placed.

Concrete overlays must be well-cured to minimize warping and curling stresses (see Curling and Warping: A Variation of Volume Change in chapter 5, page 150). Thorough curing also provides resistance to both abrasion and water penetration.

Some concrete overlays (particularly the thinner ones) require some additional material considerations:

- For bonded concrete overlays, it is important to match the thermal expansion/contraction effects of the overlay concrete material to the existing concrete substrate (pavement). If two concrete layers with vastly different coefficients of thermal expansion are bonded, the bond line will be stressed during cycles of temperature change. Materials with similar temperature sensitivity will expand and contract similarly at the interface. Thermal expansion/contraction problems generally result from different types of coarse aggregate in the original concrete slab and the concrete overlay (see Thermal Expansion/Contraction in chapter 5, page 129). (This is not an important consideration when whitetopping asphalt.)
- For ultrathin concrete whitetopping on asphalt pavements, including fibers in the overlay concrete mix (see Materials for Dowel Bars, Tiebars, and Reinforcement in chapter 3, page 61) can help control plastic shrinkage cracking and provide post-cracking integrity (Smith, Yu, and Peshkin 2002).

When an Overlay is Not a Good Idea

If the existing pavement is suffering from materials-related distress, it should not be overlaid.

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Chapter 3

Fundamentals of Materials Used for Concrete Pavements

At its simplest, concrete is a mixture of glue (cement, water, and air) binding together fillers (aggregate) (figure 3-1). But other materials, like supplementary cementitious materials (SCMs) and chemical admixtures, are added to the mixture. During pavement construction, dowel bars, tiebars, and reinforcement may be added to the system, and curing compounds are applied to the concrete surface. All these materials affect the way concrete behaves in both its fresh and hardened states.

This chapter discusses each material in turn: why it is used, how it influences concrete, and the standard specifications that govern its use.

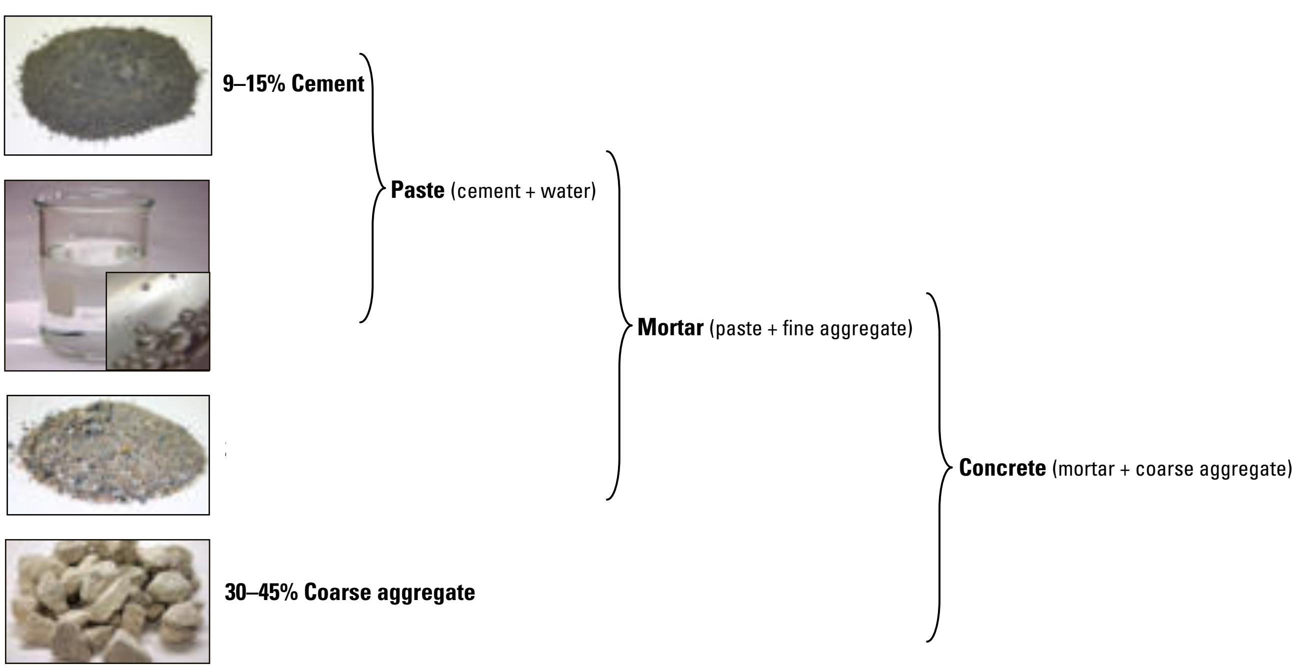

Figure 3-1. Concrete is basically a mixture of cement, water/air, and aggregates (percentages are by volume). (PCA)

Cementitious Materials

Key Points

- Cement is the glue that binds concrete together, and its chemical composition influences concrete behavior.
- Cementitious materials include hydraulic cements and a variety of pozzolans that act like or complement the behavior of hydraulic cements.
- Hydraulic cements react with water in a nonreversible chemical reaction (hydration) to form hydrated cement paste, a strong, stiff material.
  - Portland cement is a type of hydraulic cement commonly used in construction.
  - Blended cements are a manufactured blend of portland cement and one or more supplementary cementitious materials (SCMs) and, like portland cement, are used in all aspects of concrete construction.
- SCMs contribute to the fresh and hardened properties of concrete. Their basic chemical components are similar to portland cement.
  - Some SCMs behave like hydraulic cements, others like pozzolans, and some like both.
  - Pozzolans react chemically with calcium hydrate (CH) to form additional calcium silicate hydrate (C-S-H), a beneficial product of cement hydration that contributes to concrete strength and impermeability.
  - Fly ash is the most widely used SCM. It is used in about 50 percent of ready-mixed concrete.
  - Fly ash and ground, granulated blast-furnace (GGBF) slag can be beneficial in mixtures for paving projects because they prolong the strength-gaining stage of concrete.
  - It is important to test mixtures containing SCMs to ensure they are achieving the desired results, to verify the correct dosage, and to detect any unintended effects.
- Hydraulic cements can be specified using prescriptive-based specifications (ASTM C 150 / AASHTO M 85 or ASTM C 595 / AASHTO M 240) or by a performance specification (ASTM C 1157). Fly ash and natural pozzolans can be specified using ASTM C 618 / AASHTO M 295. GGBF slag can be specified using ASTM C 989 / AASHTO M 302.
- See chapter 4 for details about cement chemistry and hydration.

Cement paste (cement, water, and air) is the glue that binds together the aggregates in concrete. Although aggregates account for most of the volume in concrete, cement significantly influences the behavior of fresh and hardened concrete. For example, the hydration products of cement are most likely to be affected by chemical attack and to change dimensionally with a changing environment (e.g., drying shrinkage).

Portland cement is the most common cement used in concrete for construction. Supplementary cementitious materials (SCMs) like fly ash and ground, granulated blast-furnace (GGBF) slag are typically added to portland cement in concrete for pavements.

This section introduces the characteristics and behavior of all cementitious materials, including hydraulic cements (portland cements and blended cements) and SCMs.

For specific information on the chemistry of cements and cement hydration, see all of chapter 4. (For specific information on proportioning cementitious materials in concrete mixtures, see Absolute Volume Method in chapter 6, page 179.)

Hydraulic Cement

Hydraulic cement is a material that sets and hardens when it comes in contact with water through a chemical reaction called hydration, and is capable of doing so under water (ASTM C 125-03). Hydration is a nonreversible chemical reaction. It results in hydrated cement paste, a strong, stiff material. (For a complete discussion of hydraulic cement chemistry and hydration, see chapter 4, page 69.)

Hydraulic cements include portland cement and blended cements. (Other types of hydraulic cements are rapid-setting calcium sulfo-alumina cements used for repair materials or for pavements where fast turnaround times are critical [Kosmatka, Kerkhoff, and Panarese 2002].)

Portland Cement (ASTM C 150 / AASHTO M 85)

Portland cement is the most common hydraulic cement used in concrete for construction. It is composed primarily of calcium silicates, with a smaller proportion of calcium aluminates (see chapter 4 for more details of these compounds). By definition, the composition of portland cement falls within a relatively narrow band.

Portland cement is made by heating carefully controlled amounts of finely ground siliceous materials (shale) and calcareous materials (limestone) to temperatures above 1,400°C (2,500°F). The product of this burning is a clinker, normally in the form of hard spheres approximately 25 mm (1 in.) in diameter. The clinker is then ground with gypsum to form the gray or white powder known as portland cement. (The inventor of the first portland cement thought its color was similar to that of rock found near Portland, England; thus, the name.) The average Blaine fineness of modern cements ranges from 300 to 500 m^2/kg.

Different types of portland cement are manufactured to meet physical and chemical requirements for specific purposes and to meet the requirements of ASTM C 150 / AASHTO M 85 or ASTM C 1157 (Johansen et al. 2005). Despite their broad similarities, there are some significant differences between the AASHTO and ASTM requirements. When ordering cements, be sure to inform the manufacturer which specification applies.

Cementitious Materials

	Hydraulic cements	Pozzolans (or materials with pozzolanic characteristics)
	Portland cement Blended cement	
Supplementary cementitious materials	GGBF slag Class C fly ash	Class C fly ash Class F fly ash Natural pozzolans (calcined clay, calcined shale, metakaolin) Silica fume

Simple Definitions

Cement (hydraulic cement)—material that sets and hardens by a series of nonreversible chemical reactions with water, a process called hydration.

Portland cement—a specific type of hydraulic cement.

Pozzolan—material that reacts with cement and water in ways that improve microstructure.

Cementitious materials—all cements and pozzolans.

Supplementary cementitious materials—cements and pozzolans other than portland cement.

Blended cement—factory mixture of portland cement and one or more SCM.

ASTM C 150 / AASHTO M 85 describe types of portland cement using Roman numeral designations (table 3-1). You might see these type designations with the subscript "A," which indicates the cement contains air-entraining admixtures. However, air-entraining cements are not commonly available.

Blended Cements (ASTM C 595 / AASHTO M 240)

Blended cements are manufactured by grinding or blending portland cement (or portland cement clinker) together with SCMs like fly ash, GGBF slag, or another pozzolan (see Supplementary Cementitious Materials later in this chapter, page 31).

Blended cements are used in all aspects of concrete construction in the same way as portland cements. Like portland cements, blended cements can be the only cementitious material in concrete or they can be used in combination with other SCMs added at the concrete plant.

Blended cements are defined by ASTM C 595 / AASHTO M 240, which are prescriptive-based specifications (table 3-2). Like portland cements, blended cements can be used under ASTM C 1157, a performance-based specification.

Performance Specification for Hydraulic Cements (ASTM C 1157)

ASTM C 1157 is a relatively new specification that classifies hydraulic cements by their performance attributes rather than by their chemical composition. Under ASTM C 1157, hydraulic cements must meet physical performance test requirements, as opposed to prescriptive restrictions on ingredients or chemistry as found in other cement specifications.

ASTM C 1157 is designed generically for hydraulic cements, including portland cement and blended cement, and provides for six types (table 3-3).

Selecting and Specifying Hydraulic Cements

When specifying cements for a project, check the local availability of cement types; some types may not be readily available in all areas. If a specific cement

Using Blended Cements

There are advantages to using a manufactured blended cement in a concrete mix instead of adding portland cement and one or more SCMs separately to the mix at the concrete plant: By blending the cement and SCMs at the cement manufacturing plant, the chemical composition of the final product can be carefully and deliberately balanced, thereby reducing the risk of incompatibility problems (see Potential Materials Incompatibilities in chapter 4, page 97). There is also less variability in the properties of a manufactured blended cement compared to SCMs added at the concrete plant.

Table 3-1. Portland Cement Classifications (ASTM C 150 / AASHTO M 85)

Type	Description
I	Normal
II	Moderate sulfate resistance
III	High early strength
IV	Low heat of hydration
V	High sulfate resistance

Table 3-2. Blended Cement Classifications (ASTM C 595 / AASHTO M 240)

Type	Blend
IS	Portland blast-furnace slag cement
IP and P	Portland-pozzolan cement
I(PM)	Pozzolan-modified portland cement
S	Slag cement
I(SM)	Slag-modified portland cement

Table 3-3. Performance Classifications of Hydraulic Cement (ASTM C 1157)

Type	Performance
GU	General use
HE	High early strength
MS	Moderate sulfate resistance
MH	Moderate heat of hydration
LH	Low heat of hydration

type is not available, you may be able to achieve the desired concrete properties by combining another cement type with the proper amount of certain SCMs. For example, a Type I cement with appropriate amounts of fly ash may be able to provide a lower heat of hydration.

Allow flexibility in cement selection. Limiting a project to only one cement type, one brand, or one standard cement specification can result in increased costs and/or project delays, and it may not allow for the best use of local materials.

Do not require cements with special properties unless the special properties are necessary.

As with other concrete ingredients, if an unfamiliar portland cement or blended cement is to be used, the concrete should be tested for the properties required in the project specifications (PCA 2000; Detwiler, Bhatty, and Bhattacharja 1996).

Project specifications should focus on the needs of the concrete pavement and allow the use of a variety of materials to meet those needs. A cement may meet the requirements of more than one type or specification. Table 3-4 lists hydraulic cement types for various applications.

Supplementary Cementitious Materials

In at least 60 percent of modern concrete mixtures in the United States, portland cement is supplemented or partially replaced by SCMs (PCA 2000). When used in conjunction with portland cement, SCMs contribute to the properties of concrete through hydraulic or pozzolanic activity or both.

Hydraulic materials will set and harden when mixed with water. Pozzolanic materials require a source of calcium hydroxide (CH), usually supplied by hydrating portland cement. GGBF slags are hydraulic materials, and Class F fly ashes are typically pozzolanic. Class C fly ash has both hydraulic and pozzolanic characteristics.

Table 3-4. Cement Types for Common Applications*

Cement specification	General purpose	Moderate heat of hydration (massive elements)	High early strength (patching)	Low heat of hydration (very massive elements)	Moderate sulfate resistance (in contact with sulfate soils)	High sulfate resistance (in contact with sulfate soils)	Resistance to alkali-silica reactivity ** (for use with reactive aggregates)
ASTM C 150 / AASHTO M 85 portland cements	I	II (moderate heat option)	III	IV	II	V	Low alkali option
ASTM C 595 / AASHTO M 240 blended hydraulic cements	IS, IP, I(PM), I(SM), P, S	IS(MH), IP(MH), I(PM)(MH), I(SM)(MH)		P(LH)	IS(MS), IP(MS), P(MS), I(PM)(MS), I(SM)(MS)		Low reactivity option
ASTM C 1157 hydraulic cements ***	GU	MH	HE	LH	MS	HS	Option R

Source: Adapted from Kosmatka, Kerkhoff, and Panarese (2002)
* Check the local availability of specific cements, as all cements are not available everywhere.
** The option for low reactivity with aggregates can be applied to any cement type in the columns to the left.
*** For ASTM C 1157 cements, the nomenclature of hydraulic cement, portland cement, modified portland cement, or blended hydraulic cement is used with the type designation.

Use of SCMs in concrete mixtures has been growing in North America since the 1970s. There are similarities among many of these materials:

- SCMs' basic chemical components are similar to those of portland cement.
- Most SCMs are byproducts of other industrial processes.
- The judicious use of SCMs is desirable not only for the environment and energy conservation, but also for the technical benefits they provide to concrete.

SCMs can be used to improve a particular concrete property, like resistance to alkali-aggregate reactivity. However, mixtures containing SCMs should be tested to determine whether (1) the SCM is indeed improving the property, (2) the dosage is correct (an overdose or underdose can be harmful or may not achieve the desired effect), and (3) there are any unintended effects (for example, a significant delay in early strength gain). It is also important to remember that SCMs may react differently with different cements (see Potential Materials Incompatibilities, page 97).

Traditionally, fly ash, GGBF slag, calcined clay, calcined shale, and silica fume have been used in concrete individually. Today, due to improved access to these materials, concrete producers can combine two or more of these materials to optimize concrete properties. Mixtures using three cementitious materials, called ternary mixtures, are becoming more common.

Table 3-5 lists the applicable specifications SCMs should meet. The use of these materials in blended cements is discussed by Detwiler, Bhatty, and Bhattacharja (1996). Table 3-6 provides typical chemical analyses and selected properties of several pozzolans.

Types of Supplementary Cementitious Materials

Fly Ash. Fly ash is the most widely used SCM in concrete. It is used in about 50 percent of ready-mixed concrete (PCA 2000).

Class F and Class C fly ashes are pozzolans. Some Class C ashes, when exposed to water, will hydrate and harden, meaning that they may also be considered a hydraulic material.

Fly ash generally affects concrete as follows:

- Less water is normally required to achieve workability.
- Setting time may be delayed.
- Early strengths may be depressed, but later strengths are increased, because fly ash reaction rates are initially slower but continue longer.
- Heat of hydration is reduced.
- Resistance to alkali-silica reaction and sulfate attack may be improved when the appropriate ash substitution rate is used.
- Permeability is reduced; consequently, resistance to chloride ion penetration is improved.
- Incompatibility with some cements and chemical admixtures may cause early stiffening.

Class F fly ash is generally used at dosages of 15 to 25 percent by mass of cementitious material; Class C fly ash is generally used at dosages of 15 to 40 percent. Dosage should be based on the desired effects on the concrete (Helmuth 1987, ACI 232 2003).

Fly ash is a byproduct of burning finely ground coal in power plants. When it is used as an SCM in concrete mixtures, utilities do not have to dispose of it as a waste material. During combustion of pulverized coal, residual minerals in the coal melt and fuse in suspension and then are carried through the combustion chamber by the exhaust gases. In the process, the fused material cools and solidifies into spherical glassy ash particles (figure 3-2). The fly ash is then collected from the exhaust gases by electrostatic precipitators or fabric bag filters.

Table 3-5. Specifications for Supplementary Cementitious Materials

Type of SCM	Specifications
Ground, granulated blast-furnace slag	ASTM C 989 / AASHTO M 302
Fly ash and natural pozzolans	ASTM C 618 / AASHTO M 295
Silica fume	ASTM C 1240
Highly reactive pozzolans	AASHTO M 321

Fly ash is primarily silicate glass containing silica, alumina, calcium, and iron (the same primary components of cement). Minor constituents are sulfur, sodium, potassium, and carbon, all of which can affect concrete properties. Crystalline compounds should be present in small amounts only. The relative density (specific gravity) of fly ash generally ranges between 1.9 and 2.8. The color is gray or tan. Particle sizes vary from less than 1 µm to more than 100 µm, with the typical particle size measuring under 35 µm. The surface area is typically 300 to 500 m²/kg, similar to cement (figure 3-3).

Fly ash will lose mass when heated to 1,000°C (1,830°F), mainly due to organic volatiles and combustion of residual carbon. This mass loss is referred to as loss-on-ignition (LOI) and is limited in

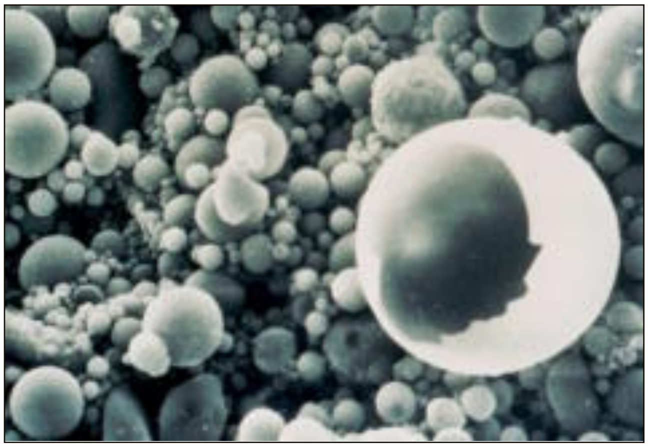

Figure 3-2. Scanning electron micrograph of fly ash particles. Note the characteristic spherical shape that helps improve workability. Average particle size is approximately 10 µm. (PCA)

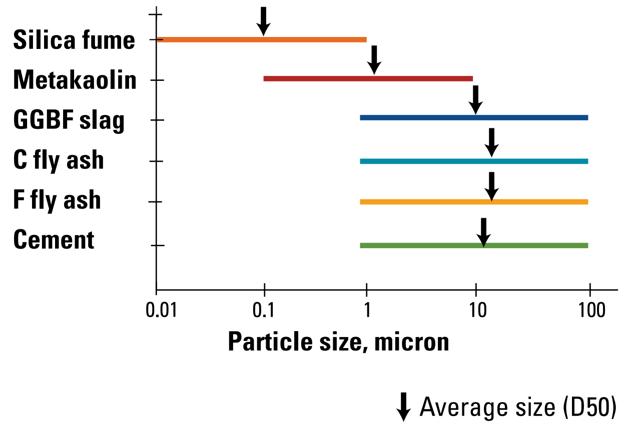

Figure 3-3. Typical size distributions of cementitious materials (CTLGroup)

Table 3-6. Chemical Analyses and Selected Properties of Type I Cement and Several Supplementary Cementitious Materials

	Type I cement	Class F fly ash	Class C fly ash	GGBF slag	Silica fume	Metakaolin
Silica (SiO_2), %	22.00	52.00	35.00	35.00	90.00	53.00
Alumina (Al_2O_3), %	5.00	23.00	18.00	12.00	0.40	43.00
Iron oxide (Fe_2O_3), %	3.50	11.00	6.00	1.00	0.40	0.50
Calcium oxide (CaO), %	65.00	5.00	21.00	40.00	1.60	0.10
Sulfate (SO_4), %	1.00	0.80	4.10	9.00	0.40	0.10
Sodium oxide (Na_2O), %	0.20	1.00	5.80	0.30	0.50	0.05
Potassium oxide (K_2O), %	1.00	2.00	0.70	0.40	2.20	0.40
Total eq. alkali (as Na_2O), %	0.77	2.20	6.30	0.60	1.90	0.30
Loss on ignition, %	0.20	2.80	0.50	1.00	3.00	0.70
Blaine fineness, m²/kg	350.00	420.00	420.00	400.00	20,000.00	19,000.00
Relative density	3.15	2.38	2.65	2.94	2.40	2.50

Source: Kosmatka, Kerkhoff, and Panarese (2002) most specifications to less than 6 percent. Class F fly ashes typically contain less than 10 percent calcium (CaO), with 5 percent LOI. Class C materials often contain 18 to 30 percent calcium (CaO), with less than 2 percent LOI.

ASTM C 618 / AASHTO M 295 Class F and Class C fly ashes are used in many different types of concrete. For more information on fly ash, see ACAA (2003) and ACI 232 (2003).

Ground, Granulated Blast-Furnace Slag. GGBF slag, also called slag cement, has been used as a cementitious material in concrete since the beginning of the 1900s (Abrams 1924). Because of its chemistry, GGBF slag behaves as a cement in that it will hydrate without the presence of added calcium, although hydration rates are accelerated when the pH of the system is increased.

Ground, granulated blast-furnace slag generally affects concrete as follows:

- Slightly less water is required to achieve the same workability.
- Setting time may be delayed.
- Early strengths may be depressed, but later strengths are increased.
- Resistance to chloride penetration is significantly improved.

When used in general purpose concrete in North America, GGBF slag commonly constitutes up to 35 percent of the cementitious material in paving mixes. Higher dosages may be considered if required for providing resistance to alkali-silica reaction or for reducing heat of hydration.

GGBF slag is a byproduct of iron smelting from iron ore. It is the molten rock material that separates from the iron in a blast furnace. It is drained from the furnace and granulated by pouring it though a stream of cold water, or pelletized by cooling it in cold water and spinning it into the air out a rotary drum. The resulting quenched solid is a glassy material that is ground to a size similar to portland cement (figure 3-4). (Slag that is not rapidly cooled or granulated is not useful as an SCM, but can be used as a coarse aggregate.)

The granulated material is normally ground to a Blaine fineness of about 400 to 700 m^2/kg. The relative density (specific gravity) for GGBF slag is in the range of 2.85 to 2.95. The bulk density varies from 1,050 to 1,375 kg/m^3 (66 to 86 lb/ft^3).

GGBF slag consists essentially of silicates and aluminosilicates of calcium, the same basic components in portland cement or fly ash. GGBF slag generally does not contain tricalcium aluminate (C_3A), which affects setting.

ASTM C 989 / AASHTO M 302 classify GGBF slag by its level of reactivity as Grade 80, 100, or 120 (where Grade 120 is the most reactive). ACI 233 (2003) provides an extensive review of GGBF slag.

Natural Pozzolans. In general, pozzolans are included in concrete mixtures to help convert calcium hydroxide (CH), a less desirable product of hydration, into the more desirable calcium silicate hydrate (C-S-H) (see the discussion of CH to C-S-H conversion in the section on Pozzolanic SCMs in chapter 4, page 94).

Natural pozzolans have been used for centuries. The term "pozzolan" comes from a volcanic ash mined at Pozzuoli, a village near Naples, Italy. However, the use of volcanic ash and calcined clay dates back to 2,000 BCE and earlier in other cultures. Many of the Roman, Greek, Indian, and Egyptian pozzolan concrete structures can still be seen today, attesting to the durability of these materials.

ASTM C 618 defines Class N pozzolans as "raw or calcined natural pozzolans." The most common Class N pozzolans used today are processed materials,

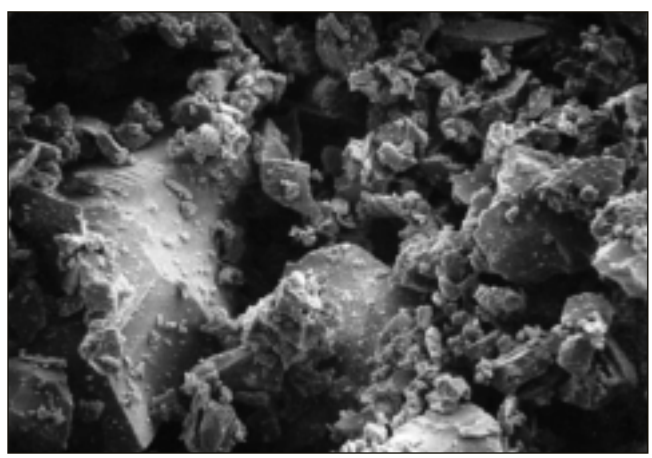

Figure 3-4. Scanning electron micrograph of GGBF slag particles. Note the angular shape. (PCA)

having been heat-treated in a kiln and then ground to a fine powder; they include calcined clay, calcined shale, and metakaolin.

Calcined clays are used in general purpose concrete construction in much the same way as other pozzolans. They can be used as a partial replacement for cement, typically in the range of 15 to 35 percent, and can enhance strength development and resistance to sulfate attack, control alkali-silica reactivity, and reduce permeability. Calcined clays have a relative density between 2.40 and 2.61, with Blaine fineness ranging from 650 to 1,350 m^2/kg.

Calcined shale may contain on the order of 5 to 10 percent calcium, which results in its having some cementing or hydraulic properties.

Metakaolin is produced by low-temperature calcination of high-purity kaolin clay. The product is ground to an average particle size of about 1 to 2 µm; this is about 10 times finer than cement, but still 10 times coarser than silica fume. Metakaolin is used in special applications where very low permeability or very high strength is required. In these applications, metakaolin is used more as an additive to the concrete rather than a replacement of cement; typical additions are around 10 percent of the cement mass.

Natural pozzolans are classified as Class N pozzolans by ASTM C 618 / AASHTO M 295. ACI 232 (2003) provides a review of natural pozzolans.

Silica Fume. Because it can reduce workability and is expensive, silica fume is typically not used in pavements except for special applications such as those subjected to studded tires or in curbs and gutters.

Silica fume, also referred to as microsilica or condensed silica fume, is a byproduct of the silicon or ferrosilicone industries. The product is the vapor that rises from electric arc furnaces used to reduce high-purity quartz with coal. When it cools, it condenses and is collected in cloth bags, then processed to remove impurities. The particles are extremely small, some 100 times smaller than cement grains, and are mainly glassy spheres of silicon oxide.

The loose bulk density is very low and the material is difficult to handle. In order to make it easier to handle, silica fume is usually densified by tumbling in an air stream that causes the particles to agglomerate into larger grains held together by electrostatic forces. It is important that concrete mixtures containing silica fume are batched and mixed in a way that ensures that the agglomerations are broken up and the material is uniformly distributed in the mix.

The material is used as a pozzolan and is specified in ASTM C 1240. The water requirement of silica fume may be high, requiring that superplasticizers be used in concrete containing more than five percent by mass of cement. The resulting concrete normally exhibits significantly increased strength and reduced permeability. Concrete containing silica fume is often at higher risk of plastic shrinkage cracking because bleeding is markedly reduced. Specific gravity of silica fume is in the range 2.2 to 2.6.

Other Pozzolans. Other industrial byproducts like rice husk ash are potentially useful as concrete constituents. A specification has been recently developed by AASHTO M 321 to serve as a specification for

Effect of Pozzolans in Cement Paste

In very broad terms, the primary reaction in hydrating cement is the following:

water + cement = calcium silicate hydrate (C-S-H) + calcium hydroxide (CH)

Calcium silicate hydrate (C-S-H) is the primary compound that contributes to the strength and impermeability of hydrated cement paste. Calcium hydroxide (CH) is not as strong and is more soluble, so it is somewhat less desirable.

Adding a pozzolan like fly ash, in the presence of water, results in conversion of the calcium hydroxide (CH) to more calcium silicate hydrate (C-S-H):

calcium hydroxide (CH) + pozzolan + water = calcium silicate hydrate (C-S-H)

This conversion is a significant benefit of adding pozzolans like fly ash to the mixture. (See chapter 4, page 69, for a detailed description of cement chemistry and hydration, including the effects of specific SCMs on the hydration process.)

these materials, which may not fall under categories covered by other specifications.

Effects of Supplementary Cementitious Materials in Concrete

SCMs in concrete affect a wide range of fresh and hardened concrete properties. Some of the effects may be considered desirable and are the reason why the materials are used. Other side effects may be less desirable and have to be accommodated. An understanding of all the potential effects is essential to prevent surprises.

The effects of SCMs on properties of fresh and hardened concrete are briefly discussed in the following sections and summarized in tables 3-7 and 3-8, respectively (see chapter 5, page 105, for a complete discussion of concrete properties).

In most cases, the extent of change in concrete behavior will depend on the particular material used, the amount used, and the properties of other ingredients in the concrete mixture.

Trial batching with unfamiliar material combinations is essential to provide assurance of critical concrete properties.

Fresh Properties. In fresh concrete, SCMs can affect workability and setting times in the following ways:

- Workability is always changed by SCMs. Fly ash will generally increase workability, as will GGBF slag to a lesser extent. Silica fume may significantly reduce workability at dosages above five percent.
- The rate of slump loss (stiffening) may be increased if there are chemical incompatibilities (see Potential Materials Incompatibilities in chapter 4, page 97).
- Setting times may be delayed and early strength gain slowed if GGBF slag and fly ash are included. However, this effect will depend on the product used.

All of these factors can have a significant effect on the timing of finishing and saw cutting in pavements, making it important that the performance of the cementitious system being selected for a project be tested in trial batches well before the project starts. Trial batches need to be tested at the temperatures expected when the paving operation will be conducted.

Durability/Permeability. SCMs generally improve potential concrete durability by reducing permeability. Almost all durability-related failure mechanisms involve the movement of fluids through the concrete. Tests show that the permeability of concrete decreases as the quantity of hydrated cementitious materials increases and the water-cementitious materials ratio decreases.

With adequate curing, fly ash, GGBF slag, and natural pozzolans generally reduce the permeability and absorption of concrete. GGBF slag and fly ash can result in very low chloride penetration test results at later ages. Silica fume and metakaolin are especially effective and can provide concrete with very low chloride penetration (Barger et al. 1997).

In order for SCMs to improve durability, they must be of adequate quality and used in appropriate amounts, and finishing and curing practices must be appropriate.

Alkali-Silica Reactivity Resistance. Alkali-silica reactivity (ASR) of most reactive aggregates (see Aggregate Durability later in this chapter, page 47) can be controlled with the use of certain SCMs. Low-calcium Class F fly ashes have reduced reactivity expansion up to 70 percent or more in some cases. At optimum dosage, some Class C fly ashes can also reduce reactivity, but at a low dosage a high-calcium Class C fly ash can exacerbate ASR.

SCMs reduce ASR (Bhatty 1985, Bhatty and Greening 1978) by (1) providing additional calcium silicate hydrates (C-S-H) that chemically tie up the alkalies in the concrete, (2) diluting the alkali content of the system, and (3) reducing permeability, thus slowing the ingress of water.

It is important to determine the optimum dosage for a given set of materials to maximize the reduction in reactivity and to avoid dosages and materials that can aggravate reactivity. Dosage rates should be verified by tests, such as ASTM C 1567 or ASTM C 1293. (Descriptions of aggregate testing and preventive measures to be taken to prevent deleterious alkali-aggregate reaction are discussed later in this chapter under Aggregate Durability, page 47.)

Table 3-7. Effects of Supplementary Cementitious Materials on Fresh Concrete Properties

	Fly ash				Natural pozzolans		
	Class F	Class C	GGBF slag	Silica fume	Calcined shale	Calcined clay	Metakaolin
Water requirements	↓↓	↓↓	↓	↑↑	↔	↔	↑
Workability	↑	↑	↑	↓↓	↑	↑	↓
Bleeding and segregation	↓	↓	↕	↓↓	↔	↔	↓
Air content	↓↓*	↓*	↓	↓↓	↔	↔	↓
Heat of hydration	↓	↕	↓	↔	↓	↓	↓
Setting time	↑	↕	↑	↔	↑	↑	↔
Finishability	↑	↑	↑	↕	↑	↑	↑
Pumpability	↑	↑	↑	↑	↑	↑	↑
Plastic shrinkage cracking	↔	↔	↔	↑	↔	↔	↔

Sources: Thomas and Wilson (2002b); Kosmatka, Kerkhoff, and Panarese (2003)

* Effect depends on properties of fly ash, including carbon content, alkali content, fineness, and other chemical properties.

Key:
↓ reduced
↓↓ significantly reduced
↑ increased
↑↑ significantly increased
↔ no significant change
↕ effect varies

Table 3-8. Effects of Supplementary Cementitious Materials on Hardened Concrete Properties

	Fly ash				Natural pozzolans		
	Class F	Class C	GGBF slag	Silica fume	Calcined shale	Calcined clay	Metakaolin
Early strength	↓	↔	↓	↑↑	↓	↓	↑↑
Long-term strength	↑	↑	↑	↑↑	↑	↑	↑↑
Permeability	↓	↓	↓	↓↓	↓	↓	↓↓
Chloride ingress	↓	↓	↓	↓↓	↓	↓	↓↓
ASR	↓↓	↕	↓↓	↓	↓	↓	↓
Sulfate resistance	↑↑	↕	↑↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage	↔	↔	↔	↔	↔	↔	↔

Sources: Thomas and Wilson (2002b); Kosmatka, Kerkoff, and Panarese (2003)

Key:
↓ reduced
↓↓ significantly reduced
↑ increased
↑↑ significantly increased
↔ no significant change
↕ effect varies

SCMs that reduce alkali-silica reactions will not reduce alkali-carbonate reactions, a type of reaction involving cement alkalies and certain dolomitic limestones.

Sulfate Resistance. With proper proportioning and materials selection, silica fume, fly ash, natural pozzolans, and GGBF slag can improve the resistance of concrete to external sulfate attack. This is done primarily by reducing permeability and by reducing the amount of reactive elements (such as tricalcium aluminate, C_3A) that contribute to expansive sulfate reactions.

One study showed that for a particular Class F ash, an adequate amount was approximately 20 percent of the cementitious system (Stark 1989). It is effective to control permeability through mixtures with low water-cementitious materials ratios (see the section on Sulfate Resistance in chapter 5, page 139).

Concretes with Class F ashes are generally more sulfate resistant than those with Class C ashes. GGBF slag is generally considered beneficial in sulfate environments. However, one long-term study in a very severe environment showed only a slight improvement in sulfate resistance in concrete containing GGBF slag compared to concrete containing only portland cement as the cementing material (Stark 1989, 1996).

Calcined clay has been demonstrated to provide sulfate resistance greater than high-sulfate resistant Type V cement (Barger et al. 1997).

Resistance to Freeze-Thaw Damage and Deicer Scaling. There is a perception that concrete containing SCMs is more prone to frost-related damage than plain concrete. This is partially due to the severity of the test methods used (ASTM C 666, ASTM C 672), but may also be related to the changing bleed rates and finishing requirements for concretes with SCMs (Taylor 2004). With or without SCMs, concrete that is exposed to freezing cycles must have sound aggregates (see Aggregate Durability later in this chapter, page 47), adequate strength, a proper air-void system, and proper curing methods.

For concrete subject to deicers, the ACI 318 (2002) building code states that the maximum dosage of fly ash, GGBF slag, and silica fume should be 25 percent, 50 percent, and 10 percent by mass of cementitious materials, respectively. Total SCM content should not exceed 50 percent of the cementitious material. Concretes, including pavement mixtures, with SCMs at dosages higher than these limits may still be durable, however.

Selection of materials and dosages should be based on local experience. Durability should be demonstrated by field or laboratory performance when new materials and dosages are introduced.

Drying Shrinkage. When used in low to moderate amounts, the effect of fly ash, GGBF slag, calcined clay, calcined shale, and silica fume on the drying shrinkage of concrete of similar strength is generally small and of little practical significance.

Aggregates

Key Points

- In concrete, aggregate (rocks and minerals) is the filler held together by the cement paste. Aggregate forms the bulk of the concrete system.
- Aggregates are generally chemically and dimensionally stable; therefore, it is desirable to maximize aggregate content in concrete mixtures compared to the more chemically reactive cement paste.
- Aggregate strongly influences concrete's fresh properties (particularly workability) and long-term durability.
- It is critical that aggregate be well-graded (that is, there should be a wide range of aggregate sizes). Well-graded aggregate has less space between aggregate particles that will be filled with the more chemically reactive cement paste. It also contributes to achieving a workable mix with a minimum amount of water.
- For durable concrete pavements, the aggregate should be durable (in general, not alkali reactive, prone to frost damage, or susceptible to salt damage). Many kinds of aggregate can be used, but granite and limestone are common in concrete pavements.
- Always prepare trial batches of concrete using the specific project aggregates to establish the final mixture characteristics and, if necessary, make adjustments to the mix.
- The physical and durability requirements of aggregate for concrete mixtures, as well as classifications of coarse and fine aggregates, are covered in ASTM C 33.

Aggregate—rocks and minerals—is the filler held together by cement paste. Aggregate typically accounts for 60 to 75 percent of concrete by volume. Compared to cement paste, aggregates are generally more chemically stable and less prone to moisture-related volume changes. Therefore, in concrete mixtures it is desirable to maximize the volume of aggregate and reduce the volume of cement while maintaining desired concrete properties.

Aggregates used in concrete mixtures for pavements must be clean, hard, strong, and durable and relatively free of absorbed chemicals, coatings of clay, and other fine materials that could affect hydration and bonding with the cement paste. Aggregates are often washed and graded at the pit or plant. Some variation in type, quality, cleanliness, grading, moisture content, and other properties is expected from load to load.

Service records are invaluable in evaluating aggregates, particularly with respect to alkali-silica reactivity. In the absence of a performance record, aggregates should be tested before they are used in concrete. As with the introduction of any material into a concrete mix design, prepare trial batches using the specific project aggregates to establish the characteristics of the resultant concrete mixture and identify any necessary mix adjustments.

This section describes the types of aggregate and the properties of aggregates that affect concrete mixes for pavements.

Aggregate Types

Aggregates are sometimes identified by their mineralogical classification, that is, by their chemistry and how they were formed. These classifications are important because they provide a means of partially predicting a specific aggregate's effect on plastic and hardened concrete mixtures. However, different materials from the same geological formation may be significantly different. Before using aggregate from a new source or quarry, verify its performance in concrete mixtures.

Ways to Describe Aggregates

Aggregates—rocks and minerals—can be described by their general composition, source, or origin:

- General composition.
  - Mineral: naturally occurring substance with an orderly structure and defined chemistry.
  - Rock: mixture of one or more minerals.
- Source.
  - Natural sands and gravels: formed in riverbeds or seabeds and usually dug from a pit, river, lake, or seabed; sands are fine aggregates; gravels are coarser particles.
  - Manufactured aggregate (crushed stone or sand): quarried in large sizes, then crushed and sieved to the required grading; also, crushed boulders, cobbles, or gravel.
  - Recycled: made from crushed concrete.
- Origin.
  - Igneous: cooled molten material; includes siliceous materials primarily consisting of compounds of silica (for example, granite).
  - Sedimentary: deposits squeezed into layered solids; includes carbonate materials from deposited sea shells (for example, limestone).
  - Metamorphic: igneous or sedimentary rocks that have been transformed under heat and pressure.

Naturally occurring aggregates, like those from pits or quarries, are a mixture of rocks and minerals (see ASTM C 294 for brief descriptions). A mineral is a naturally occurring solid substance with an orderly internal structure and a narrow chemical composition. Rocks are generally composed of several minerals.

Single-mineral rocks that may be used for concrete aggregates include dolomite and magnetite. Minerals that appear in rocks used for aggregates include silica (e.g., quartz), silicates (e.g., feldspar), and carbonates (e.g., calcite). Rock types composed of more than one mineral include granite, gabbro, basalt, quartzite, traprock, limestone, shale, and marble.

These lists are not exhaustive. More information is shown in tables 3-9 and 3-10.

Rocks are classified according to their origin. Igneous rocks are the product of cooled molten magma, sedimentary rocks are the product of sediment deposits squeezed into layered solids, and metamorphic rocks are the product of igneous or sedimentary rocks that have been transformed under heat and pressure.

Coarse-grained igneous rocks (for example, granite) and sedimentary rocks consisting of carbonate materials from deposited sea shells (for example, limestone) are two rock types commonly used as aggregate in concrete, as discussed below. Carbonate materials are primarily composed of calcium compounds, while siliceous materials (including granite) are predominantly based on compounds of silica.

For a detailed discussion of other rock types, see Barksdale (1991).

The types of aggregates have different effects on the performance of concrete in different environments and traffic. For instance, siliceous materials tend to resist wearing and polishing. Carbonate rocks have low coefficients of thermal expansion, which is beneficial in reducing expansion and shrinkage in climates where large fluctuations in temperature occur (see the section on Aggregate Coefficient of Thermal Expansion later in this chapter, page 47).

Some rock types are unsound for use in concrete mixtures because they expand, causing cracking. Examples include shale and siltstone.

Carbonate Rock

There are two broad categories of carbonate rock: (1) limestone, composed primarily of calcite, and (2) dolomite, composed primarily of the mineral dolomite. Mixtures of calcite and dolomite are common (figure 3-5).

Carbonate rock has several different modes of origin and displays many textural variations. Two carbonate rocks having the same origin may display a great range of textures. In some carbonated rocks, the texture is so dense that individual grains are not visible. Others may have coarse grains with the calcite or dolomite readily recognizable. In many carbonate rocks fragments of seashells of various kinds are present. Shell sands and shell banks, as well as coral reefs and coralline sands, are examples of carbonate deposits.

Table 3-9. Mineral Constituents in Aggregates

	Minerals
Silica	Quartz Opal Chalcedony Tridymite Cristobalite

Silicates	Feldspars
	Ferromagnesian
	  Hornblende
	  Augite
	Clay
	  Illites
	  Kaolins
	  Chlorites
	  Montmorillonites
	Mica
	Zeolite

Carbonate	Calcite Dolomote
Sulfate	Gypsum Anhydrite
Iron sulfide	Pyrite Marcasite Pyrrhotite
Iron oxide	Magnetite Hematite Goethite Imenite Limonite

Source: Kosmatka, Kerkoff, and Panarese (2002)

Carbonate rocks display a large range of physical and chemical properties. They vary in color from almost pure white through shades of gray to black. The darker shades are usually caused by plant-based (carbonaceous) material. The presence of iron oxides creates buffs, browns, and reds. Dolomite is commonly light in color. It often has ferrous iron compounds that may oxidize, tinting the rock shades of buff and brown.

The properties of limestone and dolomite vary with the degree of consolidation. The compressive strength of commercial limestone typically varies from 70 to 100 MPa (10,000 to 15,000 lb/in^2). The porosity of most limestone and dolomite is generally low, and the absorption of liquids is correspondingly small.

Granite

Granites are igneous rocks composed predominantly of forms of silica (for example, quartz) and silicates (for example, feldspar). The grain or texture varies from fine to coarse. Granites may vary markedly in color and texture within individual quarries, but more commonly the color and texture are uniform for large volumes of rock.

Because of its mineral composition and interlocking crystals, granite is hard and abrasion resistant. Its compressive strength typically ranges from 50 to 400 MPa (7,000 to 60,000 lb/in^2), with the typical value of 165 MPa (24,000 lb/in^2) in the dry state. Most granite is capable of supporting any load to

Table 3-10. Rock Constituents in Aggregates

Igneous rocks	Sedimentary rocks	Metamorphic rocks

Granite
Syenite
Diorite
Gabbro (Traprock)
Peridotite
Pegmatite
Volcanic glass
  Obsidian
  Pumice
  Tuff
  Scoria
  Perlite
  Pitchstone
Felsite
Basalt
	Conglomerate
	Sandstone
	  Quartzite
	  Graywacke
	  Subgraywacke
	  Arkose
	Claystone, siltstone,
	  argillite, and shale
	Carbonate
	  Limestone
	  Dolomite
	  Marl
	  Chalk
	Chert
		Marble
		Metaquartzite
		Slate
		Phyllite
		Schist
		Amphibolite
		Hornfels
		Gneiss
		Serpentinite

Source: Kosmatka, Kerkoff, and Panarese (2002)
* Roughly in order of abundance

which it might be subjected during ordinary construction uses. The flexural strength of intact granite, expressed as a modulus of rupture, varies from about 9 to 28 MPa (1,300 to 4,000 lb/in^2). The modulus of elasticity of granite is higher than that of any of the other rock types for which data are available.

Gravel and Sand

Close to half of the coarse aggregates used in concrete in North America are natural gravels dug or dredged from a pit, river, lake, or seabed. Weathering and erosion of rocks produce particles of stone, gravel, sand, silt, and clay. Gravel (including sand) is natural material that has broken off from bedrock and has been transported by water or ice. During transport, gravel is rubbed smooth and graded to various sizes.

Gravel and sand are often a mixture of several minerals or rocks. The quality (or soundness) of sand and gravel depends on the bedrock from which the particles were derived and the mechanism by which they were transported. Sand and gravel derived from sound rocks, like many igneous and metamorphic rocks, tend to be sound. Sand and gravel derived from rocks rich in shale, siltstone, or other unsound materials tend to be unsound.

Sand and gravel deposited at higher elevations from glaciers may be superior to deposits in low areas. The reason is that the rock high in an ice sheet has been carried from higher, more mountainous areas, which tend to consist of hard, sound rocks. Sand and gravel that have been smoothed by prolonged agitation in water (figure 3-6[b]) usually are considered better quality because they are harder and have a more rounded shape than less abraded sand and gravel.

Manufactured Aggregate

Manufactured aggregate (including manufactured sand) is often used in regions where natural gravels and sands are either not available in sufficient quantities or are of unsuitable quality (Addis and Owens 2001). It is produced by crushing sound parent rock at stone crushing plants.

Manufactured aggregates differ from gravel and sand in their grading, shape, and texture. Because of the crushing operation, they have a rough surface texture, are very angular in nature (figure 3-6[a]), and tend to be cubical in shape (depending on the method of crushing) and uniform in grade (size) (Wigum et al. 2004). In the past, manufactured sands were often produced without regard to sizing, but producers can now provide high-quality

Mineral component, %	(1) Calcite (mineral), $CaCO_3$	100	90	80	70	60	50	40	30	20	10	0
	(2) Dolomite (mineral), $CaMg(CO_3)_2$	0	10	20	30	40	50	60	70	80	90	100
Rock type		High calcium limestone	Magnesium limestone		Dolomitic limestone				Calcitic dolomite			Dolomite

Figure 3-5. Family of carbonate minerals showing rock and mineral names (CTLGroup)

material meeting specified particle shapes and gradations (Addis and Owens 2001). In many cases, the particle elongation and flakiness of manufactured sands can be reduced through appropriate crushing techniques. Impact crushers generate better particle shape than compression crushers.

Many of the characteristics of manufactured aggregates are attributable directly to the inherent properties of the rock type from which they were produced. Manufactured aggregates are less likely than gravel and sand to be contaminated by deleterious substances such as clay minerals or organic matter (Addis and Owens 2001). Some specifications permit higher fines content in manufactured sands because of the expectation of less clay contamination (Addis and Goldstein 1994).

The sharpness and angularity of manufactured sands may result in a "harsh" mixture: one that is difficult to work and finish. Such mixtures also typically require more water (Quiroga and Fowler 2004). On the other hand, the appropriate use of manufactured sand can improve edge slump control during slipform paving and may also lead to slight increases in concrete strength for a fixed water content (McCaig 2002). As with the introduction of any material into a concrete mix design, prepare trial batches using the specific project materials to establish the characteristics of the resultant concrete mixture and identify any necessary mix adjustments.

a) Aggregates from crushing

b) River gravel

Figure 3-6. Aggregates produced by crushing operation (top) have a rougher surface texture and are angular compared to round river gravel (bottom). (PCA)

Recycled Aggregates

Recycling concrete pavement is a relatively simple process. It involves breaking and removing the pavement, removing reinforcement and other embedded items, and crushing the concrete into material with a specified size. The crushing characteristics of hardened concrete are similar to those of natural rock and are not significantly affected by the grade or quality of the original concrete.

According to an FHWA study (2002), many States use recycled aggregate as an aggregate base. Recycled-aggregate bases have experienced some leaching of calcium carbonate into the subdrains (Mulligan 2003).

In addition to using recycled aggregate as a base, some States use recycled concrete in new portland cement concrete. Most of these agencies specify recycling the concrete material directly back into the project being reconstructed. When used in new concrete, recycled aggregate is generally combined with virgin aggregate. Recycled material is not recommended for use as fine aggregate, however, because of the high water demand.

The quality of concrete made with recycled coarse aggregate depends on the quality of the recycled aggregate. Typically, recycled coarse aggregate is softer than natural aggregate and may have a higher alkali or chloride content than natural aggregate. Recycled aggregate may also have higher porosity, leading to higher absorption. Therefore, relatively tighter quality controls may be required to prevent constructability problems. The recycled aggregate should be taken from a single pavement that is known not to have experienced materials-related problems. Care must be taken to prevent contamination of the recycled aggregate by dirt or other materials, such as asphalt.

Physical Properties of Aggregates

The factors that can be monitored in an aggregate from a given source are the grading, particle shape, texture, absorption, and durability. In general, the required physical and durability characteristics of aggregates are covered in ASTM C 33.

Aggregate Gradation

Gradation is a measure of the size distribution of aggregate particles, determined by passing aggregate through sieves of different sizes (ASTM C 136-04 / AASHTO T 27). Grading and grading limits are usually expressed as the percentage of material passing (or retained on) sieves with designated hole sizes. Aggregates are classified as fine or coarse materials by ASTM C 33 / AASHTO M 6/M 80:

- Coarse: Aggregate retained on a #4 sieve (greater than 4.75 mm [3/16 in.] in diameter) (Abrams and Walker 1921); consists of gravel, crushed gravel, crushed stone, air-cooled blast-furnace slag (not the GGBF slag used as a supplementary cementitious material), or crushed concrete; the maximum size of coarse aggregates is generally in the range of 9.5 to 37.5 mm (3/8 to 1½ in.).
- Fine: Aggregate passing a #4 sieve (less than 4.75 mm [3/16 in.] in diameter) (Abrams and Walker 1921); consists of natural sand, manufactured sand, or a combination.
- Clay: Very small, fine particles with high surface area and a particular chemical form.

Why Well-Graded Aggregate is Critical. Because aggregates are generally more chemically and dimensionally stable than cement paste, it is important to maximize the amount of aggregate in concrete mixtures (within other limits, like the need for sufficient paste to coat all the aggregate particles for workability). This can be accomplished largely by selecting the optimum aggregate grading. Well-graded aggregate—that is, aggregate with a balanced variety of sizes—is preferred, because the smaller particles fill the voids between the larger particles, thus maximizing the aggregate volume (figure 3-7).

In addition, the amount of mix water is often governed by the aggregate properties. In order to be workable, concrete mixtures must contain enough paste to coat the surface of each aggregate particle. But too much water in the paste reduces long-term concrete durability by reducing strength and increasing permeability. So, it is important to achieve optimum water content—not too little, not too much. This, too, can largely be accomplished by selecting the optimum aggregate size and grading. Smaller (finer) aggregates

Generally Desirable Physical Properties of Aggregate

Although mixtures can be developed to compensate for the lack of some of the following characteristics in the aggregate, in general it is desirable that the aggregate have the following qualities:

- Well-graded (for mixtures that require less water than mixtures with gap-graded aggregates, have less shrinkage and permeability, are easier to handle and finish, and are usually the most economical).
- Angular (for aggregate interlock).
- Rough surface texture (for bond and interlock).
- Low absorption (reduces water requirement variability).
- Low alkali-aggregate reactivity (for reduced risk of deleterious alkali-silica reactivity and alkali-carbonate reactivity).
- Frost resistant (for durability associated with D-cracking and popouts).
- Low salt susceptibility (for durability).
- Low coefficient of thermal expansion (for reduced cracking from volume change due to changing temperatures).
- Abrasion resistant (for durability and skid resistance).

require more paste because they have higher surface-to-volume ratios. In natural sands, it is common for much of the very fine (<150 µm, #100 sieve) particles to be clay, with extremely high surface areas. Therefore, the amount of such fine materials is limited in specifications. (Crushed fine aggregate is less likely to contain clay particles, and consideration may be given to permitting slightly higher dust contents.)

Finally, mixtures containing well-graded aggregate generally will have less shrinkage and permeability, will be easier to handle and finish, and will be the most economical.

The use of gap-graded (single-sized) aggregate, on the other hand, can result in mixtures that segregate and require more water to achieve workability. Very fine sands are often uneconomical; they may increase water demand in the mixture and can make entraining air difficult. Very coarse sands and coarse aggregate can produce harsh, unworkable mixtures. In general, aggregates that do not have a large deficiency or excess of any size (they will give a smooth grading curve) will produce the most satisfactory results.

Fine-Aggregate Grading Requirements. ASTM C 33 / AASHTO M 6 permit a relatively wide range in fine-aggregate gradation. In general, if the ratio of water to cementitious materials is kept constant and the ratio of fine-to-coarse aggregate is chosen correctly, a wide

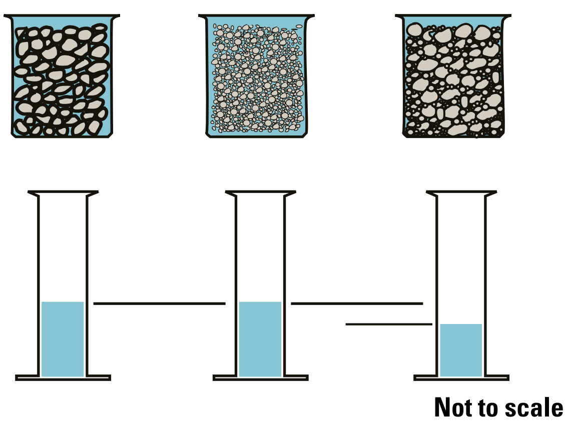

Figure 3-7. The level of liquid in the cylinders, representing voids, is constant for equal absolute volumes of aggregates of uniform (but different) sizes. When different sizes are combined, however, the void content decreases. (PCA)

Consistent Grading is Critical

Variations in aggregate grading between batches can seriously affect the uniformity of concrete from batch to batch.

range in grading can be used without a measurable effect on strength. However, it may be most economical to adjust the proportions of fine and coarse aggregate according to the gradation of local aggregates.

In general, increasing amounts of fine material will increase the water demand of concrete. Fine-aggregate grading within the limits of ASTM C 33 / AASHTO M 6 is generally satisfactory for most concretes. The amounts of fine aggregate passing the 300 µm (#50) and 150 µm (#100) sieves affect water demand, workability, surface texture, air content, and bleeding of concrete. Large amounts of fine material may increase the water demand and increase stickiness, while insufficient fines could result in bleeding. Most specifications allow 5 to 30 percent to pass the 300 µm (#50) sieve.

Other requirements of ASTM C 33 / AASHTO M 6 are as follows:

- The fine aggregate must not have more than 45 percent retained between any two consecutive standard sieves.
- The fineness modulus must be not less than 2.3, nor more than 3.1, nor vary more than 0.2 from the typical value of the aggregate source. If this value is exceeded, the fine aggregate should be rejected unless suitable adjustments are made in the proportions of fine and coarse aggregate.

The fineness modulus (FM) is a measure of the fineness of an aggregate—the higher the FM, the coarser the aggregate. According to ASTM C 125, the FM is calculated by adding the cumulative percentages by mass retained on each of a specified series of sieves and dividing the sum by 100. The specified sieves for determining FM are 150 µm (#100), 300 µm (#50), 600 µm (#30), 1.18 mm (#16), 2.36 mm (#8), 4.75 mm (#4), 9.5 mm (3/8 in.), 19.0 mm (3/4 in.), 37.5 mm (1½ in.), 75 mm (3 in.), and 150 mm (6 in.).

Fineness modulus is not a unique descriptor, and different aggregate gradings may have the same FM. However, the FM of fine aggregate can be used to estimate proportions of fine and coarse aggregates in concrete mixtures.

Coarse-Aggregate Grading Requirements. The coarse-aggregate grading requirements of ASTM C 33 / AASHTO M 80 also permit a wide range in grading and a variety of grading sizes. As long as the proportion of fine aggregate to total aggregate produces concrete of good workability, the grading for a given maximum-size coarse aggregate can be varied moderately without appreciably affecting a mixture's cement and water requirements. Mixture proportions should be changed if wide variations occur in the coarse-aggregate grading.

The maximum coarse aggregate size to be selected is normally limited by the following: (1) local availability, (2) a maximum fraction of the minimum concrete thickness or reinforcing spacing, and (3) ability of the equipment to handle the concrete.

Combined-Aggregate Grading. The most important grading is that of the combined aggregate in a concrete mixture (Abrams 1924). Well-graded aggregate, indicated by a smooth grading curve (figure 3-8), will generally provide better performance than a gap-graded system. Crouch (2000) found in his studies on air-entrained concrete that the ratio of water to cementitious materials could be reduced by more than eight percent using combined aggregate gradation.

Combinations of several aggregates in the correct proportions will make it possible to produce a combined aggregate grading that is close to the preferred envelope. Sometimes mid-sized aggregate, around the 9.5-mm (3/8-in.) size, is not available, resulting in a concrete with high particle interference, high water demand, poor workability, poor place-ability, and high shrinkage properties.

A perfect gradation does not exist in the field, but you can try to approach it by blending the available materials in optimized proportions. If problems develop due to a poor gradation, consider using alternative aggregates, blending aggregates, or conducting a special screening of existing aggregates.

No Local Source of Well-Graded Aggregate?

If a well-graded system of aggregates is not available from local sources, satisfactory concrete can still be made and placed, but it will require more attention to detail in the construction phase.

Tools that can be used to evaluate the grading of a combined system are available (see Aggregate Grading Optimization in chapter 6, page 176; and the Combined Grading test method in chapter 9, page 253). These include the coarseness and workability factors, along with the 0.45 power curve (Shilstone 1990).

Aggregate Particle Shape

Aggregate particles are described as being cubic, flat, or elongated. Aggregate of any shape can be used in concrete to obtain high strength and durability, provided the quantity of mortar at a given ratio of water to cementitious materials is adjusted. However, keep in mind some rules of thumb:

- In pavements, angular particles are generally preferred to rounded because they lead to

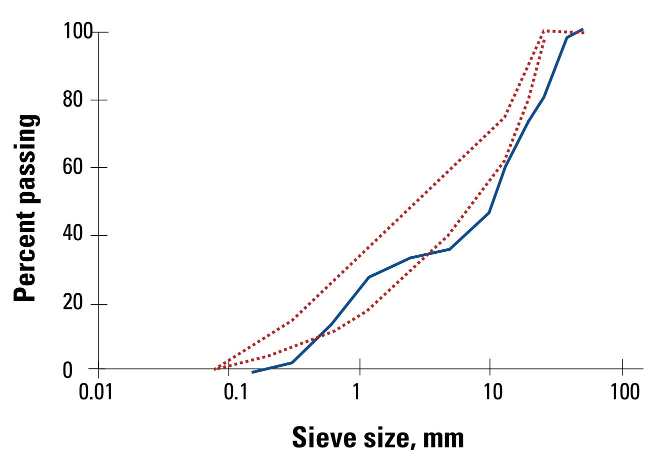

Figure 3-8. An example of a smooth grading curve that would be preferred (red lines define an acceptable envelope) and an actual aggregate system that was not optimum (blue) (CTLGroup)

higher flexural strengths due to aggregate interlock.

- Angular, nonpolishing fine aggregate particles are also desirable at the surface to promote high skid resistance, although they also reduce workability.
- Flat or elongated particles may reduce concrete workability due to particle interference while in the plastic state. This is especially true of particles between the 9.5-mm (3/8-in.) and 2.36-mm (#8) sieves.

Aggregate Surface Texture

Aggregate with any texture, varying from smooth to rough, can be used in portland cement concrete, provided the mixture is properly proportioned. A rough texture is an advantage when beams are tested for quality control because better bond and interlock is provided at the junction of the mortar and aggregate.

Aggregate Absorption

Absorption is the penetration of liquid into aggregate particles. The amount of water added to the concrete mixture at the batch plant must be adjusted for the moisture conditions of the aggregates in order to accurately meet the water requirement of the mix design. If not accounted for, dry aggregate particles will absorb water from the concrete mixture, so water will have to be added to the mix to achieve the desired workability; this may ultimately reduce long-term concrete durability.

The moisture conditions of aggregates (figure 3-9) are designated as follows:

- Oven dry—fully absorbent.
- Air dry—dry at the particle surface but containing some interior moisture, thus still somewhat absorbent.
- Saturated surface dry (SSD)—neither absorbing water from nor contributing water to the concrete mixture.
- Damp or wet—containing an excess of moisture on the surface (free water).

Absorption values for various types of aggregate range from virtually zero to over 7 percent of the dry aggregate mass for natural aggregates, and up to 10 percent for lightweight or manufactured materials. However, the absorption values of most aggregates range from 0.2 to 4 percent by mass.

Using aggregates with high absorption values often results in large variations in concrete quality because of the difficulties controlling the aggregates' moisture content. Aggregates that are less than SSD will absorb water from the paste, making the concrete stiffen and lose workability. This effect is reduced when probes are used to monitor the moisture of the aggregates in storage and when the water in the concrete mix is adjusted to accommodate the difference between the actual moisture content and the SSD condition (see Moisture/Absorption Correction in chapter 6, page 183, and Stockpile Management and Batching in chapter 8, pages 206–207).

Aggregate Coefficient of Thermal Expansion

A material's coefficient of thermal expansion (CTE) is a measure of how much the material changes in length (or volume) for a given change in temperature. Typically, an increase in temperature will result in lengthening, and a decrease will result in shortening. Because aggregates make up a majority of a concrete's volume, the CTE of the aggregate particles will dominate the CTE for the concrete overall.

CTE values are considered in design calculations for pavements (NCHRP 2004) and are used in thermal modeling of concretes. Limestone and marble have the lowest, and therefore most desirable, thermal expansions. Table 3-11 shows some typical linear CTE values of several aggregates.

Aggregate Durability

One of the reasons that concrete pavements are economically desirable is that they last longer than

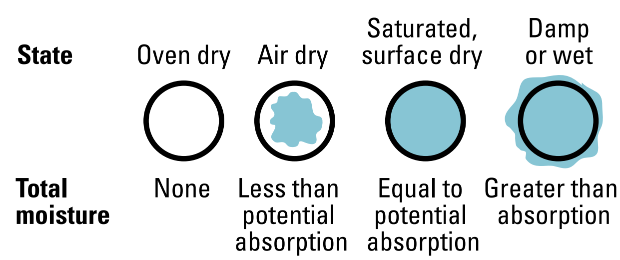

Figure 3-9. Moisture conditions of aggregates (PCA)

pavements made from other systems. It is therefore important to ensure that new pavements are as durable as possible. Some of the aggregate mechanisms related to pavement durability include alkali-aggregate reactivity, frost resistance, coefficient of thermal expansion, and abrasion resistance.

Aggregate Durability and Alkali-Aggregate Reactivity. Aggregates containing certain minerals (table 3-12) can react with alkali hydroxides in concrete to form a gel that expands when exposed to moisture. This reaction and expansion eventually results in cracking in the aggregate and the concrete (figure 3-10).

Reactive minerals are often found in specific types of rocks (table 3-12), which in turn may or may not be reactive, depending on the exact makeup of the rock (table 3-13). The reactivity is potentially harmful only when it produces significant expansion.

Alkali-aggregate reactivity has two forms—alkali-silica reactivity (ASR) and alkali-carbonate reactivity (ACR). For more information, see Farny and Kosmatka (1997) and Folliard, Thomas, and Kurtis (2004).

ASR is much more common than ACR. The best way to avoid ASR is to take appropriate precautions before concrete is placed. Expansion tests (ASTM C 1260 / AASHTO T 303 and ASTM C 1293) and petrography (ASTM C 295) are the most commonly used methods to determine the potential susceptibility of an aggregate to ASR if the performance of the aggregate in the field is not available. (These and other tests and methods for controlling ASR are discussed in detail under Alkali-Silica Reaction in chapter 5, page 141.)

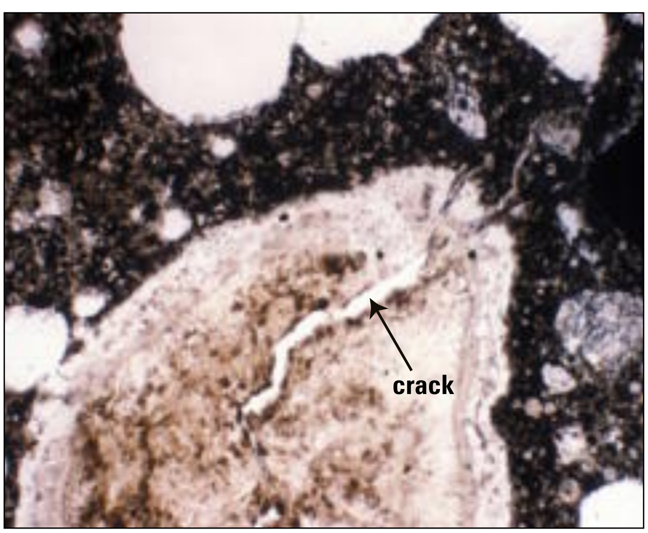

Figure 3-10. An aggregate particle that has cracked due to alkali-silica reaction (CTLGroup)

Table 3-11. Typical CTE Values for Common Portland Cement Concrete Ingredients

	Coefficient of thermal expansion	
	10^{-6}/°C	10^{-6}/°F
Aggregate		
Granite	7 to 9	4 to 5
Basalt	6 to 8	3.3 to 4.4
Limestone	6	3.3
Dolomite	7 to 10	4 to 5.5
Sandstone	11 to 12	6.1 to 6.7
Quartzite	11 to 13	6.1 to 7.2
Marble	4 to 7	2.2 to 4
Cement paste (saturated)		
w/c = 0.4	18 to 20	10 to 11
w/c = 0.5	18 to 20	10 to 11
w/c = 0.6	18 to 20	10 to 11
Steel	11 to 12	6.1 to 6.7

Sources: FHWA (2004b) and PCA (2002)
Note: These values are for aggregates from specific sources, and different aggregate sources may provide values that vary widely from these values.

Table 3-12. Mineral Constituents of Aggregate That Are Potentially Alkali-Reactive

Alkali-reactive mineral	Potentially deleterious amount
Optically strained, micro fractured or microcrystalline quartz	More than 5%
Chert or chalcedony	More than 3%
Trydimite or cristobalite	More than 1%
Opal	More than 0.5%
Natural volcanic glass	More than 3.0 %

Source: PCA

To prevent ACR, avoid using reactive rock. If this is not feasible, then dilute the aggregate with nonreactive stone (Ozol 1994).

Aggregate Durability and Frost Resistance. Concrete containing aggregates that are not frost resistant may experience D-cracking, popouts, or deterioration from deicing salts.

D-Cracking

Aggregate particles with coarse pore structure may be susceptible to freeze-thaw damage. When these particles become saturated and the water freezes, expanding water trapped in the pores cannot get out. Eventually, the aggregate particles cannot accommodate the pressure from the expanding water; the particles crack and deteriorate. In concretes with appreciable amounts of susceptible aggregate, this freeze-thaw deterioration of the aggregate ultimately results in cracking in the concrete slab, called D-cracking. D-cracking is generally a regional problem caused when locally available, susceptible aggregate is used in concrete.

D-cracks are easy to identify. They are closely spaced cracks parallel to transverse and longitudinal joints (where the aggregate is most likely to become saturated). Over time, the cracks multiply outward from the joints toward the center of the pavement slab (figure 3-11).

D-cracking is a serious problem that will compromise the integrity of concrete. It cannot be stopped or undone; it can only be prevented. Therefore, when designing a mixture it is critical to select aggregates that are not susceptible to freeze-thaw deterioration. If marginal aggregates must be used, you may be able to reduce D-cracking susceptibility by reducing the maximum particle size and by providing good drainage for carrying water away from the pavement base.

Popouts

A popout is usually a conical fragment that breaks out of the surface of concrete, leaving a shallow, typically conical, depression (figure 3-12). Generally, a fractured aggregate particle will be found at the bottom of the hole with the other part of the aggregate still adhering to the point of the popout cone. Most popouts are about 25 to 50 mm (1 to 2 in.) wide; however, popouts caused by sand particles are much smaller, and very large popouts may be up to 300 mm (1 ft) in diameter.

Unless they are very large, popouts are only a cosmetic flaw and do not generally affect the service life of the concrete.

Table 3-13. Rock Types Potentially Susceptible to Alkali-Silica Reactivity

Rocks
Arenite
Argillite
Arkose
Chert
Flint
Gneiss
Granite
Graywacke
Hornfels
Quartz-arenite
Quartzite
Sandstone
Shale
Silicified carbonate
Siltstone

Source: Folliard, Thomas, and Kurtis (2003)

Figure 3-11. D-cracking (Jim Grove, CPTech Center)

Popouts may occur in concretes where the surface contains small amounts of coarse (rather than fine) aggregate particles with higher porosity values and medium-sized pores (0.1 to 5 µm) that are easily saturated. (Larger pores do not usually become saturated or cause concrete distress, and water in very fine pores does not freeze readily.) As the offending aggregate absorbs moisture and freezing occurs, the swelling creates enough internal pressure to rupture the concrete surface. Sometimes, all that is needed for expansion to occur is a season of high humidity.

Aggregates containing appreciable amounts of shale, soft and porous materials (clay lumps, for example), and certain types of chert may be prone to popouts. These particles are often of lighter weight and can float to the surface under excessive vibration. This will increase the number of popouts, even when the amount of these particles is small or within specification limits. Specifications for concrete aggregates, such as ASTM C 33, allow a small amount of deleterious material because it is not economically practical to remove all of the offending particles.

The presence of weak, porous particles in the aggregate can be reduced by jigging, heavy-media separation, or belt picking; however, these methods may not be available or economical in all areas.

Figure 3-12. A popout at the surface of concrete (PCA)

Salt (Sulfate) Susceptibility

Certain aggregates such as ferroan dolomites are susceptible to damage by salts. These aggregates may exhibit excellent freeze-thaw resistance but deteriorate rapidly when deicing salts are used. In the presence of salts, the crystalline structure of such aggregates is destabilized, therefore increasing the rate of damage under freeze-thaw conditions.

Aggregate Durability and Abrasion Resistance. An important property of pavements is their ability to provide an adequate skid resistance by resisting abrasion or resisting wear. The abrasion resistance of concrete is related to both aggregate type and concrete compressive strength (figure 3-13). Strong concrete has more resistance to abrasion than does weak concrete, while hard aggregate is more wear-resistant than soft aggregate. In other words, high-strength concrete

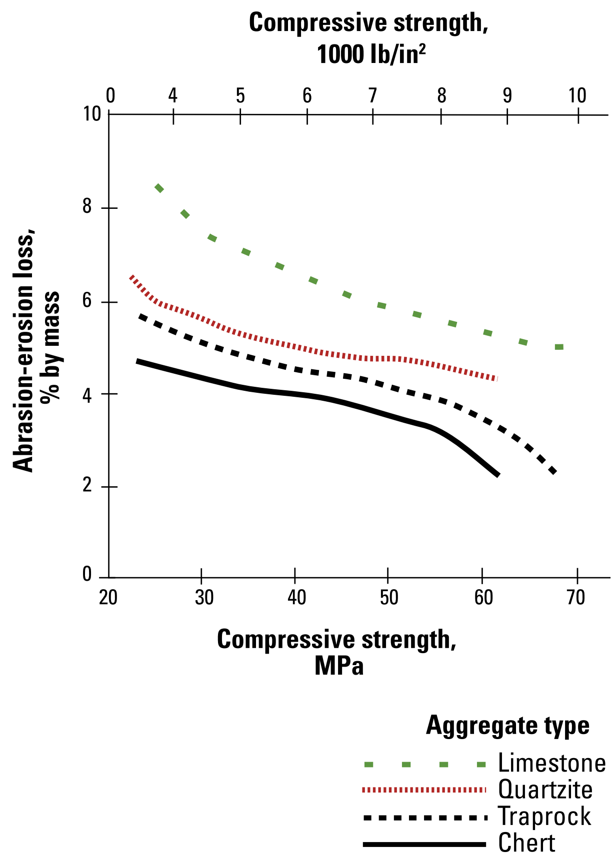

Figure 3-13. Effect of compressive strength and aggregate type on the abrasion resistance of concrete (ASTM C 1138-97)

made with a hard aggregate is highly resistant to abrasion (Liu 1981) The use of natural sands in concrete mixtures will improve abrasion resistance and can result in improved abrasion resistance of concrete, even when soft coarse aggregates are used.

The abrasion resistance of an aggregate can be used as a general indicator of its quality. Using aggregate with low abrasion resistance may increase the quantity of fines in the concrete during mixing and consequently may increase the water requirement. In general, siliceous aggregates are more resistant to abrasion than calcareous (acid-soluble) materials. As a result, some specifications limit the amount of calcareous material in aggregate to ensure adequate abrasion resistance (see Abrasion Resistance in chapter 5, page 146).

Coarse aggregate abrasion resistance is usually measured using the Los Angeles (LA) abrasion test method (ASTM C 535 and ASTM C 131). The MicroDeval test, developed in France during the 1960s, is under evaluation as an alternative to the LA abrasion test (Kandhal and Parker 1998).

Water

Key Points

- Mixing water can consist of batch water, ice, free moisture on aggregates, water in admixtures, and water added after initial mixing.
- Ideally, water for concrete should be potable (fit for human consumption).
- Some water recycled from returned concrete and plant washing can be acceptable.
- Questionable mixing water should be tested for its effect on concrete strength and setting time.
- The specification for mixing water in concrete mixtures is ASTM C 1602.

This section focuses on water sources and quality. (For information about achieving the optimum quantity of water in concrete mixtures, see Calculating Mixture Proportions in chapter 6, page 179. Concrete mixtures must contain enough paste [cement and water] to thoroughly coat the aggregates and to make the mix workable. Too much water reduces long-term concrete durability. It is critical to achieve optimum water content for each specific mix and project.)

Sources of Water in the Mixture

Water discharged into the mixer is the main but not the only source of mixing water in concrete:

- During hot-weather concreting, ice may be used as part of the mixing water to cool the concrete. The ice should be completely melted by the time mixing is completed.
- Aggregates often contain surface moisture, and this water can represent a substantial portion of the total mixing water. Therefore, it is important that the water brought in by the aggregate is free from harmful materials and accounted for when batching concrete ingredients.
- Water contained in admixtures also represents part of the mixing water if it affects the mixture's ratio of water to cementitious materials by 0.01 or more.

Water Quality

The quality of water used in concrete mixtures can play a role in the quality of concrete. Excessive impurities in mixing water may affect setting time and concrete strength and can result in salt deposits on the pavement surface, staining, corrosion of reinforcement materials, volume instability, and reduced pavement durability.

Many State departments of transportation have specific requirements for mixing water in concrete (NRMCA 2005). In general, suitable mixing water for making concrete includes the following:

- Potable water.
- Nonpotable water.
- Recycled water from concrete production operations.

Both nonpotable water and recycled water must be tested to ensure they do not contain impurities that negatively affect concrete strength, set time, or other properties. Water containing less than 2,000 parts per million (ppm) of total dissolved solids can generally be used satisfactorily for making concrete. Water containing organic materials or more than 2,000 ppm of dissolved solids should be tested for its effect on strength and time of set (Kosmatka 2002).

Water of questionable suitability can be used for making concrete if concrete cylinders (ASTM C 39 / AASHTO T 22) or mortar cubes (ASTM C 109 /

Mix Water and Aggregate Moisture

To account for mix water properly, you need to know the assumed moisture condition of aggregates used in the mix design. In the trial batch and at the beginning of construction, you may need to adjust water content based on the actual moisture condition of the aggregates used. For more information, see Moisture/Absorption Correction in chapter 6, page 183, and Stockpile Management and Batching in chapter 8, pages 206 and 207, respectively.

AASHTO T 106) made with it have seven-day strengths equal to at least 90 percent of companion specimens made with potable or distilled water. Setting time tests should be conducted to ensure that impurities in the mixing water do not adversely shorten or extend the setting time of concrete (ASTM C 403 / AASHTO T 197) or cement (ASTM C 191 / AASHTO T 131). In addition, the density of the water (ASTM C 1603) has to be tested if water from concrete production operations or water combined from two or more sources is to be used as mixing water. Acceptance criteria for water to be used in concrete are given in ASTM C 1602 / AASHTO T 26 (table 3-14).

Optional limits may be set on chlorides, sulfates, alkalies, and solids in the mixing water (table 3-15), or appropriate tests should be performed to determine the effect the impurity has on concrete properties. Some impurities may have little effect on water requirement, strength, and setting time while adversely affecting concrete durability and other properties.

Recycled Water

Recycled water is primarily a mixture of water, admixtures, cementitious materials, and aggregate fines resulting from processing returned concrete. Recycled water may also include truck wash water and storm water from the concrete plant. Usually, recycled water is passed through settling ponds where the solids settle out, leaving clarified water. In some cases, recycled water from a reclaimer unit is kept agitated to maintain the solids in suspension for reuse as a portion of the batch water in concrete (figure 3-14). Solid content in recycled water varies from 2.5 to 10 percent by mass.

Using recycled water in concrete mixtures may affect the water requirement, setting time, strength, and permeability of concrete. ASTM C 1602 /

Table 3-14. Acceptance Criteria for Combined Mixing Water

	Limits	Test Methods
Compressive strength, minimum % control at 7 days *, **	90	ASTM C 31 / ASTM C 31M, ASTM C 39 / ASTM C 39M
Time of set, deviation from control (h:min*)	From 1:00 early to 1:30 later	ASTM C 403 / ASTM C 403M

* Comparisons shall be based on fixed proportions for a concrete mix design representative of questionable water supply and a control mix using 100% potable water or distilled water.

** Compressive strength results shall be based on at least two standard test specimens made from a composite sample.

Table 3-15. Optional Chemical Limits for Combined Mixing Water

	Limits	Test Methods
Maximum concentration in combined mixing water, ppm*		
A. Chloride (Cl^-), ppm		
1. in prestressed concrete, bridge decks, or otherwise designated	500**	ASTM C 114
2. other reinforced concrete in moist environments or containing aluminum embedments or dissimilar metals or with stay-in-place galvanized metal forms	1,000**	ASTM C 114
B. Sulfate (SO_4), ppm	3,000	ASTM C114
C. Alkalies (Na_2O + 0.658 K_2O), ppm	600	ASTM C 114
D. Total solids by mass, ppm	50,000	ASTM C 1603

* ppm is the abbreviation for parts per million

** The requirements for concrete in ACI 318 shall govern when the manufacturer can demonstrate that these limits for mixing water can be exceeded. For conditions allowing the use of calcium chloride ($CaCl_2$) accelerator as an admixture, the chloride limitation is permitted to be waived by the purchaser

AASHTO M 157 permit the use of wash water as concrete mix water, with approval from the purchaser who can invoke chemical limits for chlorides, sulfates, alkalis, and solids. The maximum permitted solids content is 50,000 ppm, or five percent, of the total mixing water. This amounts to about 8.9 kg/m³ (15 lb/yd³) solids in a typical concrete mixture. A solids content of approximately 50,000 ppm represents water with a relative density (specific gravity) of 1.03. Research at the National Ready Mixed Concrete Association (Lobo and Mullings 2003) identified several important effects of using recycled water on properties of concrete in comparison to control concrete mixtures made with tap water; see table 3-16.

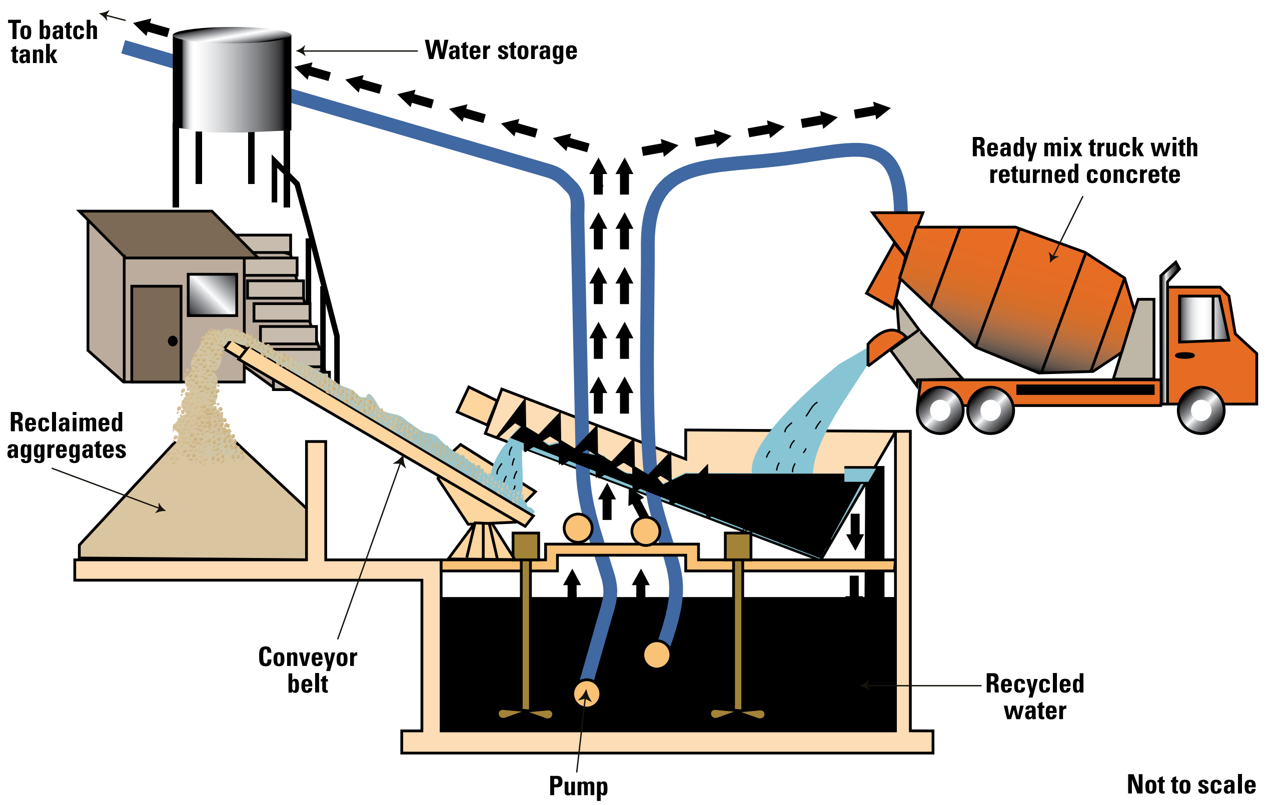

Figure 3-14. Recycled water and reclaimed aggregate at a ready-mixed concrete plant (PCA)

Table 3-16. Effect of Recycled Water on Concrete Properties

Recycled water with	Water demand	Setting time	Compressive strength	Permeability	Freeze-thaw resistance
Solid contents within ASTM C 94 limits (≤ 8.9 kg/m³ or ≤15 lb/yd³)	↔	↔	↔	↔	↔
High solid contents (>8.9 kg/m³ or >15 lb/yd³)	↑	↓	↓**	↑**	↔
High solid contents and treated with hydration stabilizing admixture	↔	↔	↔	no data	no data

Source: After Lobo and Mullings (2003)

* Compared to reference concrete with tap water.

** Strength and permeability effects were concomitant to increased mixing water content.

Key: ↓ decreased
↑ increased
↔ no trend

Chemical Admixtures

Key Points

- Admixtures are materials added to concrete mixtures to modify concrete properties such as air content, water requirement, and setting time. Admixtures should complement, not substitute for, good concrete proportioning and practice.
- Admixtures may have unintended side effects. Therefore, run trial batches with job materials and under job conditions.
- Generally, for every one percent entrained air, concrete loses about five percent of its compressive strength.
- Air-entraining admixtures are specified by ASTM C 260. Water-reducing and set-modifying admixtures are specified by ASTM C 494 / AASHTO M 194.
- For information about possible incompatibilities of various chemical admixtures, see the section on Potential Materials Incompatibilities in chapter 4, page 97.

Chemical admixtures are added to concrete during mixing to modify fresh or hardened concrete properties such as air content, workability, or setting time. Table 3-17 lists common admixtures used in concrete for pavements. Table 3-18 lists admixtures specified under ASTM C 494 / AASHTO M 194.

Adding chemical admixtures may help concrete designers achieve desired concrete properties more efficiently or economically than adjusting other ingredients or mix proportions. Admixtures are also used to maintain specific properties during concreting operations or under unusual conditions. However, admixtures should not be used as a substitute for good concrete practice. They should be used to enhance good concrete, not to fix bad concrete. Chemical admixtures may have unintended side effects that must be accommodated.

An admixture's effectiveness depends on many mix factors, including cementitious materials properties, water content, aggregate properties, concrete materials proportions, mixing time and intensity, and temperature.

Common admixtures are air-entraining, water-reducing, and set-modifying admixtures.

Table 3-17. Common Chemical Admixture Types for Paving Applications

Class	Function
Air-entraining admixture (AEA)	To stabilize microscopic bubbles in concrete, which can provide freeze-thaw resistance and improve resistance to deicer salt scaling.
Water-reducing admixture (WR)	To reduce the water content by 5 to 10%, while maintaining slump characteristics.
Mid-range water reducer (MRWR)	To reduce the water content by 6 to 12%, while maintaining slump and avoiding retardation.
High-range water reducer (HRWR)	To reduce the water content by 12 to 30%, while maintaining slump.
Retarder	To decrease the rate of hydration of cement.
Accelerator	To increase the rate of hydration of cement.

Table 3-18. Admixture Types Defined by ASTM C 494 / AASHTO M 194

Class	Name
Type A	Water reducing
Type B	Retarding
Type C	Accelerating
Type D	Water reducing and retarding
Type E	Water reducing and accelerating
Type F	Water reducing, high range
Type G	Water reducing, high range, and retarding

Note: Air-entraining admixtures are specified by ASTM C 260 / AASHTO M 154, and superplasticizers are specified by ASTM C 1017.

Air-Entraining Admixtures

Air-entraining agents are the most commonly used chemical admixtures in concrete. They are typically derived from pine wood resins, vinsol resins, and other synthetic detergents.

Specifications and methods of testing air-entraining admixtures are given in ASTM C 260 / AASHTO M 154 and ASTM C 233 / AASHTO T 157. Applicable requirements for air-entraining cements are given in ASTM C 150 / AASHTO M 85.

Function of Air Entrainment in Concrete

Stabilized air bubbles in hardened concrete are called air voids or entrained air. Concrete with proper air entrainment contains a uniform distribution of small, stable bubbles, or air voids, throughout the cement paste (figure 3-15). Proper air entrainment will do the following:

- Dramatically improve the durability of concrete exposed to moisture during cycles of freezing and thawing.
- Improve concrete's resistance to surface scaling caused by chemical deicers.
- Tend to improve the workability of concrete mixtures, reduce water demand, and decrease mixture segregation and bleeding.

An air-void system consisting of many smaller, closely spaced voids provides the greatest protection against freeze-thaw damage. The average distance between any point in the paste and an air void should typically be less than 0.20 mm (0.008 in.) (figure 3-16).

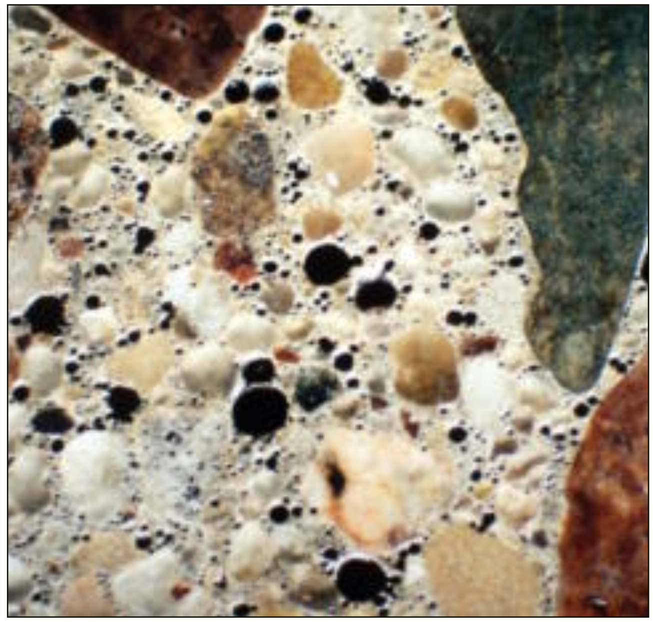

Figure 3-15. Entrained air bubbles in concrete (PCA)

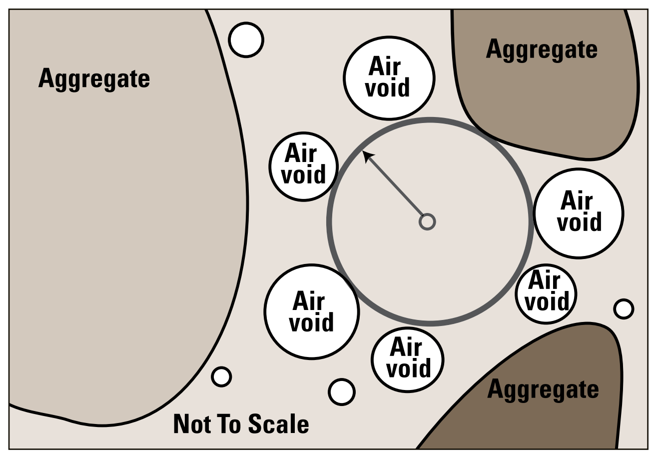

Figure 3-16. Spacing factor is the average distance from any point to the nearest air void. (Ozyildirim)

How Entrained Air Improves Concrete Freeze-Thaw Resistance

Entrained air plays a critical role in improving concrete pavements' durability by reducing their susceptibility to freeze-thaw damage. Here's how:

When most of the cement in a concrete mixture has reacted with water in the mixture, some of the remaining water is lost to evaporation, leaving behind capillary pores. Any remaining water can move through these pores. If the temperature drops below freezing, water in capillary pores turns to ice and expands. As the freezing, expanding water forces its way through the pores, it exerts pressure on the surrounding hardened cement paste. Entrained air voids act as a pressure relief valve, providing space for the water/ice to expand and relieving pressure on the surrounding concrete. Without adequate air voids, the pressure may cause the hardened cement paste to crack, initiating early pavement deterioration.

Air-Entraining Agent Mechanisms

Air-entraining admixtures stabilize millions of tiny air bubbles in the concrete mixture (created by the concrete mixing action) by causing a soap-like coating to form around the air bubbles. Molecules of air-entraining agent are attracted to water at one end and to air at the other end, reducing surface tension at the air-water interface; the ends that protrude into water are attracted to cement particles (figure 3-17). It is critical that sufficient mixing time be allowed for the air bubbles to be generated and stabilized.

The air-void system will be affected by the type/amount of agent, mixing time, placement methods, carbon impurities (see discussion of loss on ignition, or LOI, on page 33) from SCMs or aggregates, and other reactive materials in the mix, including water-reducing admixtures. For example, mixtures with high-range water-reducing admixtures show a shift towards larger void sizes (Whiting and Nagi 1998).

Table 3-19 lists trends of the effects of concrete ingredients and production on air entrainment. The extent of the changes will depend on specific materials, practices, and equipment. This table may suggest ways to correct high or low air contents.

If you do not have prior experience with the specific job materials and job equipment, develop a trial mix to determine the proper dosage and minimum mixing time.

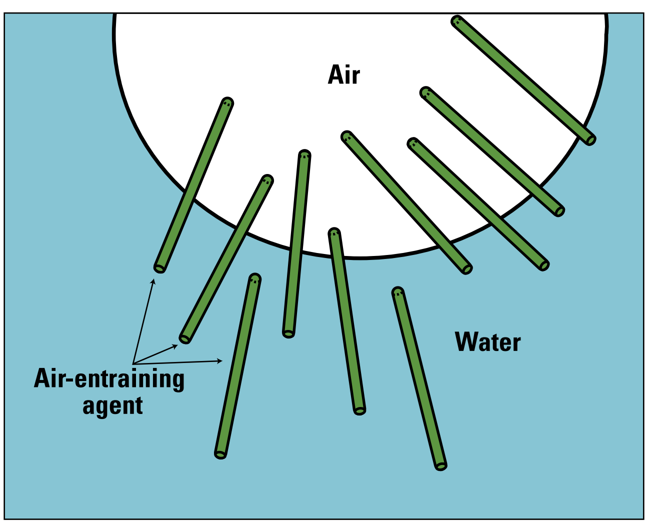

Figure 3-17. Stabilization of air voids by air-entraining admixture molecules (PCA)

Side Effects of Air-Entraining Admixtures

Generally, for every one percent entrained air, concrete loses about five percent of its compressive strength, everything else being equal (Whiting and Nagi 1998). However, this loss of strength can generally be mitigated by adjusting the water-cementitious materials ratio of the mixture. With non-vinsol water-reducing admixtures, air voids may coalesce around

Table 3-19. Effects of Materials and Practices on Air Entrainment

Material/practice	Change	Effect
Cement	Increase in cement content	↓
	Increase in fineness	↓
	Increase in alkali content	↑
Supplementary cementitious materials	Fly ash (especially with high carbon)	↓↓
	Silica fume	↓↓
	Slag with increasing fineness	↓
	Metakaolin	↔
Aggregates	Increase in maximum size	↓
	Sand content	↑
Chemical admixtures	Water reducers	↑
	Retarders	↑
	Accelerators	↔
	High-range water reducers	↑
W/CM	Increase W/CM	↑
Slump	Increase in slump up to 150 mm (6 in.)	↑
	High slump (> 150 mm or 6 in.)	↓
	Low slump concrete (< 75 mm or 3 in.)	↓
Production	Batching	↑↓
	Increased mixer capacity	↑
	Mixer speeds to 20 rpm	↑
	Longer mixer time	↑
Transport and delivery	Transport	↓
	Long hauls	↓
	Retempering	↑
Placing and finishing	Belt conveyers	↓
	Pumping	↓↓
	Prolonged internal vibration	↓
	Excessive finishing	↓

Source: Thomas and Wilson (2002a)

Key:
↓ decrease in air content
↓↓ significant decrease
↑ increase in air content
↔ no significant change
↑↓ increase or decrease in air content

aggregates, leading to reduced concrete strength (Cross et al. 2000) (see Air-Void System Incompatibilities, page 100). This result tends to occur in concrete with higher air contents that have had water added after initial mixing, and may also be affected by the type of aggregate.

Water Reducers

Water reducers are the second most commonly used chemical admixtures. A summary of the various classes is given in table 3-18. Mid-range products are generally a combination of natural, petroleum-based, and/or polycarboxylate chemical compounds (see the sidebar below). Type F and G water reducers are not normally used in pavements because of their high cost and because it is difficult to control the slump range required for slipform paving with their use.

Function of Water Reducers

You will remember that more water than is needed for cement hydration must be added to concrete mixtures to make them workable. Too much water, however, can reduce concrete durability by increasing porosity and permeability in the hardened concrete, allowing aggressive chemicals to penetrate the pavement. Water reducers are therefore added to mixtures to reduce the amount of water needed to maintain adequate workability in plastic concrete.

Water-reducing admixtures also indirectly influence concrete strength. For concretes of equal cement content, air content, and slump, the 28-day strength of a water-reduced concrete can be 10 percent greater than concrete without such an admixture. Water-reducing admixtures are specified by ASTM C 494 / AASHTO M 194.

The effectiveness of water reducers on concrete is a function of their chemical composition, concrete temperature, cementitious material content and properties, and the presence of other admixtures. Typical ranges of water reduction and slump are shown in table 3-17.

High-range water reducers (HRWRs) (Types F and G, also called superplasticizers) can be used to reduce necessary water content by 12 to 30 percent. In older products, however, the rate of slump loss is not reduced and in most cases is increased. Newer generation HRWRs do not exhibit as rapid a rate of slump loss. Rapid slump loss results in reduced workability and less time to place concrete. High temperatures can also aggravate slump loss. Some modern Type F water-reducing admixtures may entrain air, meaning that less air-entraining admixture will be required.

Water-Reducing Agent Mechanisms

Water reducers operate predominantly by applying surface charges on cement particles, which breaks up agglomerations of particles. As the cement particles

Three Generations of Water-Reducing Admixtures

First-generation water-reducing admixtures were primarily derived from natural organic materials such as sugars and lignins (extracted from wood pulp). These products had a limited effectiveness and may have been somewhat variable in performance, depending on the source material. These water reducers would often retard the mixture, particularly when overdosed. They are still used as Type A, B, and D products.

Second-generation (early high-range) water-reducing admixtures were derived from petroleum feedstocks: sulfonated naphthalene or melamine condensates with formaldehyde. These products offer greater water reduction and are less detrimental when overdosed. They often only provide about 20 minutes of effectiveness before the concrete exhibits significant slump loss. These products can be re-dosed after this time to maintain workability, if required.

Third-generation water-reducing admixtures are polycarboxylates, which are copolymers synthesized from carefully selected monomers. These products are currently used in mid- or high-range water-reducing admixtures (Type F and G). These admixtures can be fine-tuned for a given application, including a range of effectiveness and setting times. They may also increase air entrainment.

break up and move apart, trapped water is made available for hydration (figure 3-18). Some newer polycarboxylate-based water reducers also use a steric repulsion effect. These have polymers with long side chains that attach to the surface of cement grains to keep the grains apart physically. Ramachandran (1995) contains more detail on admixture mechanisms.

Side Effects of Water Reducers

Newer, polycarboxolate water-reducing admixtures have been reported to increase air entrainment in some cases. Types D, E, and G water-reducing admixtures can significantly affect setting behavior. Overdoses of water reducers, particularly normal-range products, may severely retard or prevent setting.

Set-Modifying Admixtures

Admixtures may be used to control (i.e., retard or accelerate) the rate of setting and strength gain of concretes. These effects can be particularly important for hot- and cold-weather concreting operations. They can also be useful for fast-track construction and to control production cycles, permit longer haul times, or compensate for slower strength gain of concretes made with some supplementary cementitious materials.

Chemical admixtures containing calcium chloride ($CaCl_2$) should not be used in reinforced pavements because of the risk of corrosion of steel.

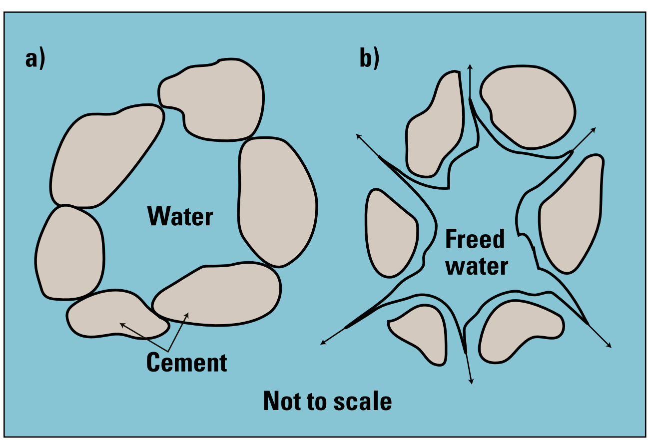

Figure 3-18. One mechanism by which water reducers work is dispersion. (a) Charged cement particles cling together, trapping water. (b) Water reducers separate cement grains, releasing the water and making it available for hydration.

Retarders are designated as Type B admixtures under ASTM C 494 / AASHTO M 194, although retardation is associated with Types D and G as well (table 3-18).

Accelerators are designated as Type C admixtures under ASTM C 494 / AASHTO M 194. Type E admixtures also have accelerating properties.

Primary Function of Set-Modifying Admixtures

Retarding admixtures are used to slow the rate of concrete setting. They may be used during hot-weather paving, when high concrete temperatures often cause an increased rate of stiffening that makes placing and finishing difficult. Retarders chemically control cement hydration, consequently reducing the maximum temperature. Retarders may also be used to delay setting under difficult or unusual placement conditions.

Accelerating admixtures are used to increase the rate of strength development of concrete at an early age, including in cold weather. However, excess acceleration may result in cracking before finishing and/or saw cutting can be completed.

Set-Modifying Agent Mechanisms

The mechanisms by which accelerators and retarders work are complex. However, some retarders appear to form a coating around cement grains that prevents or slows hydration. Eventually, the coating is breached and the hydration resumes.

Some accelerating admixtures, such as calcium chloride, appear to preferentially accelerate hydration of the silicate phases (alite [C_3S] and belite [C_2S]), while others appear to accelerate other phases. For more information, see Ramachandran (1995) and Thomas and Wilson (2002).

Side Effects of Set-Modifying Admixtures

The effects of set-modifying admixtures on other properties of concrete, like shrinkage, may not be predictable. Therefore, acceptance tests of set modifiers should be made with job materials under anticipated job conditions to detect possible side effects:

Set-Retarding Admixtures' Side Effects. Effects may include the following:

- Many retarders also act as water reducers; they are frequently called water-reducing retarders.

- Set-retarding admixtures may increase air content in the mixture.
- Delaying setting of a mix may increase the risk of plastic shrinkage cracking and may interfere with the saw-cutting window.
- In general, use of retarders may be accompanied by some reduction in strength at early ages (one to three days), but later strengths may be higher.
- With retarders, the bleeding rate and bleeding capacity of concrete are increased.
- Set-retarding admixtures are useful in extending setting times of concrete, but not all are effective in decreasing slump loss and extending workability prior to placement at elevated temperatures (Whiting and Dziedzic 1992).

Set-Accelerating Admixtures' Side Effects. Accelerators like calcium chloride are not antifreeze agents. Precautions should be taken during cold weather to protect the concrete from freezing prior to achieving sufficient strength.

When calcium chloride is used, it should be added to the concrete mix in solution form as part of the mixing water. If added in dry form, the particles may not completely dissolve. Undissolved lumps in the mix can cause popouts and dark spots in hardened concrete. An overdose can result in placement problems and can cause rapid stiffening, a large increase in drying shrinkage, corrosion of reinforcement, and loss of strength at later ages.

Other Admixtures

Several other admixtures may be used in concrete, including lithium-based materials for mitigating alkali-silica reaction, shrinkage-reducing admixtures, and corrosion inhibitors. More information can be found in Thomas and Wilson (2002); Kosmatka, Kerkhoff, and Panarese (2002); and Ramachandran (1995).

Dowel Bars, Tiebars, and Reinforcement

Key Points

- Dowel bars are placed across transverse joints to provide vertical support and to transfer loads across joints.
- Tiebars are placed across longitudinal joints (centerlines or where slabs meet) to prevent the slabs from separating and to transfer loads across the joints.
- Slab reinforcement may be used in concrete pavements to improve the ability of concrete to carry tensile stresses and to hold tightly together any random transverse cracks that develop in the slab.
- Epoxy-coated tiebars should conform to ASTM A 775 / AASHTO M 284, and epoxy-coated dowel bars should conform to AASHTO M 254.

Dowel bars, tiebars, and reinforcement may be used in concrete pavements to help the concrete carry tensile stresses (i.e., stresses that pull the concrete apart) and/or to transfer loads across joints. Collectively, these materials are often called "steel," although they may be made of other materials.

(Additional information can be found under Dowel Bars and Tiebars in chapter 8, page 218.)

Dowel Bars (Smooth Bars)

Dowel bars (smooth bars), or simply dowels, are placed in concrete across transverse joints to provide vertical support and to transfer loads across joints. Dowel bars are typically used on heavy truck routes. Dowel bars reduce the potential for faulting, pumping, and corner breaks in jointed concrete pavements (Smith et al. 1990; ACPA 1991).

Dowels are smooth and round or oval. Because they are smooth, they do not restrict the horizontal movement of the slab at the joint related to seasonal expansion and contraction of the slab.

The recommended dowel bar diameter is roughly one-eighth of the pavement thickness. The minimum diameter is 32 mm (1¼ in.), except at construction joints (or headers) in pavements less than 180 mm (7 in.) thick. Dowel sizes of 25 mm (1 in.) and less in heavy-traffic pavements have been shown to cause high bearing stresses on the concrete surrounding the dowel bar, resulting in damage in the concrete around the place the dowel emerges from the side of the slab, known as dowel socketing.

Typical dowel lengths are 455 mm (18 in.), although some 380-mm (15-in.) bars are used. This length is primarily related to the required embedment length on each side of the joint. Most States specify 455-mm long (18-in. long) dowel bars with 150 mm (6 in.) of embedment on each side of the joint. This leaves 150 mm (6 in.) in the center of the bar as a tolerance for the sawing of the joint and the formation of the subsequent crack.

A 305-mm (12-in.) spacing between bars is standard, although a 380-mm (15-in.) spacing can be used for lighter-traffic facilities. Dowels are typically placed across the entire length of the joint, primarily for constructability purposes. However, only three or four dowels are needed in each wheel path to sufficiently transfer load from one slab to the next (ACPA 1991); this is common practice when dowels are retrofitted in pavements originally constructed without dowels.

Shapes other than round bars have been tested and installed in limited trials. The most promising is the elliptical dowel, which allows for smaller effective diameter bars with the same bearing capacity as round bars. This reduces the weight and cost of the dowel assembly because of the reduced amount of steel used. Elliptical dowels have been shown to have similar performance to round dowels (Porter 2002).

Other mechanical load transfer systems include flat (plate) dowels and square dowels, both of which are not typically used in roadway or highway pavements.

Tiebars (Deformed Bars)

Tiebars (deformed bars), or rebar, are placed across longitudinal joints (centerlines or where slabs meet). Tiebars prevent faulting and lateral movement of the slabs and assist with load transfer between slabs. Tiebars are also used to connect edge fixtures such as curbs and gutters to the pavement.

Because tiebars are deformed, they bond to the concrete and do not allow movement (unlike smooth dowel bars, which by design allow such movement.) Tiebars thus minimize longitudinal joint opening between slabs and so maintain aggregate interlock.

Tiebar size, spacing, and length vary with the thickness of the pavement, tiebar material, and amount of pavement tied together (table 3-20). Tiebar sizes and embedment lengths should reflect the actual forces acting in the pavement, not only the working strength of the steel. Specifiers should choose standard manufactured tiebar lengths.

Tiebars should not be placed within 380 mm (15 in.) of transverse joints, or they can interfere with joint movement (ACPA 1991), leading to cracking. This space should increase to 450 mm (18 in.) if the tiebars are longer than 800 mm (32 in.). No more than three lanes should be tied together.

While corrosion of tiebars is not a common problem, some protection should be provided if deicing salts are going to be used on the pavement. ASTM D 3963 / AASHTO M 284 provide guidelines for such protection in the form of a coating. The coating should be no thicker than 125 to 300 µm (5 to 12 mil) or the bonding capacity of the bar is reduced.

Reinforcement

Reinforcement may be used in concrete pavements to improve the ability of concrete to carry tensile stresses and to hold tightly together any random transverse cracks that develop in the slab. Generally, cracking in jointed concrete pavements is controlled by limiting the spacing between joints. When the concrete slab is reinforced, joint spacing can be increased.

Current practice does not generally include any distributed reinforcement in concrete slabs, with the exception of continuously reinforced concrete pavements (see Basic Concrete Pavement Types in chapter 2, page 9). However, some agencies reinforce odd-shaped panels to hold expected cracks tight (ACPA 2003a) and use jointless, continuously reinforced concrete for high-traffic urban routes.

Conventional reinforcement is generally in the form of welded wire fabric or deformed bars that are placed at specific locations in the pavement. As an alternative, reinforcing fibers are added to fresh concrete during the batching and mixing process. Fibers, which are available in a variety of lengths, shapes, sizes, and thicknesses, are equally distributed throughout the concrete, are much shorter than bars, and take up a much smaller cross-sectional area of the pavement.

Materials for Dowel Bars, Tiebars, and Reinforcement

These items are often collectively referred to as “steel” but may be made of other materials.

Steel

Steel is the most common material for dowels, tiebars, and reinforcement. Dowels and tiebars should

Table 3-20. Tiebar Dimensions and Spacings

Slab thickness mm (≈in.)	Tiebar size x length, mm (≈in.)	Tiebar spacing, mm (≈in.) — Distance to nearest free edge or to nearest joint where movement can occur: 3.0 m (≈10ft)	3.7 m (≈12 ft)	4.3 m (≈14 ft)	7.3 m (≈24 ft)
130 (5)	13M x 600 (24)	760 (30)	760 (30)	760 (30)	700 (28)
150 (6)	13M x 600 (24)	760 (30)	760 (30)	760 (30)	580 (23)
180 (7)	13M x 600 (24)	760 (30)	760 (30)	760 (30)	500 (20)
200 (8)	13M x 600 (24)	760 (30)	760 (30)	760 (30)	430 (17)
230 (9)	16M x 760 (30)	900 (35)	900 (35)	900 (35)	600 (24)
250 (10)	16M x 760 (30)	900 (35)	900 (35)	900 (35)	560 (22)
280 (11)	16M x 760 (30)	900 (35)	900 (35)	860 (34)	500 (20)
310 (12)	16M x 760 (30)	900 (35)	900 (35)	780 (31)	460 (18)

Source: Adapted from ACI 325.12R

conform to ASTM A 615 / AASHTO M 31. Their typical yield strength is 420 MPa (60 ksi); 280 MPa (40 ksi) is allowable. Tiebars can be Grade 420 (60) or 280 (40); yield strength determines required length.

Steel fibers are generally 12.7 to 63.5 mm (0.5 to 2.5 in.) long and 0.45 to 1.0 mm (0.017 to 0.04 in.) in diameter. The usual amount of steel fibers ranges from 0.25 to 2 percent by volume, or 20 to 157 kg/m^3 (33 to 265 lb/yd^3). Steel fibers are generally used at high rates for improved hardened properties. The benefits of steel fibers include up to 150 percent increase in flexural strength, reduced potential for cracking during concrete shrinkage, and increased fatigue strength (Kosmatka, Kerkhoff, and Panarese 2002).

Epoxy-Coated Bars

Corrosion resistance is key for embedded steel, particularly in harsh climates where deicing chemicals are used on pavements. The most common method of resisting or delaying corrosion is coating steel bars with epoxy 0.2 to 0.3 mm (0.008 to 0.012 in.) thick. Epoxy-coated tiebars should conform to ASTM A 775 / AASHTO M 284, and epoxy-coated dowel bars should conform to AASHTO M 254.

Epoxy-coated steel is still susceptible to corrosion, particularly when incorrect handling in the field results in nicks or scratches in the epoxy coating.

Epoxy-coated dowels should be coated with a bond-breaking material to prevent them from locking up the joint. This material is typically applied by the manufacturer. If the dowels are left exposed to the elements for an extended time (e.g., at a project site or over the winter), the bond breaker must be reapplied on at least one end of each bar. Materials applied in the field are typically form-release oil or white-pigmented curing compound. Do not use grease, as it will form a void space around the bar, preventing the concrete from consolidating adequately and fully encasing the dowel.

Stainless Steel Bars

Some agencies have experimented with stainless steel (304 and 316) reinforcing bars for long-life concrete pavements. Solid stainless steel is very expensive, but it has a much longer service life. Stainless steel dowels should conform to ASTM A 955.

Stainless-Clad Bars

Stainless-clad steel dowel bars have a 1.8- to 2.3-mm thick (0.070- to 0.090-in. thick) stainless steel cladding that is metallurgically bonded to a carbon steel core. They are quite expensive compared to epoxy-coated bars, but they cost less than solid stainless steel while offering its long service life.

Fiber-Reinforced Polymer

Considerable research has been conducted in the use of fiber-reinforced polymer dowel bars. They offer promise but are still quite expensive.

Synthetic Fibers

Synthetic reinforcing fibers are manufactured from materials like acrylic, aramid, carbon, nylon, polyester, polyethylene, or polypropylene. Their use has been increasing steadily, generally at low dosage rates to reduce plastic shrinkage. Their primary use in pavements is in ultrathin whitetopping, where 50 to 100 mm (2 to 4 in.) of concrete is bonded to asphalt (see Concrete Overlays in chapter 2, page 23).

The most common synthetic fibers in concrete pavements are made of fibrillated polypropylene. They are normally used at a rate of at least 0.1 percent by volume. Ultrathin whitetopping typically uses 1.8 kg/m^3 (3 lb/yd^3) of such fibers. The benefits of these fibers include reduced plastic shrinkage and subsidence cracking, and increased toughness or post-crack integrity. In fresh concrete, polypropylene fibers also reduce settlement of aggregate from the pavement surface, resulting in a less permeable and more durable, skid-resistant pavement (ACPA 2003b).

Other Materials

Stainless steel tubes and pipe filled with concrete have also been used experimentally (ASCE 2004), but their long-term performance has not yet been demonstrated. Low-carbon microcomposite steels have been shown to be more corrosion-resistant than epoxy-coated steel in some tests, and quite cost effective. Zinc-coated dowel bars are also showing promise as longer-term performance is becoming more desirable. These proprietary steels are less resistant to corrosion than stainless steel, but are also less costly. Plastic coating, approximately 0.5 mm (0.02 in.) thick, is used by some agencies on dowel bars.

Curing Compounds

Key Points

- Curing compounds must be applied thoroughly to concrete surfaces after texturing to reduce moisture loss from the surface.
- The most common curing compounds are liquid membrane-forming materials.
- Use pigmented curing compounds so you can see that coverage is complete and uniform.
- Liquid membrane-forming curing compounds are specified by ASTM C 309 and ASTM C 1315.

Curing compound is applied to the surface and exposed edges of concrete soon after the concrete has been placed and textured. (Some people consider the proper time for applying curing compound to be approximately at initial set, when bleeding is complete [Poole 2005].) The purpose is to seal the surface—that is, to prevent or slow water evaporation from the surface—so that hydration can continue for preferably seven or more days (figure 3-19).

Cement hydration is a slow chemical reaction (see all of chapter 4). If the concrete surface is allowed to dry prematurely, the reaction stops and desirable properties of the concrete, such as durability, will be compromised at the surface. It is important not to let this happen, because the concrete surface carries the traffic and is exposed to aggressive environments. Proper curing will reduce surface permeability and increase surface resistance to wear and weather.

Curing compound must be thoroughly applied to fresh concrete before the surface dries; otherwise there is no benefit.

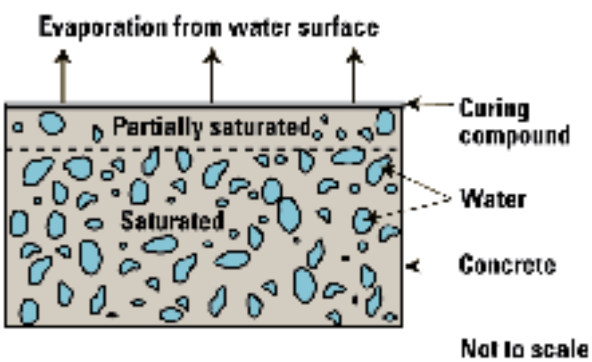

Figure 3-19. Curing compounds keep concrete partially saturated near the surface during the curing period. (PCA)

Types of Curing Compounds

Liquid membrane-forming curing compounds are among the most widely used curing materials for concrete pavements. They are commonly wax- or resin-based compounds, emulsified in water or dissolved in a solvent. (These compounds are used rather than water curing for their convenience and economy.) After they are applied to the concrete surface, the water or solvent evaporates and the wax or resin forms a membrane on the concrete surface. Liquid membrane-forming compounds need to conform to the requirements of ASTM C 309 / AASHTO M 148 and ASTM C 1315, as applicable. ASTM C 156 / AASHTO T 155 specify a method for determining the efficiency of curing compounds, waterproof paper, and plastic sheeting.

Pigmented curing compounds are recommended because they make it easy to verify proper application. When placing concrete on sunny days and in hot weather, the curing compound should contain a white pigment to reflect the sun's heat. Translucent compounds may contain a fugitive dye that makes it easier to check visually for complete coverage of the concrete surface when the compound is applied. The dye fades soon after application.

Not to be confused with curing compounds, evaporation-retarding materials are applied immediately after concrete is placed and *before* it is finished. These materials can be worked into the surface during finishing without damaging the concrete. They form a thin, continuous film that retards loss of bleed water, reducing the risk of plastic shrinkage cracking before finishing/curing, particularly in hot, dry weather. If used, evaporation-retarding materials should be applied as soon as possible. They should not be used as a finishing aid.

References

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AASHTO M 6, Fine Aggregates for Portland Cement Concrete

AASHTO M 31, Standard Specification for Deformed and Plain Carbon Steel Bars for Concrete Reinforcement

AASHTO M 80, Coarse Aggregates for Portland Cement Concrete

AASHTO M 85, Portland Cement

AASHTO M 148, Liquid Membrane-Forming Compounds for Curing Concrete

AASHTO M 154, Air-Entraining Admixtures for Concrete

AASHTO M 194, Chemical Admixtures for Concrete

AASHTO M 240, Blended Hydraulic Cement

AASHTO M 254, Specification for Corrosion Resistant Coated Dowel Bars

AASHTO M 284, Standard Specification for Epoxy-Coated Reinforcing Bars: Materials and Coating Requirements

AASHTO M 295, Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

AASHTO M 302, Ground Granulated Blast Furnace Slag for Use in Concrete and Mortars

AASHTO M 321, High-Reactivity Pozzolans for Use in Hydraulic-Cement Concrete, Mortar, and Grout

AASHTO T 22, Compressive Strength of Cylindrical Concrete Specimens

AASHTO T 26, Quality of Water to Be Used in Concrete

AASHTO T 27, Sieve Analysis of Fine and Coarse Aggregates

AASHTO T 106, Compressive Strength of Hydraulic Cement Mortar (Using 50-mm or 2-in. Cube Specimens)

AASHTO T 131, Time of Setting of Hydraulic Cement by Vicat Needle

AASHTO T 155, Water Retention by Concrete Curing Materials

AASHTO T 157, Air-Entraining Admixtures for Concrete

AASHTO T 197, Time of Setting of Concrete Mixtures by Penetration Resistance

AASHTO T 303, Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction

ASTM standards may be found in *Annual Book of ASTM Standards*, ASTM International. www.astm.org.

ASTM A 615/A615M-04b, Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement

ASTM A 775, Specification for Epoxy-Coated Steel Reinforcing Bars

ASTM A 955, Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement

ASTM C 33/AASHTO M6, Specification for Concrete Aggregates

ASTM C 39/AASHTO T 22, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C 109/AASHTO T 106 Compressive Strength of Hydraulic Cement Mortar (Using 50-mm or 2-in. Cube Specimens)

ASTM C125-03 Standard Terminology Relating to Concrete and Concrete Aggregates

ASTM C 131, Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

ASTM C136-04/AASHTO T27 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

ASTM C 150/AASHTO M 85, Specification for Portland Cement

ASTM C 156/AASHTO T 155, Test Method for Water Retention by Concrete Curing Materials,

ASTM C 191/AASHTO T 131 Test Method for Time of Setting of Hydraulic Cement by Vicat Needle

ASTM C 233/AASHTO T 157, Test Method for Air-Entraining Admixtures for Concrete

ASTM C 260/AASHTO M 154, Specification for Air-Entraining Admixtures for Concrete

ASTM C 294-04 Standard Descriptive Nomenclature for Constituents of Concrete Aggregates

ASTM C 295, Standard Guide for Petrographic Examination of Aggregates for Concrete

ASTM C 309/AASHTO M 148, Specification for Liquid Membrane-Forming Compounds for Curing Concrete

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ASTM C 403/AASHTO T 197, Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance

ASTM C 494/AASHTO M 194, Specification for Chemical Admixtures for Concrete

ASTM C 535, Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

ASTM C 595/AASHTO M 240, Specification for Blended Cement

ASTM C 618/AASHTO M 295, Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete

ASTM C 666/AASHTO T 161, Test Method for Resistance of Concrete to Rapid Freezing and Thawing

ASTM C 672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

ASTM C 989/AASHTO M 302, Specification for Ground Granulated Blast Furnace Slag for Use in Concrete and Mortars

ASTM C1138-97 Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)

ASTM C 1157, Performance Specification for Hydraulic Cements

ASTM C 1240/AASHTO M 307, Specification for Use of Silica Fume for Use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout

ASTM C 1260/AASHTO T 303. Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)

ASTM C 1293, Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

ASTM C 1315, Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete

ASTM C 1567, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

ASTM C1602/C1602M-04. Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete

ASTM C 1603-04. Standard Test Method for Measurement of Solids in Water

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Chapter 4

Transformation of Concrete from Plastic to Solid

At the concrete plant, the ingredients discussed in chapter 3—cementitious materials, water, aggregates, and chemical admixtures—are mixed together. During the next few hours, the mixture changes from a plastic mixture to a solid concrete slab. Central to this transformation is a complex process called hydration—an irreversible series of chemical reactions between water and cement. Hydration is a mystery to many people involved in designing and constructing concrete pavements. The goal of chapter 4 is to demystify this process, focusing on the practical implications for designers and construction personnel.

Why should readers care about hydration? The chemical reactions taking place during the first few hours influence how the concrete mixture behaves when it is being placed and finished. Later reactions govern how strong and durable the hardened concrete becomes. With a general understanding of these reactions, readers can help prevent or correct problems and ensure that the concrete performs as it was designed.

Notes to help you use chapter 4:

- Chapter 4 takes two, overlapping approaches to describing hydration. The first approach focuses on five stages of hydration. (The Stages of Hydration chart on pages 4-8 through 4-15 is replicated in a full-sized, foldout poster accompanying this manual.) The second approach provides a more in-depth discussion of the chemical processes involved in hydration, focusing on the compounds in cement and the compounds created during hydration.
- There is some repetition of information throughout the chapter, as the text moves from a basic discussion to a more technical and detailed discussion.
- The general information about hydration is based on a nominal concrete pavement mixture with a low water-cementitious materials (w/cm) ratio. Many factors, like actual w/cm ratio, cement fineness, aggregate gradation, consolidation, curing, and environment, all strongly influence the performance of a pavement. These factors are discussed in more detail in other chapters, especially chapters 3, 6, and 8.
- The time/heat curve used throughout this chapter represents a small, insulated concrete sample. It illustrates only changes in heat generally associated with cement hydration. It does not represent an actual time/heat curve of a full-depth concrete slab, which would likely reflect heat contributed from external sources like sunlight, and slower cooling due to insulation plus the thermal mass of a full-depth slab.
- Chapter 4 uses cement chemists' shorthand notation to describe compounds: A=Al_2O_3, C=CaO, F=Fe_2O_3, H=H_2O, M=MgO, S=SiO_2, and $\overline{S}$=SO_3. Thus, tricalcium silicate is C_3S.

Stages of Hydration: Overview

Hydration begins as soon as water and cement come into contact. The cement particles partially dissolve, and the various dissolved components start to react at various rates. During the reactions, heat is generated and new compounds are produced. The new compounds cause the cement paste to harden, bond to the aggregate in the concrete mixture, and become strong and dense.

Portland cement is manufactured by mixing limestone, clay, and shale together at a very high temperature, then grinding the resulting clinker with gypsum. This process results in three primary ingredients in cement that react during hydration (figure 4-1):

- Calcium silicates (referred to as silicates).
- Calcium aluminates (referred to as aluminates).
- Calcium sulfates (referred to as gypsum).

Silicates contain silicon (as in glass). Aluminates contain aluminum (as in pottery clay, and the sand in sandpaper). Gypsum contains sulfur (as in rotten eggs). All three compounds contain calcium (as in bones and teeth) and oxygen.

The reactions of these compounds with water can be described in five stages—mixing, dormancy, hardening, cooling, and densification. The reactions can also be tracked by monitoring heat at each stage (figure 4-2): a brief heat spike during mixing; no heat generated during dormancy; a significant, steady rise in heat during hardening; a peak and then continuous drop in heat during cooling; and, finally, relatively little heat generated during densification.

The basic explanation of the five stages on pages 4-3 through 4-6 describes how concrete generally reacts when the system is balanced and performing as designed.

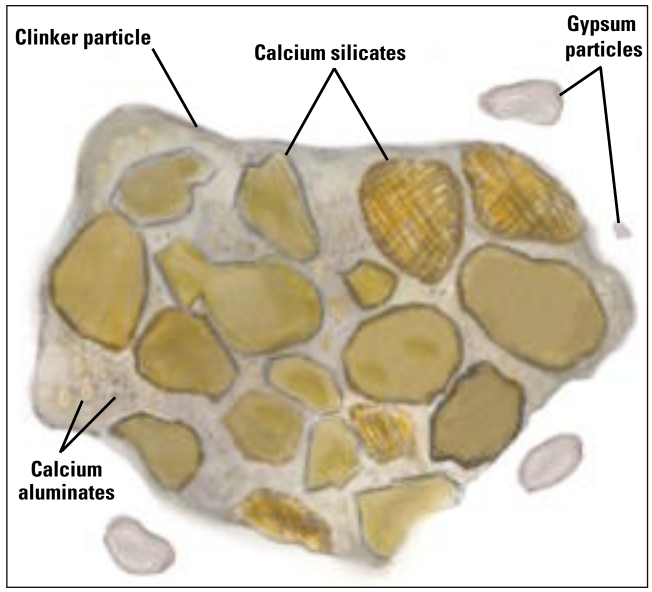


Figure 4-1. Compounds in cement

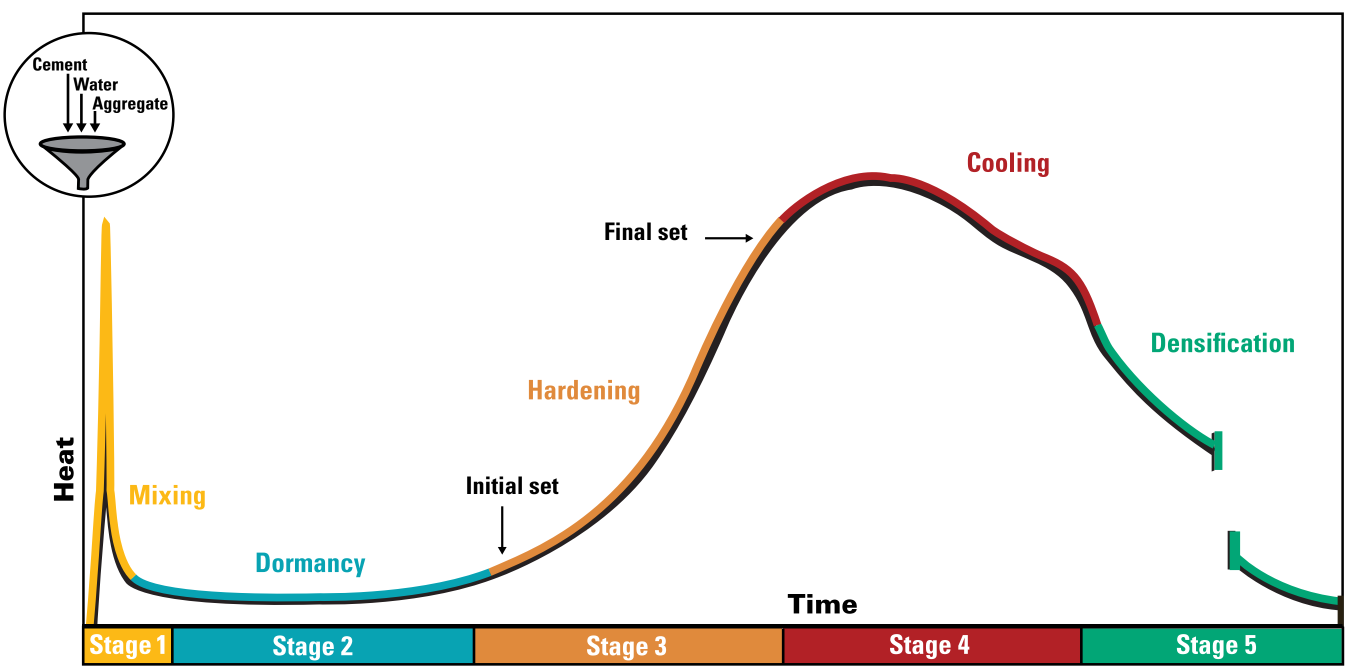


Figure 4-2. General hydration curve delineating the five stages

Mixing

In general, during hydration the reactions between silicates and water produce the primary compounds that make concrete strong and durable. But silicates dissolve very slowly and do not have an immediate effect.

Aluminates and gypsum, on the other hand, dissolve and react within minutes of being mixed with water, with immediate effect. Together with water, the dissolved aluminate begins developing new compounds, generating significant heat. Unchecked, these reactions would cause irreversible, flash set or stiffening of the concrete.

Fortunately, the fast-dissolving gypsum reacts with the dissolved aluminate and water to create a gel-like substance that coats the cement compounds (figure 4-4). The coating slows the aluminate reactions almost as soon as they start, reducing the amount of heat generated and the potential for flash set (figure 4-3).

Dormancy

Aluminate reactions are generally controlled for about two to four hours, the dormant period. During this time, the concrete is plastic and does not generate heat (figure 4-5). The dormant stage gives the construction crew time to transport, place, and finish the concrete while it is workable.

During dormancy, it looks as though nothing is happening in the mixture. However, the cement is continuing to dissolve, and the water is becoming saturated with dissolved calcium and OH (hydroxyl) ions (figure 4-6).

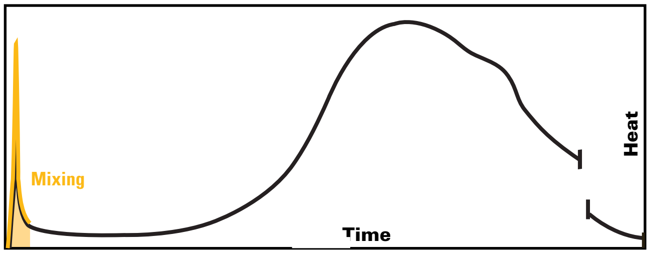


Figure 4-3. A very brief heat spike occurs during mixing.

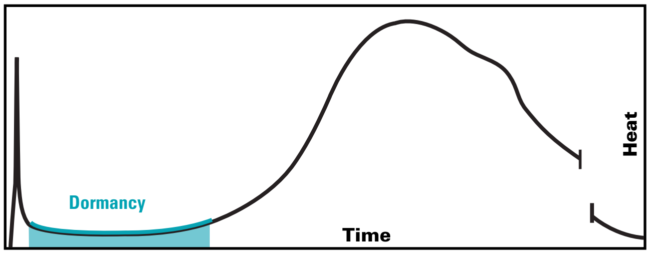


Figure 4-5. The concrete does not generate heat during the dormancy stage.

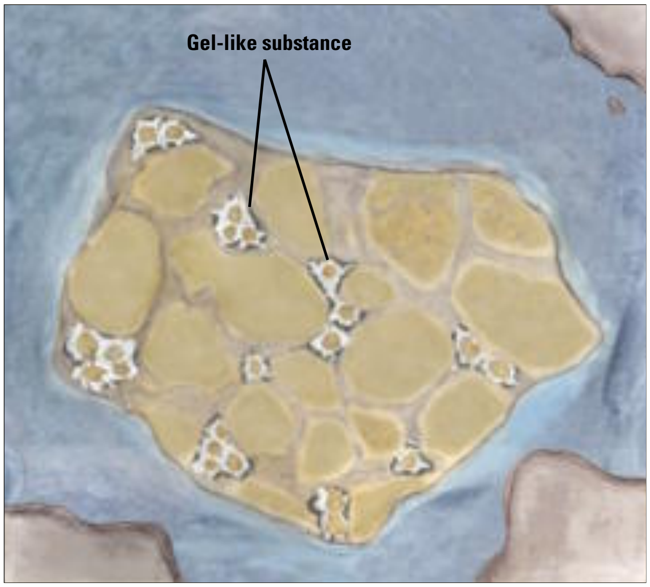


Figure 4-4. A gel-like substance coats cement compounds, controlling the reactions and heat.

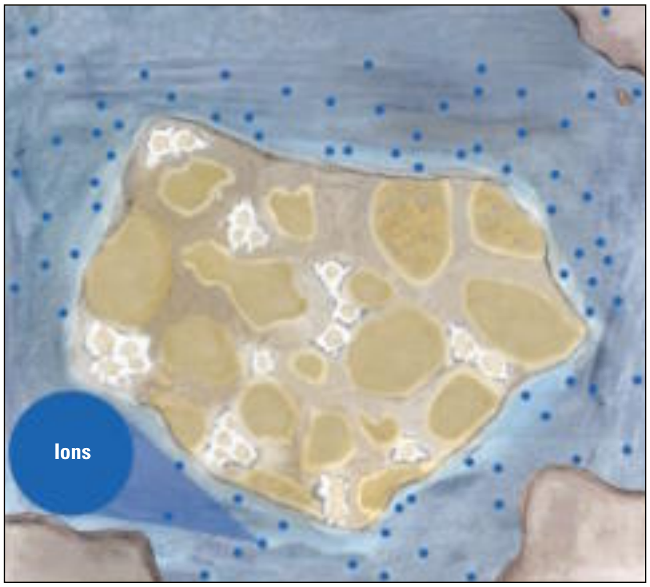


Figure 4-6. During dormancy, the water becomes saturated with dissolved ions.

Hardening

When the water becomes supersaturated with dissolved calcium ions, new compounds begin forming, heat is generated, and the mixture begins stiffening. This is the beginning of the hardening stage (figure 4-7).

Initial set occurs soon after the mixture begins stiffening. After initial set, construction workers should not work, vibrate, or finish the concrete (any segregation of materials during this stage will be permanent). Workers should apply curing compound as soon as possible after finishing to control evaporation from the concrete surface.

During the hardening stage, new compounds (products of hydration) continue growing and heat continues to be generated. Some of the compounds are finger-like, fibrous growths; others are more crystalline (figure 4-8). These compounds interweave and mesh together around the aggregates, causing the concrete to become stiffer and eventually become a solid. At final set, the concrete has become strong enough to walk on. Still, the concrete cannot carry traffic.

Cooling

Due to changes in temperature and moisture content, the concrete shrinks. Friction between the shrinking concrete and the base layer under the pavement causes stress that will eventually cause the concrete to separate or crack. To relieve the stress and prevent concrete from cracking randomly, workers must saw joints. (Joints simply control the crack locations.)

There is only a brief period of time, perhaps two to four hours, to saw joints successfully. This period is called the sawing window. The sawing window begins when the concrete can be sawed without excessive raveling, and ends before the concrete begins to crack randomly.

Approximately four to six hours after initial set, hydration slows and the amount of heat generated begins to drop (figure 4-9).

This slowdown is caused by the buildup of hydration products, which have begun to interfere with contact between the remaining water and cement in the concrete (figure 4-10).

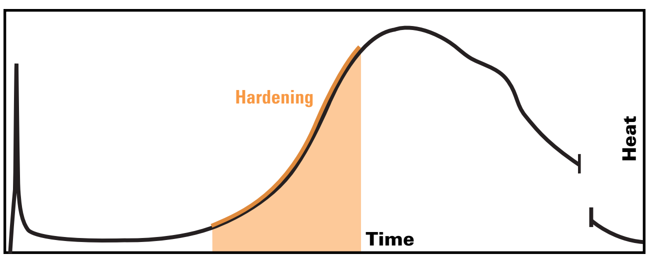


Figure 4-7. Significant heat is generated during the hardening stage.

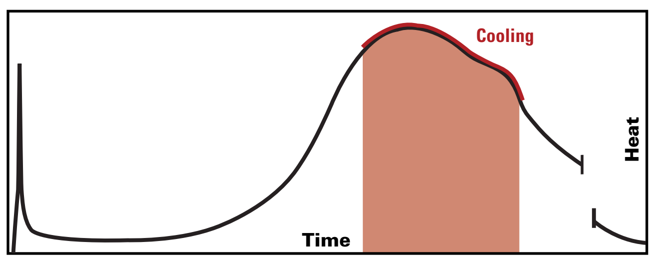


Figure 4-9. Heat energy peaks and then drops during cooling.

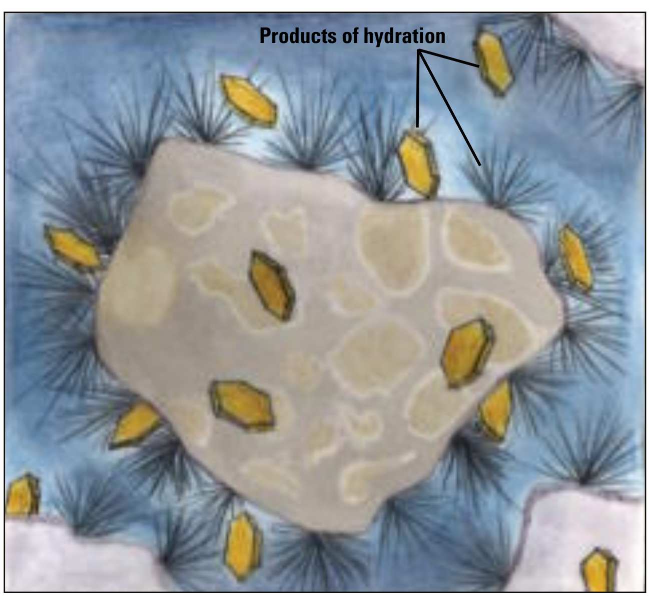


Figure 4-8. Hydration products grow.

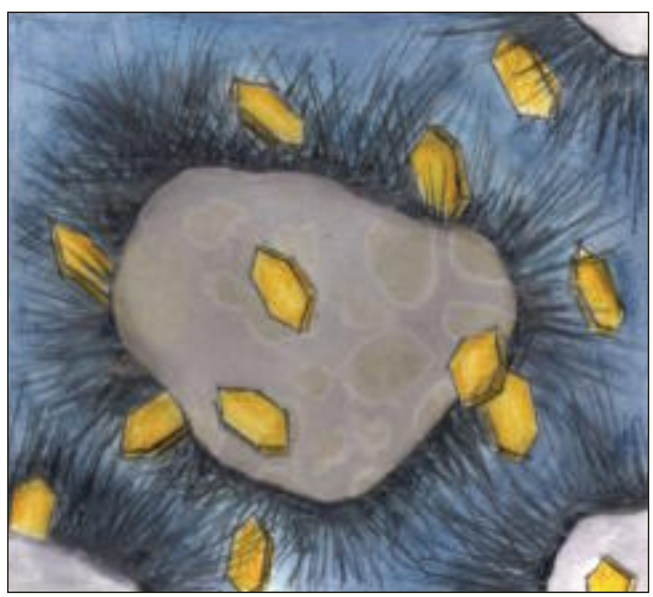


Figure 4-10. Hydration products grow during cooling.

Densification

During the final stage of hydration, the reactions continue slowly, generating little heat (figure 4-11).

Continued growth and meshing of hydration products results in a strong, solid mass (figure 4-12). Long after the concrete is strong enough to carry traffic, this process will continue—as long as cement and water are present in the concrete—increasing the slab's strength and reducing its permeability.

Construction crews can do two final things to help ensure long-term pavement performance:

After sawing joints, insulate the pavement if air temperatures are expected to drop rapidly and significantly. (If the pavement surface cools too quickly, the slab may crack.)

Keep traffic and construction equipment off the pavement as long as possible (preferably, at least 72 hours) to protect the curing compound. Curing compound reduces moisture loss from the concrete and thus enables continued hydration, increasing concrete strength and reducing its permeability.

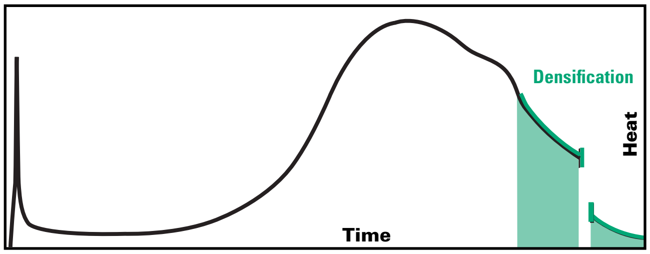


Figure 4-11. Very little heat is generated during the final, densification stage.

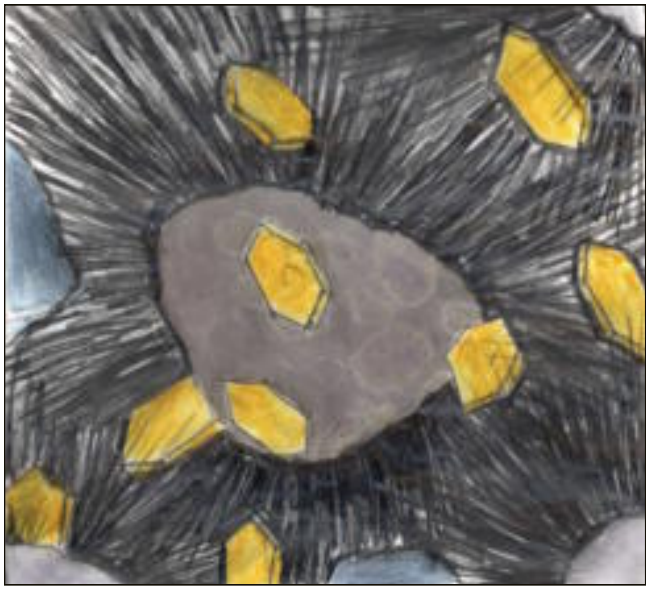


Figure 4-12. Hydration products mesh into a dense solid.

Summary

As you can see, hydration is the underlying and unifying process that must be understood and managed or mitigated throughout a concrete pavement project, from mix design and materials selection to construction.

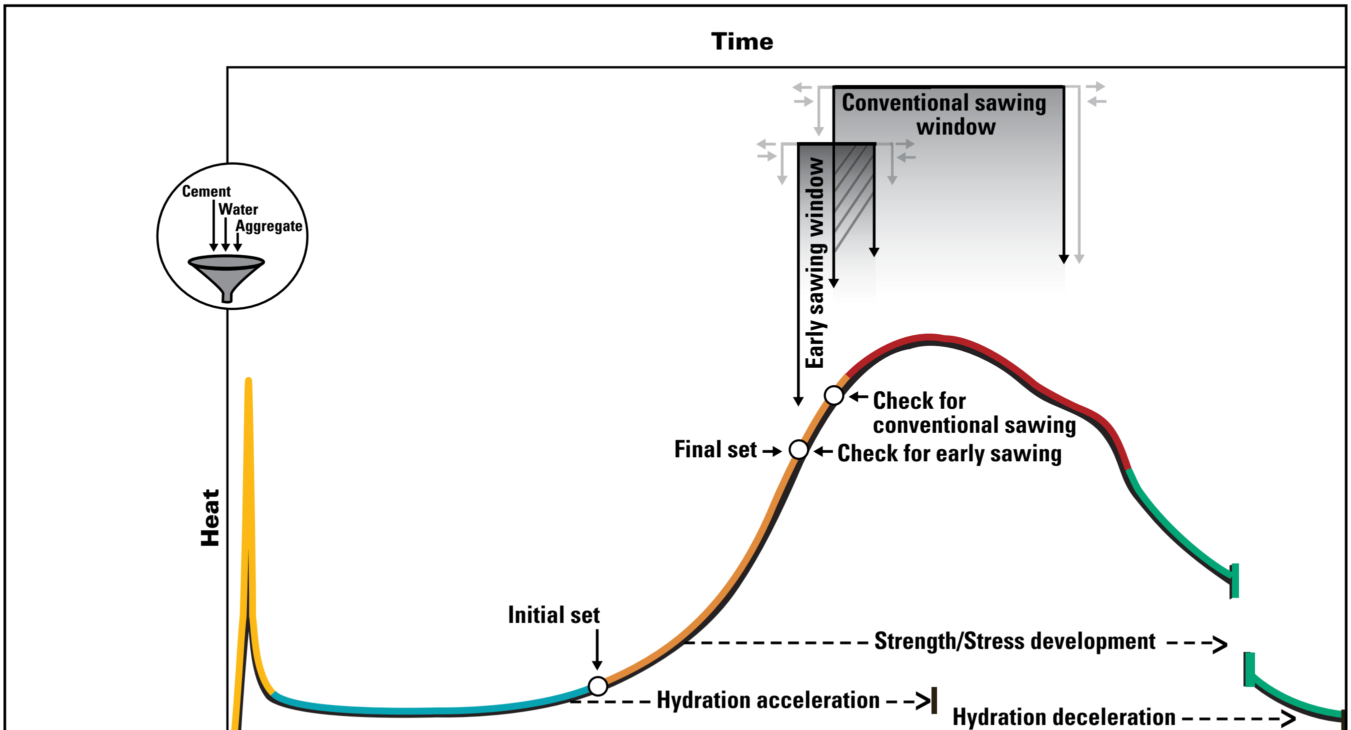
The previous overview covers only the most basic information regarding the stages of cement hydration. A somewhat more detailed description is given in the next section, which includes Stages of Hydration charts beginning on page 76 (and reproduced in the enclosed poster).

You can find more information about several related topics throughout this manual:

- Effects of SCMs on concrete mixtures, see Supplementary Cementitious Materials in chapter 3, page 31.
- Effects of fine cements on concrete mixtures, see Cement Fineness Affects Hydration and Concrete Properties, page 87.
- Effects of admixtures on concrete mixtures, see Chemical Admixtures in chapter 3, page 55.
- Possible problems with early or late stiffening during hydration, see Potential Materials Incompatibilities later in this chapter, page 97; Chemical Admixtures in chapter 3, page 55; Factors Affecting Setting in chapter 5, page 114; and Stiffening and Setting in chapter 6, page 186.
- Hydration considerations during concrete pavement construction, see all of chapter 8, beginning on page 203.
- Maximizing the water-cementitious materials ratio for optimum hydration, see Step 2: Water-Cementitious Materials Ratio in chapter 6, page 179.
- Cement hydration and concrete strength, see Strength and Strength Gain in chapter 5, page 116; and Strength in chapter 6, page 187.
- Cement hydration and concrete cracking, see Concrete Strength Gain, Tensile Stress, and the Sawing Window later in this chapter, page 93; Shrinkage and Temperature Effects in chapter 5, pages 125 and 127, respectively; and Early-Age Cracking in chapter 5, page 148.

- Optimizing hydration for reduced permeability, see Factors Affecting Permeability in chapter 5, page 131; and Adjusting Properties in chapter 6, page 185.

Figure 4-13 briefly describes the characteristics of concrete and the implications for workers at each stage of hydration.



	Stage 1 Mixing	Stage 2 Dormancy	Stage 3 Hardening	Stage 4 Cooling	Stage 5 Densification
	Lasts about 15 minutes	**Lasts about 2–4 hours**	**Lasts about 2–4 hours**		**Continues for years**
Characteristics of concrete mixture	High heat is generated immediately, followed by rapid cooling.	Mixture is plastic, workable, and not generating significant heat.	• Hydration generates significant heat. • Mixture sets, begins to harden, and gains strength. • Stress begins developing in the concrete.	Stress development will exceed strength development if stress is not relieved.	Slab continues to become stronger and less permeable.
What engineers, supervisors, and workers must do to ensure durable pavement	Ensure adequate mixing.	Transport, place, and finish the concrete while plastic and workable.	• Begin curing as soon as possible. • Thoroughly apply curing compound.	Saw joints to relieve stress and control cracking.	• Insulate the slab if the air temperature is expected to cool rapidly and significantly. • Protect curing compound as long as possible.

Figure 4-13. Concrete characteristics, and implications for workers, during stages of hydration

Stages of Hydration: Details

The Stages of Hydration charts (pages 76 through 83, also included with this manual as a full-sized poster) provide more details about hydration and the transformation of concrete from a plastic mixture to a solid slab. The charts illustrate and explain the following:

- Specific chemical reactions occurring between cement and water at various stages of hydration.
- How these reactions
  - Are observed in changes in heat.
  - Result in physical changes in the mixture.
  - Influence construction practice.
- How supplementary cementitious materials change the system.
- How chemical admixtures change the system.
- How incompatibilities may occur.
- Issues related to cracking.
- Issues related to the air-void system.

These topics are covered in greater depth later in the second half of this chapter, beginning on page 84, which focuses more on the compounds involved in cement hydration than on the stages.

Primary Compounds in Unhydrated Cement

The three ingredients in cement—silicates, aluminates, and sulfates—consist of several primary compounds:

- Silicates.
  - Alite (C_3S).
  - Belite (C_2S).
- Aluminates.
  - Tricalcium aluminate (C_3A).
  - Ferrite (C_4AF).
- Sulfates ($C\overline{S}$).
  - Gypsum (dihydrate).
  - Plaster (hemihydrate).
  - Anhydrite.

The Stages of Hydration charts on the following pages focus on alites (C_3S), belites (C_2S), the aluminate C_3A, and sulfates (figure 4-14). These are the compounds in cement that have the most significant influence on the formation of concrete.

Primary Hydration Products

The primary products of hydration are

- Calcium silicate hydrate (C-S-H).
- Calcium hydroxide (CH).
- Ettringite (C-A-$\overline{S}$-H).
- Monosulfate (C-A-$\overline{S}$-H).

The charts on the following pages focus on the formation of C-S-H and CH. These compounds are central to concrete strength and durability.

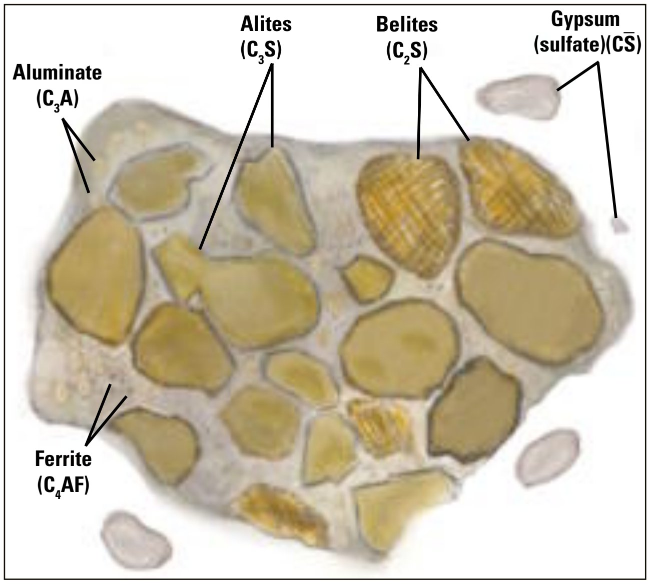
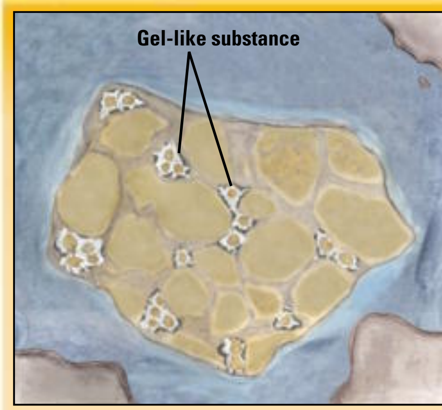


Figure 4-14. Compounds in cement

Basics

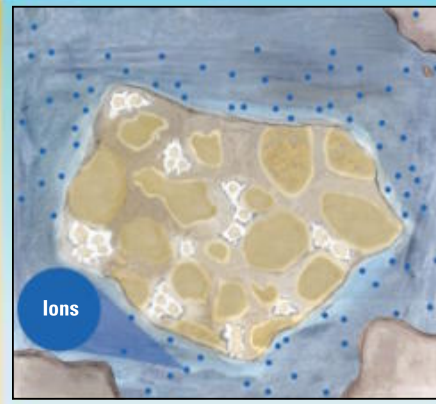
Stage1: Mixing



Within minutes of mixing cement and water, the aluminates start to dissolve and react, with the following results:

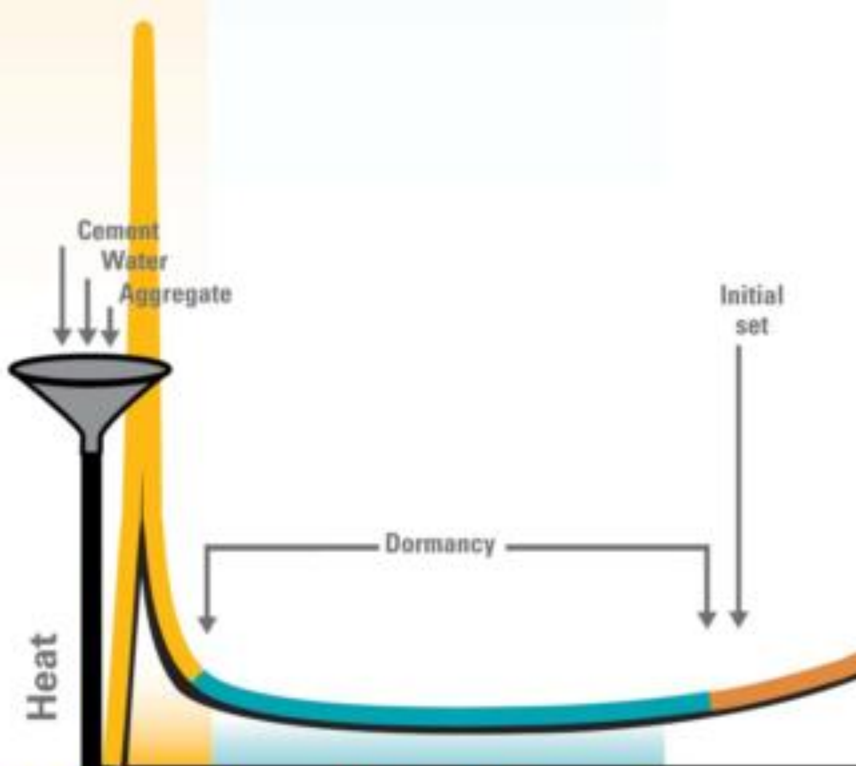
- Aluminate* reacts with water and sulfate, forming a gel-like material (C-A-$\bar{S}$-H). This reaction releases heat.
- The C-A-$\bar{S}$-H gel builds up around the grains, limiting water's access to the grains and thus controlling the rate of aluminate reaction. This occurs after an initial peak of rapid hydration and heat generation.

Stage 2: Dormancy



For about two to four hours after mixing, there is a dormant period, during which the following events occur:

- The C-A-$\bar{S}$-H gel is controlling aluminate* reactions. Little heat is generated, and little physical change occurs in the concrete. The concrete is plastic.
- During dormancy, as silicates (alite [C_3S] and belite [C_2S]) slowly dissolve, calcium ions and hydroxyl (OH) ions accumulate in solution.



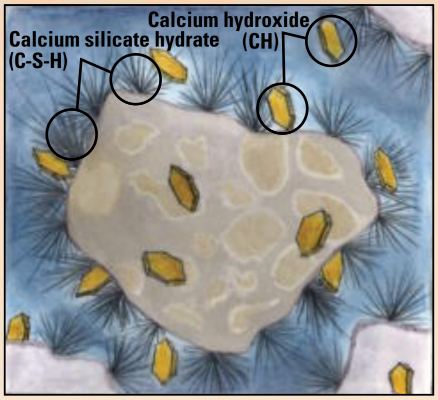
Lasts about 15 min | Lasts about 2–4 hr

Compounds key

- Silicates
  - Alite (C_3S)
  - Belite (C_2S)
- Aluminates*
  - Tricalcium aluminate (C_3A)
  - Ferrite (C_4AF)
- Sulfates ($C\bar{S}$)
  - Gypsum (dihydrate)
  - Plaster (hemihydrate)
  - Anhydrite
- Calcium silicate hydrate (C-S-H)
- Calcium hydroxide (CH)
- Ettringite (C-A-$\bar{S}$-H)
- Monosulfate (C-A-$\bar{S}$-H)

* In the Stages of Hydration chart, "aluminate" refers generically to tricalcium aluminate (C_3A). Ferrite (C_4AF) hydration does not contribute significantly to concrete properties.

Stage 3: Hardening



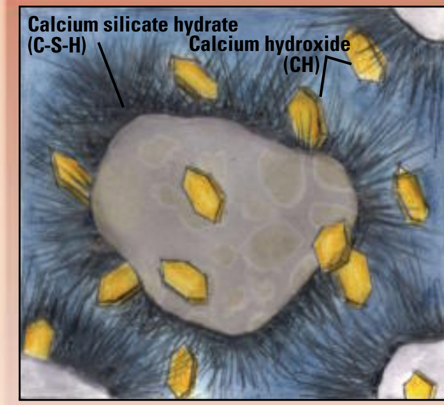
This stage is dominated by alite (C_3S) hydration and the resulting formation of C-S-H and CH crystals:

- When the solution becomes supersaturated with calcium ions (from dissolving alite [C_3S] primarily), fiber-like C-S-H and crystalline CH start to form. This generates heat. Meshing of C-S-H with other solids causes the mixture to stiffen and set.
- The increasing heat and stiffening of the cement paste mark the beginning of hydration acceleration, which lasts several hours. Initial set occurs early in this stage.
- Acceleration is characterized by a rapid rate of hydration, significant heat, continued hardening, and strength development.
- The rates of reaction are faster for finer cementitious materials and for systems with higher alkali contents. Slower reacting systems will react longer and will generally provide a better microstructure in the long run.
- During acceleration, aluminate* and sulfate continue to react, and needle-like ettringite (C-A-$\overline{S}$-H) crystals form.
- Final set—about when the concrete is hard enough to walk on—occurs before heat energy peaks (before alite [C_3S] reactions begin to slow).
- After final set, tensile stresses start to develop due to temperature and drying effects, the mixture's increasing stiffness, and the slab's friction with the pavement base.

Final set

Lasts about 2–4 hr

Stage 4: Cooling

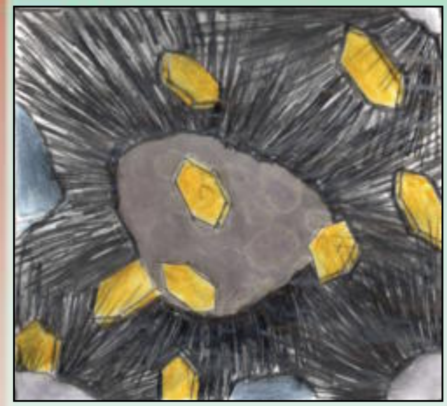


After final set, the rate of alite (C_3S) reactions begins to slow, and the amount of heat generated peaks and begins to drop. This occurs because the buildup of C-S-H and CH interferes with contact between remaining water and undissolved cement grains.

During this stage, several things are occurring:

- The concrete is gaining strength, as the amount of C-S-H (and CH) increases. However, the concrete is still somewhat porous and should carry only light construction traffic.
- Tensile stresses may be building faster than tensile strength. At some point, stress will exceed strength, causing the concrete to crack. Unless joints are sawed to control crack location, random cracking will occur.
- Sometime after the temperature peaks, sulfate, which has continued reacting with aluminate* (see stages 1 and 2 on the previous page) will be depleted. Any remaining aluminate* now reacts with ettringite to form monosulfate, which may be associated with a brief increase in heat. (Monosulfate does not significantly affect concrete properties.)

Stage 5: Densification



This stage is critical for continued development of concrete strength and reduction of concrete permeability. (When concrete has low permeability, substances like water and dissolved salts cannot readily penetrate it and it is less susceptible to freeze-thaw damage.) The concrete must be kept moist as long as possible. Here's why:

- As long as alite (C_3S) remains and there is water in the concrete, the alite will continue to hydrate. As the volume of hydration products grows, concrete porosity (and permeability) decreases, and the concrete gains strength. Eventually, the products—particularly C-S-H—will combine into a solid mass.
- Belite (C_2S), which reacts more slowly than alite (C_3S), also produces C-S-H. After several days, in the presence of water, most of the alite has reacted and the rate of belite hydration begins to be noticeable. It is important to maintain sufficient moisture long enough for belite reactions to occur.
- Hydration products will continue to develop, permeability will continue to decrease, and strength will continue to increase slowly for days, weeks, even years, as long as cementitious material and water are present. This process is affected by factors like cement type and fineness.

Can continue for years

Effects of Supplementary Cementitious Materials (SCMs)

SCMs, like fly ash and ground, granulated blast-furnace (GGBF) slag, are included in more than 65 percent of concrete mixtures in the United States. In general, they consist of the same basic elements—silicon, aluminum, and calcium—and perform basically the same function as cement. (Pozzolans require a source of calcium, usually provided by hydrating portland cement, to hydrate.) SCMs are used in concrete to take advantage of available materials and achieve desired workability, strength gain, and durability.

See Supplementary Cementitious Materials in chapter 3, page 31. See Reactions of Supplementary Cementitious Materials later in this chapter, page 94.

Stage 1: Mixing

If SCMs contain large amounts of calcium (for instance, Class C fly ash), the calcium may be in the form of aluminate,* which will increase the risk of flash set if there is insufficient sulfate in solution, as discussed in the Incompatibilities chart (page 81).

Fly ashes with high loss-on-ignition (LOI) (mass loss when heated to 1,000°C [1,830°F]) will likely interfere with the development of the air-void system. That is because high LOI fly ashes contain unburned carbon that absorbs air-entraining admixture. Higher and more variable dosages of air-entraining agents may be required.

Mixtures with SCMs may require less water to achieve workability.

Stage 2: Dormancy

Like portland cement, during dormancy the silicates in SCMs are slowly dissolving and releasing calcium ions and hydroxyl (OH) ions.

Stage 3: Hardening

Silicates in the SCMs react with the CH from the cement reactions to form additional C-S-H, thus reducing porosity of the system and increasing strength and durability. These reactions are slow and, while they start in this stage, they may only be noticeable in stage 5. They will continue for a long time, and generally lead to higher long-term concrete strengths.

In mixtures with SCMs,

- Setting time may be delayed, and working time may be extended. Heat and rate of hydration are often reduced, and the duration of hydration extended.
- Early strengths may be depressed.
- These effects may be especially significant for construction in cold weather.

Stage 4: Cooling

The magnitude of the heat peak is often reduced in systems containing SCMs due to slower hydration rate. This generally results in less shrinkage later and, thus, potentially less stress. A second peak may be observed as the SCMs hydrate.

Generally as a result of reducing the hydration rate and heat, SCMs influence the duration and timing of the saw-cutting window. The influence depends on the system chemistry and the environment. If SCMs are being used for the first time or if sources change, then close attention is required to prevent random cracking.

Stage 5: Densification

In the long term, silicates in SCMs chemically combine with CH from cement hydration to form additional C-S-H.

Strength development may be slower initially but continues longer, normally leading to higher long-term strength. Permeability is often significantly reduced, thus improving potential durability.

Systems containing GGBF slag and fly ash are reportedly more prone to frost damage. The extent of, and mechanisms behind, this perception are still under investigation.

Low-calcium fly ash and GGBF slag are effective in reducing alkali reactivity of mixtures for three reasons. These SCMs

- Reduce the mixture's alkali content.
- Reduce concrete permeability.
- Reduce the system's calcium/silica ratio.

High-calcium fly ashes may have the same effect, and should be tested using the materials under consideration.

Heat

Time

Lasts about 15 min | Lasts about 2–4 hr | Lasts about 2–4 hr | | Can continue for years

Compounds key

Silicates
- Alite (C_3S)
- Belite (C_2S)

Aluminates*
- Tricalcium aluminate (C_3A)
- Ferrite (C_4AF)

Sulfates ($C\bar{S}$)
- Gypsum (dihydrate)
- Plaster (hemihydrate)
- Anhydrite

Calcium silicate hydrate (C-S-H)

Calcium hydroxide (CH)

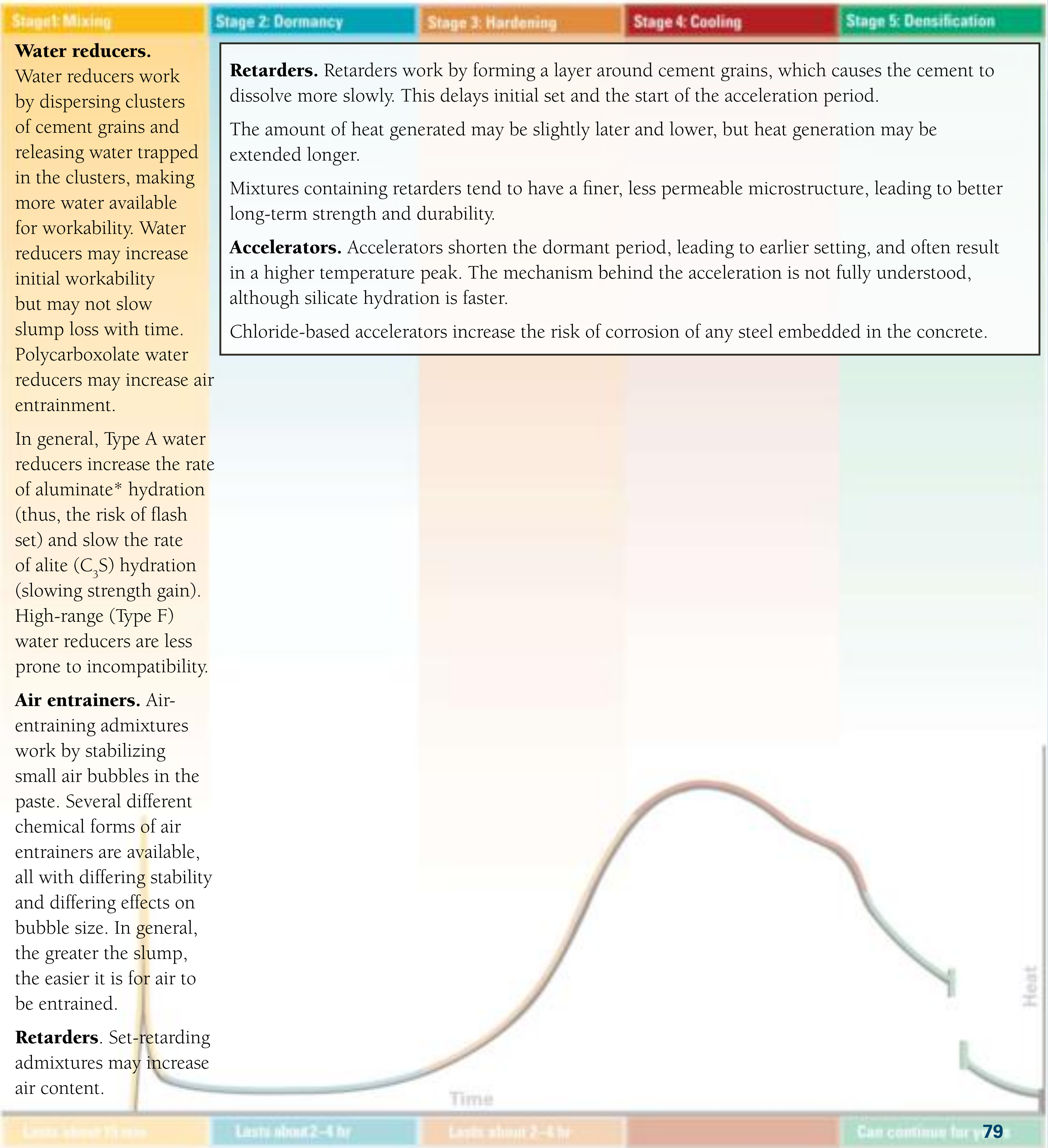
Ettringite (C-A-$\bar{S}$-H)

Monosulfate (C-A-$\bar{S}$-H)

* In the Stages of Hydration chart, "aluminate" refers generically to tricalcium aluminate (C_3A). Ferrite (C_4AF) hydration does not contribute significantly to concrete properties.

Effects of Chemical Admixtures

See Chemical Admixtures in chapter 3, page 55.



Water reducers. Water reducers work by dispersing clusters of cement grains and releasing water trapped in the clusters, making more water available for workability. Water reducers may increase initial workability but may not slow slump loss with time. Polycarboxolate water reducers may increase air entrainment.

In general, Type A water reducers increase the rate of aluminate* hydration (thus, the risk of flash set) and slow the rate of alite (C_3S) hydration (slowing strength gain). High-range (Type F) water reducers are less prone to incompatibility.

Air entrainers. Air-entraining admixtures work by stabilizing small air bubbles in the paste. Several different chemical forms of air entrainers are available, all with differing stability and differing effects on bubble size. In general, the greater the slump, the easier it is for air to be entrained.

Retarders. Set-retarding admixtures may increase air content.

Retarders. Retarders work by forming a layer around cement grains, which causes the cement to dissolve more slowly. This delays initial set and the start of the acceleration period.

The amount of heat generated may be slightly later and lower, but heat generation may be extended longer.

Mixtures containing retarders tend to have a finer, less permeable microstructure, leading to better long-term strength and durability.

Accelerators. Accelerators shorten the dormant period, leading to earlier setting, and often result in a higher temperature peak. The mechanism behind the acceleration is not fully understood, although silicate hydration is faster.

Chloride-based accelerators increase the risk of corrosion of any steel embedded in the concrete.

Implications of Cement Hydration for Construction Practices

See chapter 8, beginning on page 203.

Stage 1: Mixing

If using dump trucks or agitator trucks, mix materials and place the mixture into the transport vehicle. Look out for stiffening during transportation (see early stiffening under Incompatibilities on the next page).

If using ready-mix trucks, place materials into truck and mix during transport.

In both cases, ensure adequate mixing is provided.

Stage 2: Dormancy

Transport, place, finish, and texture the concrete during the dormant period, before initial set, while the concrete is cool, plastic, and workable.

Use appropriate transport methods and equipment to prevent segregation.

If visible bleeding occurs, finish the surface after bleeding has stopped and bleed water has evaporated. Do not work bleed water back into the surface, because it increases porosity and permeability of the surface layer. (In hot weather, bleeding may be helpful in reducing plastic shrinkage cracking.)

If necessary (e.g., in hot, windy weather) apply a (polymeric) evaporation retarder before finishing.

Stage 3: Hardening

After stiffening begins, do not work, vibrate, or consolidate the concrete. Segregation of the ingredients at this point will be permanent.

Thoroughly apply curing compound to the concrete surface and edges as soon as possible after finishing, to reduce the rate of water evaporation from the concrete. Protecting the concrete with curing compound is critical because it results in stronger, less permeable concrete. (When water evaporates from the concrete, more cement remains unhydrated and fewer products form. Also, water evaporation leaves capillary pores behind, reducing concrete's durability because it is more susceptible to freeze-thaw damage and attack by aggressive fluids.)

During this stage, prepare joint-sawing equipment. Beginning at final set, start checking concrete for readiness for saw cutting.

Stage 4: Cooling

To prevent random cracking due to buildup of tensile stresses, saw joints during a brief sawing window:

- The sawing window begins when concrete is strong enough not to ravel when sawed, and ends before the concrete cracks in front of the saw—typically, no later than 24 hours after placement.
- Conventional sawing windows generally begin after final set but before the heat peaks, and end after the heat peaks; how long after depends on the specific mixture, cement, SCMs, ambient temperatures, etc.
- For early-age saws, the window may begin at or slightly before final set (stage 3) and will end earlier than for conventional sawing.

Cover the slab, especially if temperatures will cool significantly during the first night. Insulation prevents extreme temperature and moisture variations within the slab that can lead to curling and warping and related cracking. Insulation also helps keep the slab moist and warm.

Stage 5: Densification

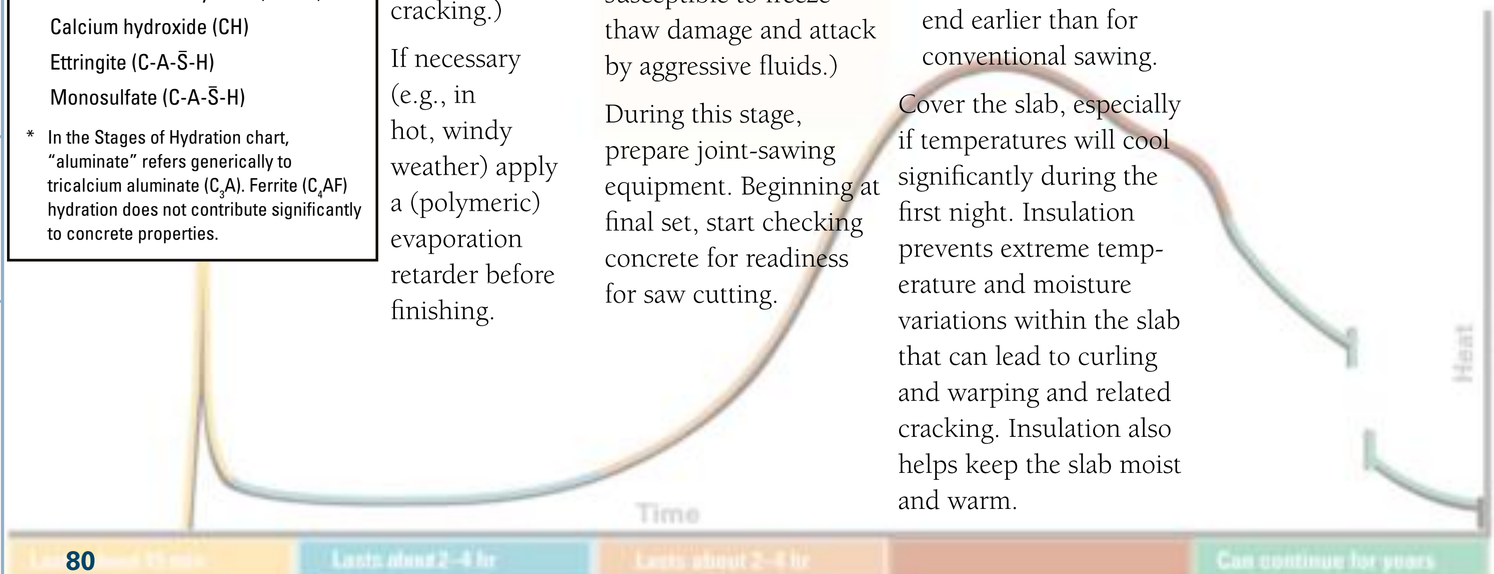
Keep concrete thoroughly covered and protected with curing compound as long as possible, at least for the first 72 hours after mixing.

The longer the curing compound remains in place (that is, protected from equipment and construction traffic), the more moisture will be retained in the concrete for hydration and thus for development of strength and reduction of permeability.

Compounds key

- Silicates
  - Alite (C_3S)
  - Belite (C_2S)
- Aluminates*
  - Tricalcium aluminate (C_3A)
  - Ferrite (C_4AF)
- Sulfates ($C\bar{S}$)
  - Gypsum (dihydrate)
  - Plaster (hemihydrate)
  - Anhydrite
- Calcium silicate hydrate (C-S-H)
- Calcium hydroxide (CH)
- Ettringite (C-A-$\bar{S}$-H)
- Monosulfate (C-A-$\bar{S}$-H)

* In the Stages of Hydration chart, "aluminate" refers generically to tricalcium aluminate (C_3A). Ferrite (C_4AF) hydration does not contribute significantly to concrete properties.



Incompatibilities: Early Stiffening/ Retardation

The risk of incompatibilities occurring is higher
- When using finer cementitious materials.
- At low water-cementitious materials ratios.
- At high temperatures.

See Potential Materials Incompatibilities later in this chapter, page 97. See Chemical Admixtures in chapter 3, page 55.

Stage 1: Mixing

If insufficient sulfate is in solution for the amount of aluminate* (from cement and fly ash), uncontrolled aluminate hydration may cause rapid, permanent stiffening or flash set. This is characterized by a temperature rise. Aluminate hydration is accelerated by some Type A water-reducing admixtures and high temperature; more sulfate may be needed to maintain an adequate shell around the aluminate* particles to control flash set.

Excess sulfate in solution results in gypsum crystals being deposited out, prematurely stiffening the system, resulting in (temporary) false set. The gypsum eventually dissolves as the mixture is mixed, which is why false set is temporary. There is no effect on other hydration processes.

The amount of sulfate in solution is controlled by the amount/form of sulfate in the cement. Gypsum dissolves slowly (increasing the risk of flash set). Plaster dissolves rapidly (increasing the risk of false set). Cement manufacturers normally balance these materials.

Stages 2–3: Dormancy and Hardening

If calcium is consumed by poorly controlled aluminate reactions earlier in Stage 1, then supersaturation of calcium ions will be slowed and alite hydration retarded. This retardation can potentially continue for several days, severely delaying or even preventing setting. It is possible to have a mixture that exhibits false set, followed by severe retardation.

Alite (C_3S) hydration is accelerated by high temperatures, high alkali contents (from cementitious materials), and high cement fineness. This accelerates setting, which can accelerate the start of, and shorten the duration of, the saw-cutting window.

Alite hydration is retarded by some Type A water-reducing admixtures and low temperatures, slowing setting and thus delaying the beginning of the saw-cutting window.

Implications of Cement Hydration for Cracking

Materials tend to expand as they get warmer and shrink when they get cooler. Cement paste tends to move more with such volume changes than does aggregate. Cement paste also shrinks as it dries. Objects that are restrained when they move (shrink or expand) will be stressed, leading to cracking if the stresses exceed the strength. (Restraint comes from any connection with adjacent objects, such as friction with the subgrade.) It is therefore desirable to reduce paste content within a given mix, while still achieving workability and filling all the voids between aggregate particles.

The volume of aggregate is significantly larger than the volume of paste, and tends to control the amount of thermal movement of concrete. If aggregate with a low coefficient of thermal expansion is used, the risk of problems will decrease. See Aggregate Coefficient of Thermal Expansion in chapter 3, page 47. Concrete with high paste content and high fines content, due to improper aggregate gradation, will be at higher risk of cracking. See Early-Age Cracking in chapter 5, page 148, and Crack Prediction with HIPERPAV in chapter 8, page 231.

Stage 1: Mixing

Because chemical reactions are faster at higher temperatures, an increase in initial mixing temperature significantly increases the amount of heat generated (and corresponding stress development) in stage 3.

Compounds key

- Silicates
  - Alite (C_3S)
  - Belite (C_2S)
- Aluminates*
  - Tricalcium aluminate (C_3A)
  - Ferrite (C_4AF)
- Sulfates ($C\bar{S}$)
  - Gypsum (dihydrate)
  - Plaster (hemihydrate)
  - Anhydrite
- Calcium silicate hydrate (C-S-H)
- Calcium hydroxide (CH)
- Ettringite (C-A-$\bar{S}$-H)
- Monosulfate (C-A-$\bar{S}$-H)

* In the Stages of Hydration chart, "aluminate" refers generically to tricalcium aluminate (C_3A). Ferrite (C_4AF) hydration does not contribute significantly to concrete properties.

Stage 2: Dormancy

Drying, and consequent shrinkage, any time before final set may result in so-called plastic shrinkage cracking.

Lasts about 2–4 hr

Stage 3: Hardening

When concrete sets at high temperature, increased stresses can develop because the concrete cools (and so shrinks) more than concrete that sets at lower temperatures. The increased stresses may increase the potential for random cracking.

Lasts about 2–4 hr

Stage 4: Cooling

Drying, and consequent restrained shrinkage, before sufficient strength gain may result in random cracking.

If setting is delayed, concrete may crack because it dries while the concrete is still too soft to start saw cutting.

Faster setting may mean the concrete will crack before sawing can be completed because the sawing window is shorter than the time required for sawing.

Cementitious systems with high alkali content, aluminate* content, and fineness may shrink more than other systems, therefore increasing the risk of random cracking.

Modeling programs like HIPERPAV can be used to predict the sawing window more accurately for a given set of circumstances, helping to reduce random cracking.

Stage 5: Densification

After concrete has set, it tends to dry and cool more quickly at the top surface, setting up differential stresses through the thickness of the slab. This will cause the top and bottom surfaces to expand or shrink different amounts, resulting in curvature known as warping and curling. Depending on the support conditions and the extent of the curvature, stresses (self weight or traffic loadings) on the curved slab may result in cracking.

Can continue for years

Time

Implications of Cement Hydration for the Air-Void System

A good air-void system—that is, a uniform distribution of small, stable bubbles—in the finished concrete is necessary for concrete durability. See Air-Entraining Admixtures in chapter 3, page 56; Frost Resistance in chapter 5, page 132; and Effects of Chemical Admixtures on page 79.

Stage 1: Mixing

The air-void system develops during mixing. It is harder to entrain air in systems at high temperature, with low slump, and with very fine supplementary cementitious materials that have high loss-on-ignition (LOI) (mass loss when heated to 1,000°C [1,830°F]) and low alkali contents. Additional air-entraining admixture may be required for such systems. Set-retarding admixtures may increase air content.

Stage 2: Dormancy

The stability of the air-void system (i.e., the ability to prevent bubbles from breaking during handling) depends on the chemistry of the air-entraining admixture. Some air entrainers are more sensitive than others to the presence or dosage of other chemical admixtures or supplementary cementitious materials. (Methods are being developed to test the overall sensitivity of a paste system.)

Increased handling (e.g., transportation, placing, vibration, finishing) of unstable systems may reduce the air content and affect the quality of the in-place air-void system. Air content of concrete should be tested at the delivery point and after placing to assess the stability of the concrete mix.

Stage 3: Hardening / **Stage 4: Cooling**

The air-void system has been formed at this stage and is unlikely to change.

Stage 5: Densification

Hydration Compounds

The rest of chapter 4 describes cement chemistry and hydration in more detail, focusing on compounds in cement and concrete. First, the specific compounds in portland cement are described. Then, the role of each of these compounds in hydration is outlined, followed by the results of hydration: new compounds produced, the pore system, various stresses on the system, and the development of concrete strength and low permeability. The effects of using supplementary cementitious materials (SCMs) in the mixture are discussed and, finally, potential incompatibilities that can arise through various combinations of SCMs and admixtures in the mix are described.

Key Points

- Portland cement primarily consists of clinker ground with gypsum.
- Clinker consists of four primary compounds: two silicates and two aluminates.
- Silicates compose about 75 percent of cement. Alite (C_3S) contributes to concrete's initial set and early strength; belite (C_2S) contributes to strength gain after approximately one week.
- Tricalcium aluminate (C_3A) hydrates immediately when exposed to water; calcium sulfate (generically, gypsum) is added to portland cement to control tricalcium aluminate's hydration rate. (The other aluminate, tetracalcium aluminoferrite [C_4AF], contributes little to cement other than its grey color.)
- The fineness of portland cement affects hydration rates and concrete properties. Finer cements generally have higher initial hydration rates.

Portland Cement Compounds

Portland cement is manufactured by heating limestone, clay, and shale in a kiln to above 1,400°C (2,500°F), then grinding the resulting clinker with gypsum. The final product consists of silicates, aluminates, and sulfates. Other elements and compounds in cement are in smaller proportions, but can contribute to, or interfere with, the complex chemical reactions that occur during cement hydration. The primary compounds in portland cement are listed in table 4-1 and shown in figure 4-15.

Chemical analyses of cementitious materials by x-ray fluorescence report the elements as oxides. (This is for convenience only, as these elements are not all likely to be present as pure oxides.) The same convention is followed in the remaining sections of this chapter. An example of a mill certificate is shown in figure 4-16. A mill certificate includes specified limits, and test results, for various compounds in a specific type of portland cement.

The next sections discuss portland cement's primary components: clinker and gypsum.

Portland Cement Clinker

Clinker is the major ingredient in portland cement. Clinker is primarily composed of two silicates and two aluminates, the first four compounds listed in table 4-1.

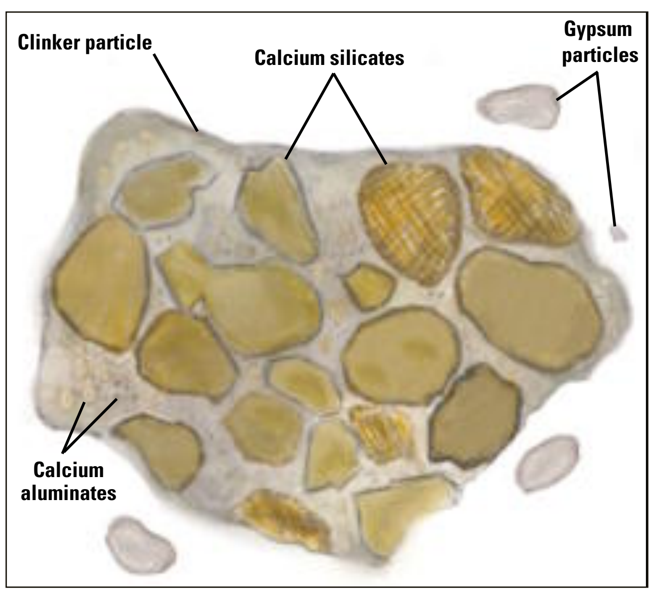


Figure 4-15. Composition of portland cement

Silicates

Silica normally composes about 20 percent of cement by mass, while calcium oxide normally contributes 60 to 65 percent. These combine to form the silicates in clinker: alite (C_3S) and belite (C_2S). Portland cements currently contain approximately 55 percent alite and 20 percent belite (Johansen et al. 2005).

During cement hydration, alite contributes to the setting and early strength development of concrete, normally beginning a few hours after mixing. Belite is the primary compound that contributes to concrete's later strength development. Its effects become noticeable about a week after mixing.

Aluminates

Alumina is included in the mixture in a cement kiln because it helps reduce the burning temperatures required to make cement. Alumina combines with calcium and iron oxide to form two calcium aluminate compounds in clinker: tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) or ferrite. Typical portland cements contain approximately 10 percent tricalcium aluminate and 10 percent ferrite.

During cement hydration, tricalcium aluminate (C_3A) reacts very rapidly when mixed with water unless controlled by the presence of sulfate. (Uncontrolled hydration of tricalcium aluminate can lead to flash set.) (See Aluminate and Sulfate reactions later in this chapter, page 88.) Ferrite reactions do not contribute significantly to the properties of concrete except for the gray color.

Gypsum

When clinker is being ground to a powder, gypsum ($C\bar{S}H_2$) is added at about a five percent dosage. The primary purpose for including gypsum in portland cement is to provide sulfate, which controls the tricalcium aluminate (C_3A) reactions during hydration. The sulfate dosage is carefully optimized because the strength of a cement is influenced by the amount of sulfate; incompatibility (including uncontrolled stiffening and setting) can occur if the amounts of sulfate and tricalcium aluminate are out of balance (see Potential Materials Incompatibilities in this chapter, page 97).

Gypsum is one of three forms of calcium sulfate normally present in portland cement. The three forms

Table 4-1. Major Compounds in Portland Cement

	Name	Phase (compound)	Shorthand notation	Effect	Amount (%)	
Aluminates		Tricalcium aluminate	C_3A	• Liberates a large amount of heat • Can cause early stiffening and flash set • Prone to sulfate attack	5–10%	Clinker
	Ferrite	Tetracalcium aluminoferrite	C_4AF	• Contributes little to strength • Contributes to gray color	5–15%	Clinker
Silicates	Alite	Tricalcium silicate	C_3S	• Hydrates and hardens rapidly • Largely responsible for initial set and early strength	50–70%	Clinker
	Belite	Dicalcium silicate	C_2S	• Hydrates and hardens slowly • Contributes to strength increase after one week • Contributes to low concrete permeability	15–30%	Clinker
Sulfates	Gypsum*	Calcium sulfate	$C\bar{S}$	• Controls the hydration of C_3A	3–5%	Gypsum

* See Table 4-2.

Plant Name
Dustytown, NJ

Plant: Example | Cement Type: II | Date

Production Period: September 4, 2003 – September 6, 2003

STANDARD REQUIREMENTS
ASTM C 150 Tables 1 and 3

CHEMICAL

Item	Spec. Limit	Test Result
SiO_2 (%)	20.0 min	20.8
Al_2O_3 (%)	6.0 max	4.4
Fe_2O_3 (%)	6.0 max	3.3
CaO (%)	A	62.9
MgO (%)	6.0 max	2.2
SO_3 (%)	3.0 max	2.7
Ignition loss (%)	3.0 max	2.7
Na_2O (%)	A	0.19
K_2O (%)	A	0.50
Insoluble residue (%)	0.75 max	0.27
CO_2 (%)	A	1.5
Limestone (%)	5.0 max	3.5
$CaCO_3$ in limestone (%)	70 min	98
Potential (%)		
C_3S	A	60
C_2S	A	21
C_3A	8 max	6
C_4AF	A	10
$C_4AF + 2(C_3A)$	A	22

PHYSICAL

Item	Spec. Limit	Test Result
Air content of mortar (volume %)	12 max	8
Blaine fineness (m^2/kg)	280 min	377
Autoclave expansion (%)	0.80 max	0.04
Compressive strength (MPa)	min	
1 day	A	
3 days	7.0	23.4
7 days	12.0	29.6
28 days	A	
Time of setting (minutes) (Vicat)		
Initial: Not less than	45	124
Not more than	375	

[A] Not applicable.

OPTIONAL REQUIREMENTS
ASTM C 150 Tables 2 and 4

CHEMICAL

Item	Spec. Limit	Test Result
$C_3S + C_3A$ (%)	58 max	66
Equivalent alkalies (%)	B	0.52

PHYSICAL

Item	Spec. Limit	Test Result
False set (%)	50 min	92
Heat of hydration (kJ/kg)		
7 days	B	300
Compressive strength (MPa)		
28 days	28.0 min	36.7

[B] Limit not specified by purchaser. Test result provided for information only.
[C] Test result for this production period not yet available.

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of the ASTM C 150 – XX or (other) ______________ specification.

Signature: ______________________ Title: ______________________

Figure 4-16. Sample mill certificate (ASTM C 150-04)

are determined by the amount of water tied to the sulfate compounds, as shown in table 4 2. (See Form of Sulfate later in this chapter, page 98.)

Note: Do not confuse the sulfate in portland cement with sulfates that may enter concrete from ground water after the concrete has set. These outside sulfates will react with the hydration products of tricalcium aluminate (C_3A), forming expansive compounds that damage the concrete. This is known as sulfate attack and is why limits on tricalcium aluminate content are imposed on sulfate-resistant cement (see Hydraulic Cement in chapter 3, page 30).

Cement Fineness Affects Hydration and Concrete Properties

When clinker leaves the kiln and is cooled, it is pulverized in a grinding mill to reduce its size from 25- to 50-mm (1- to 2-in.) particles to a powder. The fineness of the cement is controlled by the manufacturer to achieve some performance characteristics. Approximately 95 percent of cement particles are smaller than 45 micrometers, with the average particle around 15 micrometers.

With increasing fineness, cement exhibits the following characteristics:

- Increasing rate of hydration initially, leading to increased early strengths. Longer-term strength development is not as marked with finer cements.
- Increased heat of hydration.
- Reduced workability.
- Reduced bleeding.
- Possible reduced air entrainment.
- Increased risk of incompatibility.

Fineness is usually measured by the Blaine air-permeability test (ASTM C 204 / AASHTO T 153), which indirectly measures the surface area of cement particles per unit mass. The surface area of finer cements is higher than that of coarser materials. Typical Type 1 cements are in the range of 300 to 400 m^2/kg. Type 3 cements are generally finer than Type 1 cements.

Table 4-2. Forms of Calcium Sulfate

	Common names	Shorthand notation	Chemistry	Waters of crystallization	Comments
Calcium sulfate dihydrate	Gypsum	$C\bar{S}H_2$	$CaSO_4 \cdot 2H_2O$	2	Rapidly soluble
Calcium sulfate hemihydrate	Plaster or bassanite	$C\bar{S}H_{½}$	$CaSO_4 \cdot ½H_2O$	½	Slowly soluble
Anhydrous calcium sulfate	Anhydrite	$C\bar{S}$	$CaSO_4$	None	Not very common

Portland Cement Hydration

Key Points

- Hydration of portland cement is complex.
- Chemical reactions during hydration release heat.
- Tricalcium aluminate (C_3A) reacts immediately when exposed to water and can cause early stiffening or flash set. This reaction is controlled by sulfates in solution.
- Silicate reactions begin more slowly, but ultimately dominate hydration, contributing the bulk of concrete properties. Alite (C_3S) contributes to early strength gain. Belite (C_2S) contributes to long-term strength gain and low permeability.
- Calcium silicate hydrate (C-S-H) is the primary product of silicate reactions that contributes to concrete's strength and density.
- Chemical reactions at various stages of hydration have important implications for pavement construction practices, including placement, curing, sawing joints, and keeping traffic off new concrete.
- Ideally, for concrete with low permeability, hydration products will eventually fill most of the space originally occupied by water in the mix. This requires an appropriate water-cementitious materials ratio: enough water to make the mix workable but not so much that concrete durability is reduced.
- Hydration will continue for a long time, as long as water and unhydrated cement grains are available. While hydration continues, concrete strength increases and permeability decreases. Curing—primarily, protecting the concrete from moisture loss—is therefore essential for strong, durable concrete.

Hydration is a series of nonreversible chemical reactions between hydraulic cement, such as portland cement, and water. During hydration, the cement-water paste sets and hardens. Hydration begins as soon as cement comes in contact with water. The cement particles partially dissolve, and the various components start to react at various rates, generating heat (a process that may raise temperature) and resulting in various reaction products.

The heat generated by hydration does not reach zero for a long time, indicating that reactions continue slowly. The reactions can continue for years, as long as the concrete contains water and unreacted cement, resulting in continued development of strength and other desirable characteristics like low permeability.

The hydration process is complex and is the subject of extensive research. However, a basic understanding of the primary reactions and hydration products can help everyone involved in concrete pavement projects prevent or correct problems.

The rest of this section on hydration provides general, simplified descriptions of the following:

- The primary chemical reactions of aluminates, sulfates, and silicates.
- The products of those reactions.
- The development of strength and stresses within concrete during hydration.
- The importance of the development of paste density during hydration.
- The implications of various stages of hydration on construction practices to ensure strong, durable concrete pavements.

Aluminate and Sulfate Reactions

The aluminate and sulfate reactions dominate the first 15 minutes of hydration. When mixed in water, tricalcium aluminate (C_3A) immediately dissolves and reacts with water and calcium hydroxide to form calcium aluminate hydrate crystals. This reaction generates a large amount of heat and, if uncontrolled by sulfate, will cause fast, permanent hardening. This effect—known as flash set—is very undesirable.

Sulfate, however, controls the tricalcium aluminate (C_3A) reaction. Combined with sulfate in solution ($C\bar{S}$), tricalcium aluminate forms complex compounds that eventually crystallize out as needle-like ettringite (C-A-$\bar{S}$-H) (figure 4-17).

During the first few minutes, the initial hydration product (a gel-like material, which can also be roughly annotated as C-A-$\bar{S}$-H) surrounds the tricalcium aluminate, limiting water's access to the tricalcium aluminate and thereby slowing reactions (figure 4-18).

The period of time during which reactions are slowed, little heat is generated, and little physical change in the concrete is observed is known as the dormant period. The dormant period lasts two to four hours. This is important in a concrete paving project because it provides time to transport, place, and finish the concrete mixture while it is cool and plastic.

The importance of the dormant period makes it critical for sufficient sulfate to be included in the portland cement (see Potential Materials Incompatibilities later in this chapter, page 97).

After the dormant period, other chemical reactions dominate cement hydration. However, the tricalcium aluminate (C_3A) and sulfate ($C\bar{S}$) continue to react and form ettringite (C-A-$\bar{S}$-H), which contributes somewhat to concrete's early strength development.

The tricalcium aluminate (C_3A) and sulfate ($C\bar{S}$) reactions continue until all the sulfate is consumed, generally within 24 hours. Then, any remaining tricalcium aluminate will react with the ettringite to form monosulfate (figure 4-19). This reaction continues as long as calcium aluminate, ettringite, and water are available. It has little effect on the physical characteristics of concrete.

Silicate (Alite and Belite) Reactions

The silicates consist of alites (C_3S) and belites (C_2S). Alite reacts more quickly, giving concrete its early strength. Belite reacts more slowly, contributing to long-term strength gain and reduction of permeability. The hydration products of silicates and water are loosely known as calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), or lime.

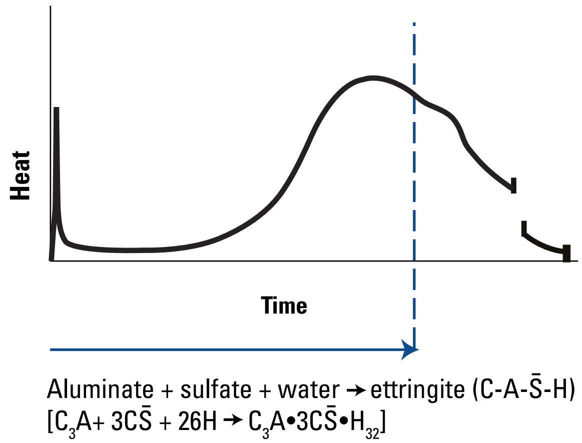


Figure 4-17. Reactions of C_3A and $C\bar{S}$, in solution, are responsible for an early heat spike during cement hydration.

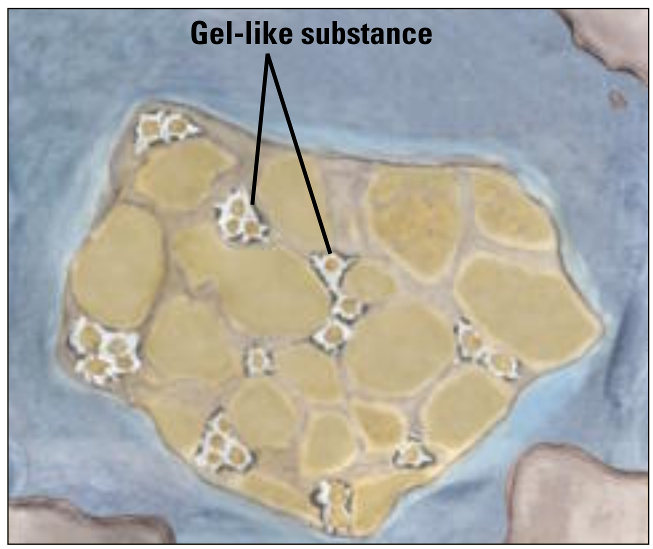


Figure 4-18. Gel-like C-A-$\bar{S}$-H limits water's access to cement particles.

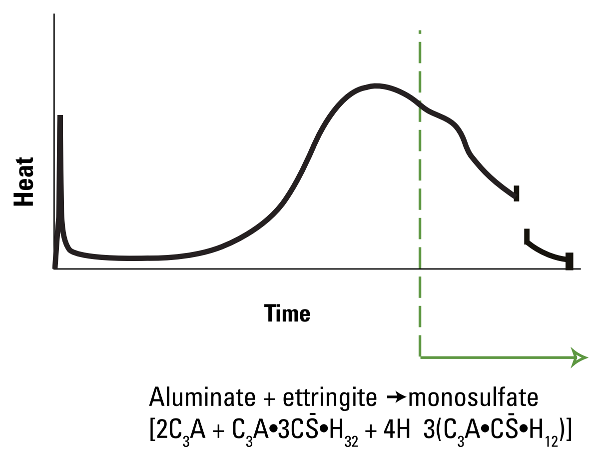


Figure 4-19. After sulfate is consumed, remaining C_3A reacts with ettringite.

Alite Reactions

Alite (C_3S) dissolves and reacts with water more slowly than tricalcium aluminate (C_3A). During dormancy, alite begins dissolving, resulting in calcium ions (and hydroxyl [OH] ions) in solution (figure 4-20). (Some calcium ions in solution also result from the dissolution of tricalcium aluminate, but alite is the primary source.)

The calcium ions accumulate for two to four hours, until the solution becomes supersaturated. When the solution is supersaturated, the calcium ions react with the silica and water to form calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) (figures 4-21 and 4-22).

Soon after the beginning of production of calcium silicate hydrate and calcium hydroxide, initial set occurs. A large amount of heat energy is released, causing the temperature to begin rising quickly, and the mixture begins stiffening. As hydration accelerates, the buildup of calcium silicate hydrate and calcium hydroxide results in progressive stiffening, hardening, and strength development.

Calcium silicate hydrate (C-S-H) is the somewhat more desirable product. These particles are in the form of fibrous growths that gradually spread, merge, and adhere to aggregates, giving concrete its strength and reducing its permeability. With sufficient hydration, C-S-H forms a solid mass.

Calcium hydroxide (CH) particles tend to be crystalline, hexagonal, and smooth, and may provide a plane of weakness when the concrete is stressed. Also, calcium hydroxide is readily soluble in water and may be attacked if the concrete is exposed to soft water or acid. However, calcium hydroxide is necessary for maintaining a high pH and for stabilizing the calcium silicate hydrate (C-S-H).

Initially, the alite reactions are rapid. After a few hours, however, the hydration products (C-S-H and CH) accumulate to a point at which they interfere with contact between the undissolved cement particles and water, slowing the reactions and thus reducing the heat of hydration (figure 4-23).

Sometime before the rate of heat evolution peaks, final set occurs. Final set is roughly associated with the time when the concrete has become hard enough

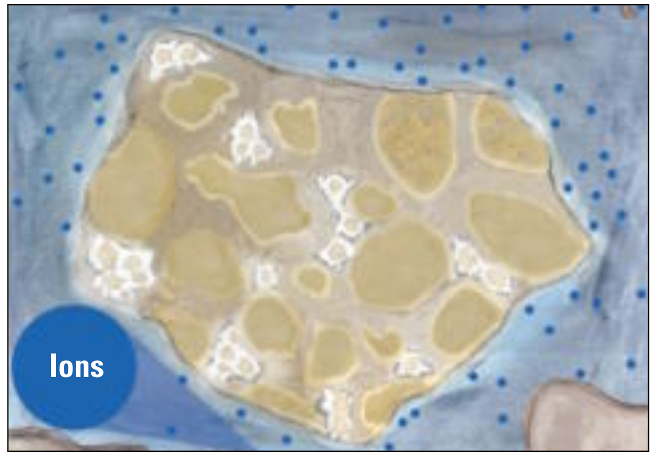
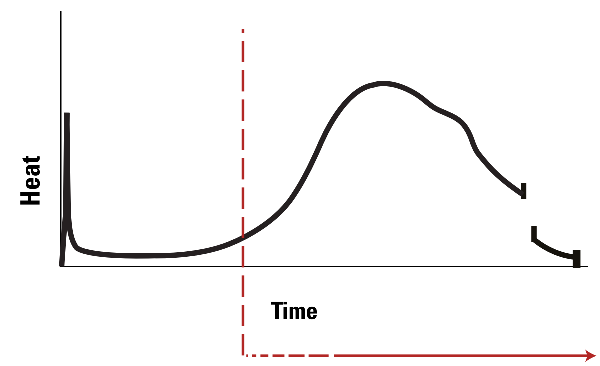


Figure 4-20. Dissolving cement results in calcium ions in solution.



Alite + water → calcium silicate hydrate + calcium hydroxide

$[2C_3S + 6H \rightarrow C\text{-}S\text{-}H + 3CH]$

Figure 4-21. Alite reactions form C-S-H and CH.

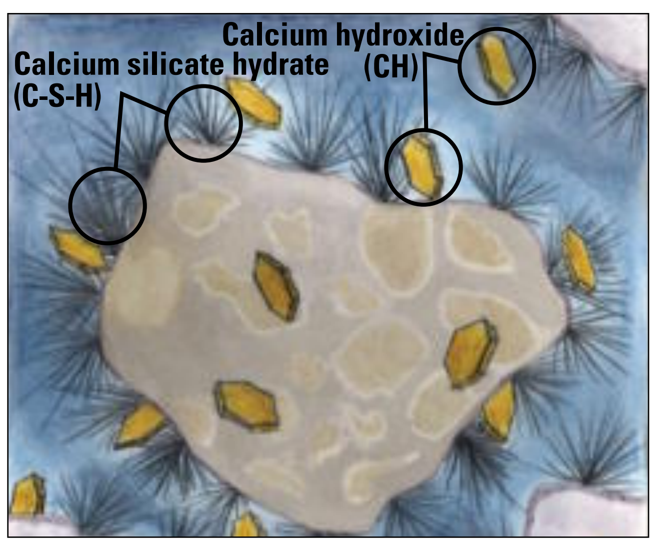


Figure 4-22. Calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) begin to form.

to walk on or to demold and test a cylinder. (Final set is defined by ASTM paste and mortar pressure tests as a point when the paste has acquired a certain degree of hardness; however, the values selected are somewhat arbitrary and do not necessarily relate directly to a physical phenomenon in the concrete.)

Alite reactions will continue slowly as long as unhydrated cement and water are present and accessible.

Belite Reactions

The other silicate compound, belite (C_2S), mimics the reactions of alite (C_3S) but at a slower pace. When mixed with water, belite dissolves and releases calcium ions very slowly. Only after several days do belite reactions (producing calcium silicate hydrate [C-S-H] and calcium hydroxide [CH] crystals) start contributing to strength, but the reactions continue for a long time (figure 4-24).

Belite reactions are critical to the long-term development of strength and reduction of permeability.

As long as alites and belites remain and there is water in the concrete, the silicates will continue to hydrate. As the volume of hydration products grows, the concrete porosity (and permeability) decreases and the concrete gains strength. Eventually, the hydration products will combine into a solid mass (figure 4-25).

Primary Products of Hydration

The primary products of cement hydration and their role in concrete are described in table 4-3.The chemical reactions in cement hydration result in changing volumes of cement compounds and hydration products (figure 4-26).

Factors Affecting Hydration Rates

The rate of stiffening of concrete from plastic to solid, and the subsequent increase in strength, depends on the rates of the chemical reactions involved in cement hydration. These in turn are influenced by the following:

- Composition of the cement (e.g., increasing alkali contents accelerate hydration).
- Cement fineness (finer cements hydrate faster).
- Mix proportions (lower water-cementitious materials ratios accelerate setting).

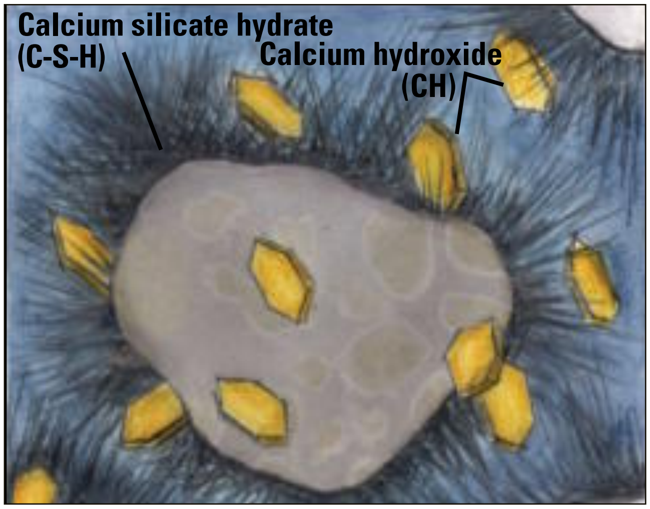
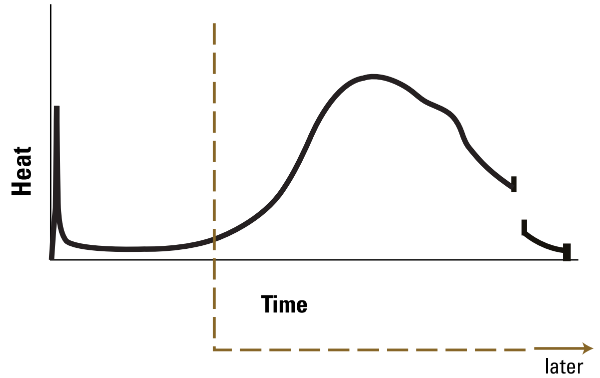


Figure 4-23. Hydration products accumulate and mesh.



Belite + water → calcium silicate hydrate + calcium hydroxide
[$2C_2S + 4H \rightarrow$ C-S-H + CH]

Figure 4-24. Belite reactions begin contributing to strength gain later.

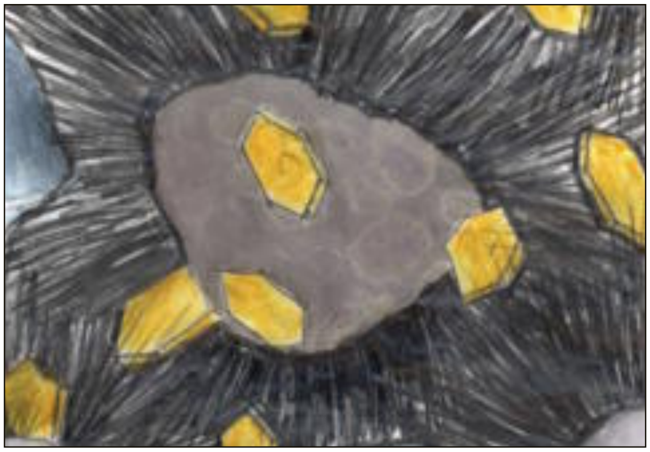


Figure 4-25. Calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) mesh into a solid mass.

- Temperature (higher temperatures accelerate hydration).
- Admixtures (water reducers retard some reactions and accelerate others; see Potential Materials Incompatibilities later in this chapter, page 97).

Pores

In general, water that does not react with the cementitious materials will either remain in the concrete or evaporate out when the concrete dries. The space occupied by unreacted water is the capillary pore system. The volume of capillary pores strongly influences concrete strength and durability because the pores provide a zone of weakness for crack growth and a route for aggressive solutions.

Ideally, most space occupied by water in the mix will be filled with hydration products. This requires sufficient cement (low water-cementitious materials ratio) and protection from moisture loss until sufficient hydration has occurred (good curing practices).

Table 4-3. Primary Products of Cement Hydration

Hydration product	Role in concrete
Calcium silicate hydrate (C-S-H)	• Calcium silicate hydrate is a product of silicate reactions—both alite (C_3S) and belite (C_2S)—with water. • Calcium silicate hydrate is the primary desirable hydration product. It bonds with other calcium silicate hydrate and with aggregate, and is a major contributor to concrete strength and low permeability. • Calcium silicate hydrate growths gradually spread and mesh with growths from other cement particles or adhere to aggregates. This buildup of solid compounds causes the paste to stiffen, harden, and develop strength and reduces permeability.
Calcium hydroxide (CH)	• Calcium hydroxide is a crystalline hydration product of silicate reactions—both alite (C_3S) and belite (C_2S)—with water. • Calcium hydroxide: ♦ May provide a plane of weakness in the concrete (on a microscale). ♦ Is readily soluble in water and may be attacked if the concrete is exposed to soft water or acid. • Calcium hydroxide is also beneficial; it helps buffer a high pH necessary for calcium silicate hydrate (C-S-H) to be stable and for protecting reinforcing steel. • The amount of calcium hydroxide produced when belite reacts with water is significantly less than that formed in the alite reaction.
Ettringite (C-A-$\bar{S}$-H)	• Ettringite, in the form of needlelike crystals, is the primary product of reactions between tricalcium aluminate (C_3A) and sulfate ($C\bar{S}_2$) in solution. These reactions continue until the sulfate is depleted, generally within 24 hours. (See monosulfate, below.) • Ettringite gel is especially important for its role in creating a dormant period early in cement hydration. It does this by limiting access of water to the particles and slowing their hydration. • Ettringite contributes somewhat to concrete's early strength but plays only a minor role in hardened concrete's strength.
Monosulfate (C-A-$\bar{S}$-H)	• When all the sulfate ($C\bar{S}_2$) has been depleted, the remaining aluminate (C_3A) reacts with the ettringite (C-A-$\bar{S}$-H) to form monosulfate crystals. • Monosulfate has little effect on concrete's physical characteristics.
Calcium aluminate hydrate (CAH) $C_3A + CH + 12H \rightarrow C_4AH_{13}$	Unless sulfate ($C\bar{S}_2$) is present in solution, the reaction of tricalcium aluminate (C_3A) with water will quickly result in undesirable calcium aluminate hydrate. This will cause irreversible setting, or flash set. See the discussion under Potential Materials Incompatibilities later in this chapter, page 97.

Concrete Strength Gain, Tensile Stress, and the Sawing Window

During cement hydration, as the hydration products calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) accumulate, the concrete develops its strength. Compressive strength is the ability to resist forces that push the concrete together (compression); tensile strength is the ability to resist forces that pull it apart (tension).

Concrete develops significant compressive strength, which makes it an ideal material for pavements that support heavy loads. Concrete's tensile strength, however, is only about one-tenth its compressive strength. With changing internal moisture and temperature, concrete experiences volume changes, but the pavement base (among other things) restrains the concrete movement. This restrained movement sets up tensile stresses, or tension, in the concrete.

Sometime after final set, the growing tensile stresses will likely exceed concrete's tensile strength, causing the concrete to crack. Sawing joints relieves tensile stresses and prevents random cracking by reducing the panel sizes, thus reducing the amount of restraint. Joints must be cut during the critical period when the concrete has hardened enough not to ravel along the saw cut (for conventional saws, this is generally soon after final set; for early-age saws, the period may begin at or slightly before final set), but before it has begun to crack randomly. That period is the sawing window.

Hydration and Concrete Permeability

One of the characteristics of durable concrete is low permeability. Salts and other harmful substances cannot easily penetrate such concrete, and it is less susceptible to freeze-thaw damage.

To ensure that new concrete pavements develop low permeability, it is important to provide the right conditions for hydration to continue sufficiently. Providing the right conditions includes retaining mix water (i.e., losing as little as possible to evaporation) and protecting the concrete from extreme temperatures, especially keeping the concrete warm during cool weather.

Reduce moisture loss from the concrete by thoroughly applying curing compound (or wet coverings) after finishing (or at the time of initial set, depending on the rate of bleeding), and then protecting the curing compound from traffic for as long as possible. In hot weather, evaporation retarders may also be applied between initial placing and finishing to further reduce moisture loss. In cold weather, protect the concrete from extreme temperature changes by covering it with insulating blankets.

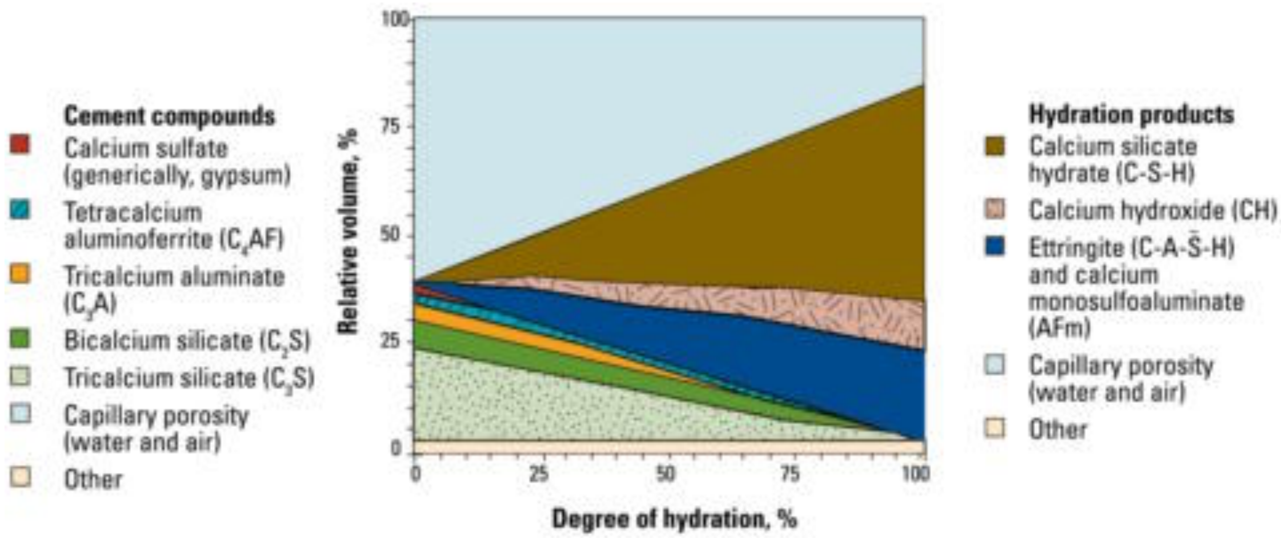


Figure 4-26. Estimates of the relative volumes of cement compounds and products of hydration with increasing hydration (adapted from Tennis and Jennings 2000).

Note: These estimates are for a 0.50 water-cementitious materials ratio; decreasing the ratio will decrease the capillary porosity.

Reactions of Supplementary Cementitious Materials

Key Points

- The basic chemical components of supplementary cementitious materials (SCMs) are similar to those of portland cement.
- In general, SCMs tend to retard hydration rates and extend the duration of hydration.
- Pozzolans convert calcium hydroxide (CH) to calcium silicate hydrate (C-S-H), with a positive effect on later-age strength gain and low permeability.
- The use of SCMs to complement portland cements has become increasingly common in concrete mixtures for pavements.
- It is important to test mixtures containing SCMs to ensure they are achieving the desired results, verify the correct dosage, and detect any unintended effects.

Supplementary cementitious materials (SCMs) are almost always included in today's concrete mixtures. They are used to substitute for some of the portland cement and/or to affect concrete properties in specific ways (see Supplementary Cementitious Materials in chapter 3, page 31). SCMs are composed of generally the same elements as portland cement (figure 4-27).

Mixtures containing SCMs should be tested to determine whether

- The SCM is achieving the desired result.
- The dosage is correct (an overdose or under-dose can be harmful or may not achieve the desired effect).
- Any unintended effect is occurring (for example, a significant delay in early strength gain).

It is also important to remember that SCMs may react differently with different cements.

Hydraulic SCMs

Hydraulic cements hydrate, set, and harden when mixed with water. Ground, granulated blast-furnace (GGBF) slag and some Class C fly ashes are SCMs with hydraulic properties.

Hydration of systems containing hydraulic SCMs is generally slower than portland cement-only mixtures.

Pozzolanic SCMs

Pozzolans include Class F fly ash, calcined clay, calcined shale, metakaolin, and (rarely in paving projects) silica fume. Class C fly ash also has pozzolanic characteristics.

Pozzolanic materials require a source of calcium hydroxide (CH) to hydrate. When pozzolans are included in concrete mixtures, they help convert calcium hydroxide (CH) (a product of silicate reactions) to calcium silicate hydrate (C-S-H) (figure 4-28). Thus, pozzolans can have a positive effect on strength gain and concrete permeability.

Pozzolanic reactions are somewhat slower than cement hydration, so setting times may be retarded and strength development is often slower. However, slower hydration can reduce the risk of cracking in some cases. In addition, pozzolanic reactions continue longer, leading to greater long-term concrete strength.

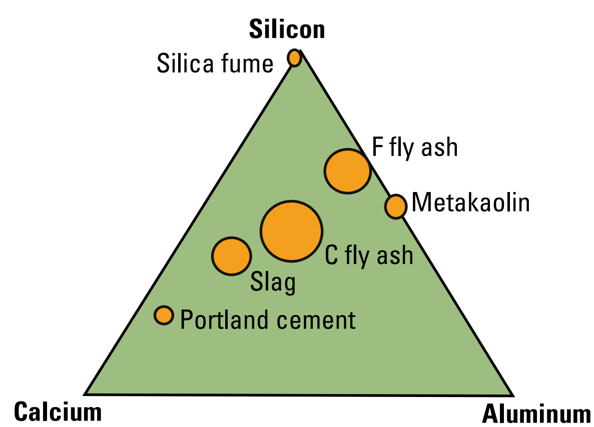


Figure 4-27. Ternary diagram illustrating the basic chemical composition of various SCMs compared to portland cement

Cements for Concrete Pavements: A Durable Tradition

Durability is a hallmark of concrete pavements. In fact, some concrete pavements constructed in the early 1900s are still in service today.

Over the years, cements for concrete have been continuously changed and improved to meet the various needs of the construction and pavement industries. In addition, the construction industry has made use of supplementary cementitious materials that enhance the performance of the concrete.

Changes in Portland Cement

In response to the construction industry's desire to shorten construction times by accelerating concrete strength gain, cement manufacturers have made appropriate changes in portland cement chemistry. Over several decades, cement manufacturers increased cements' alite (C_3S) content and reduced cements' belite (C_2S) content. In the early 1900s the proportions were about the same. Today, the amount of alite is about three times the amount of belite in Type I cement.

As shown in table 4-4, alite reactions begin sooner than belite reactions and are primarily responsible for concrete's early strength gain. Belite reactions, which are somewhat slower, are primarily responsible for concrete's long-term strength gain and for continuing reduction in concrete permeability.

Today's cements are also generally finer than they were in the early 1900s. Smaller particles have greater surface area exposed to water and, therefore, hydrate and gain strength more quickly. Finer particles also result in greater heat of hydration. In warm or hot weather, such fine systems may need to be retarded to achieve the required finished product.

Today's higher early-strength cements deliver the performance required for most building and commercial uses. They also help the concrete paving industry meet motorists' demands to open new pavements to traffic more quickly. Concrete pavement strengths after 7 and 14 days are much greater than they were years ago; after 28 days, gains in concrete strength and reductions in permeability can be somewhat smaller.

Supplementary Cementitious Materials

In the history of concrete pavements, supplementary cementitious materials (SCMs) are relative newcomers. Primarily byproducts of manufacturing processes, SCMs are generally plentiful and economical. When used properly, SCMs are useful complements to portland cement in concrete for paving applications.

Pozzolanic reactions are beneficial because (among other reasons) they consume calcium hydroxide (CH) (a hydration product of cement) to produce additional calcium silicate hydrate (C-S-H). Calcium hydroxide (CH) contributes relatively little to concrete strength, while calcium silicate hydrate (C-S-H) is the primary contributor to concrete strength and impermeability. Pozzolanic reactions also generally slow hydration initially and reduce the early heat of hydration. Pozzolanic reactions continue for a longer time, however, adding significantly to long-term strength gain and impermeability.

For example, a pavement built in Iowa in 2003 with a ternary mix of cement; ground, granulated blast-furnace slag; and Class C fly ash developed chloride penetration numbers less than 1,000 coulombs in less than a year. (A range of 1,000 to 2,000 coulombs is generally considered low permeability.)

Good Practices

Regardless of the cementitious system used, a sufficiently low water-cementitious materials ratio is critical to achieving the strength and durability needed for concrete pavements.

In addition, solid curing practices—including thoroughly covering the concrete surface with curing compound (or wet coverings) and protecting the compound from equipment and traffic as long as possible—are more important than ever because SCMs are often sensitive to poor curing. Good curing practices help ensure the continuation of cement hydration reactions that add to concrete's long-term strength and reduce its permeability.

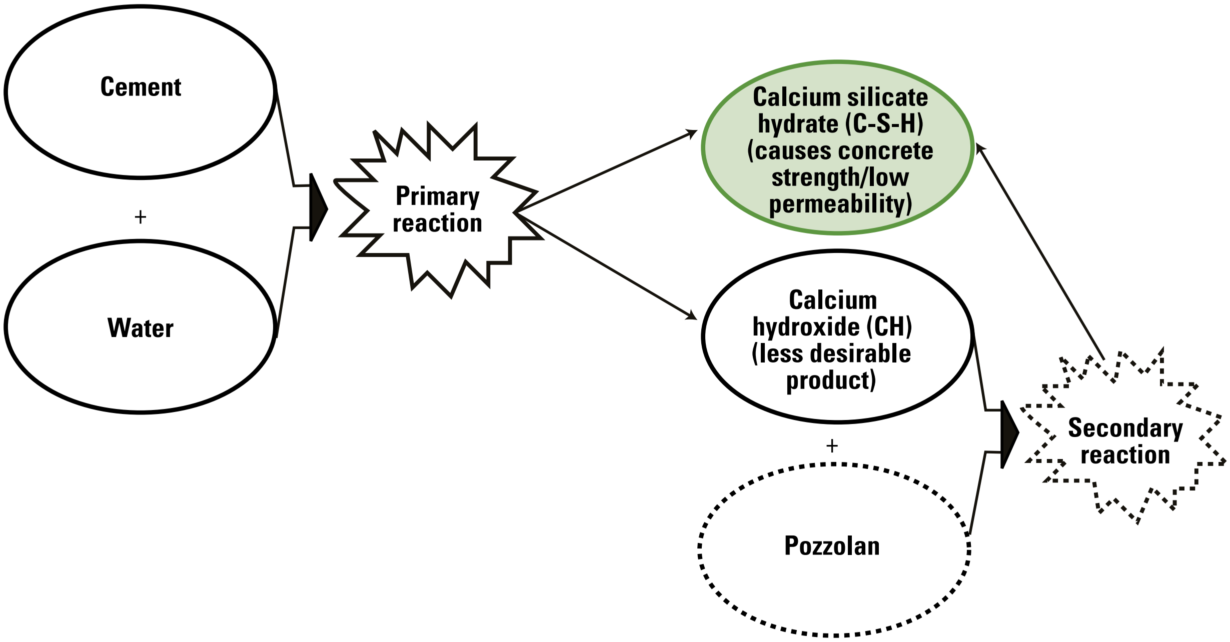


Figure 4-28. Effect of pozzolans on cement hydration

Table 4-4. Comparison of Alite and Belite Reactions

	Hydration reactions	Hydration products	Effect on concrete
Alite (C_3S) $2C_3S + 6H \rightarrow C\text{-}S\text{-}H + 3CH$	• Begin sooner • Are more rapid • Slow sooner	Forms more calcium hydroxide (CH)	• Early strength gain • Early reduction in permeability
Belite (C_2S) $2C_2S + 4H \rightarrow C\text{-}S\text{-}H + CH$	• Are slower • Continue longer	Forms less calcium hydroxide (CH)	• Later strength gain • Later reduction in permeability

Potential Materials Incompatibilities

Key Points

- Some combinations of normally acceptable materials may be incompatible. That is, they react with each other in ways that cause unexpected changes in stiffening or setting that ultimately may compromise the concrete system.
- Incompatibility is normally the result of a complex chemical interaction between the cementitious materials and chemical admixtures.
- The amount and form of calcium sulfate are important for an appropriate balance with tricalcium aluminate (C_3A) to prevent setting and stiffening problems.
- Changing the source or dosage of one of the reactive ingredients may stop the problem from recurring.
- Some incompatibility problems can be exacerbated with increasing temperatures.
- Testing the mixture at the expected temperature is strongly recommended.

Some combinations of materials may be prone to problems with setting, stiffening, or other issues. Such problems can occur even if all materials meet their specifications and perform well when used alone or with other materials. This phenomenon is generally known as incompatibility.

Incompatibility is important because small changes in the chemistry of materials, or even in temperature, can make an acceptable mixture in one batch of concrete behave in an unacceptable way in the next batch, causing problems in placing, compacting, and finishing that are often perceived to be unpredictable and uncontrollable.

Although incompatibility is not new, practitioners often say, "We've never seen this before." Incompatibility is likely occurring because we are using increasingly complex combinations of cementitious materials, chemical admixtures, and other materials while asking more of the concrete. The sections are thinner, placing rates are higher, turnaround times are faster, strengths are higher, and the construction season is starting earlier and ending later so that concrete is being placed in more extreme weather conditions. It is also becoming common for materials sources to be changed on a given project without running trial mixes or materials tests.

There is no single mechanism behind the wide range of effects that are occurring. Many of the mechanisms are complex and interactive and may require expert evaluation if they occur in the field.

Typical results of incompatibility may include one or more of the following:

- The concrete stiffens much too quickly, preventing proper consolidation or finishing work.
- The concrete sets and gains strength before joints can be cut.
- The concrete does not set in a reasonable time, increasing the risk of plastic shrinkage cracking and late sawing.
- The concrete cracks randomly despite normal efforts to prevent it.
- The air-void system is adversely affected, compromising the concrete's resistance to salt scaling and freeze-thaw damage or decreasing concrete strength.

For example, a mixture contains Class C fly ash, portland cement, and chemical admixtures, and the combined chemistry of the system causes accelerated stiffening and setting. When one of the materials—fly ash, cement, or admixture—is changed, the concrete setting behavior is normal. (Actual cases have been reported where the mixture is satisfactory at 21°C [70°F] but cannot be compacted in the paver at 27°C [80°F].)

Following are brief discussions of some of the incompatibility problems that can occur.

Stiffening and Setting

Incompatibility issues related to stiffening and setting are generally the result of a sulfate imbalance, although other factors can contribute.

Sulfate-Related Setting and Stiffening

Cement hydration in the first 15 minutes is a delicate balance between the tricalcium aluminate (C_3A) and sulfate in solution. If the balance is right, the sulfate controls the hydration rate of tricalcium aluminate. If the balance is not right, stiffening and setting problems can occur (figure 4-29).

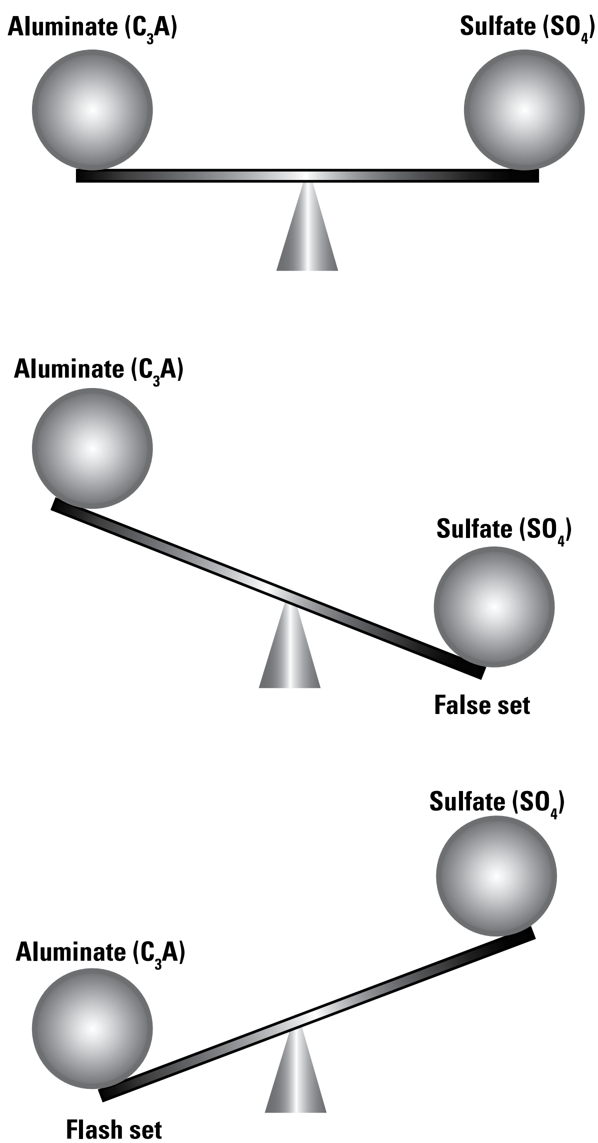


Figure 4-29. Early cement reactions are a balance of tricalcium aluminate (C_3A) and sulfate (SO_4) in solution. Excess of either will cause unexpected setting. (CTLGroup)

Too Much or Too Little Sulfate. The *amount* of sulfate in solution in hydrating cement is critical.

Flash Set

If there is insufficient sulfate in solution, the tricalcium aluminate reacts quickly with water to form calcium aluminate hydrate (CAH) (see table 4-3).This reaction generates a large amount of heat, and the fast buildup of calcium aluminate hydrate results in flash set: immediate and permanent hardening of the mix.

False Set

Too much sulfate in solution may precipitate out as solid gypsum, causing temporary stiffening of the mix, or false set. If mixing continues, the gypsum will redissolve and the stiffening will disappear.

Form of Sulfate. The *form* of calcium sulfate (that is, gypsum [$C\bar{S}H_2$], plaster [$C\bar{S}H_{1/2}$], or anhydrite [$C\bar{S}$]) in the cement is also critical, because it affects the amount of sulfate ions in solution. Plaster dissolves faster than gypsum and is therefore useful in preventing flash set; however, cement containing too much (or too little) plaster will result in too much sulfate in solution, upsetting the balance and resulting in false set, as discussed above. The presence of anhydrite may also upset the delicate balance required because it dissolves slowly and may provide insufficient sulfate in solution to control cements with high tricalcium aluminate (C_3A) contents.

Other Stiffening and Setting Incompatibilities

Other factors that can affect stiffening and setting incompatibilities include silicate reactions, supplementary cementitious materials, water reducers, cement fineness, temperature, and water-cementitious materials ratio.

Silicate Reactions. Most of the strength development in concrete is due to hydration of the silicates in cementitious materials to form calcium silicate hydrate (C-S-H). In general, these reactions start when calcium ions are supersaturated in the solution. If calcium has been consumed during the initial stages of hydration (such as in uncontrolled tricalcium aluminate [C_3A] hydration), then it is possible that the silicate reactions (and so setting) may be significantly retarded. Silicate reactions can also be affected by the presence of other materials in the mixture as discussed in the following paragraphs.

Supplementary Cementitious Materials Incompatibilities. In general, supplementary cementitious materials (SCMs) tend to retard silicate hydration rates, partially due to dilution and partially due to changes in the chemical balances of the system. Hydration is normally extended, however, leading to strength gain beginning more slowly but continuing longer.

An SCM containing additional tricalcium aluminate (C_3A) (typically high-calcium fly ash) can compromise the aluminate-sulfate balance, causing or exacerbating the stiffening and setting problems discussed previously. It may therefore be desirable to use factory-blended cements rather than site-blended cements because the manufacturer can optimize the sulfate form and content for the whole cementitious system.

Water Reducer Incompatibilities. Some water-reducing admixtures will interfere with the hydration rates of cement compounds. Lignin-, sugar-, and triethanolamine (TEA)-based products (normally Type A or B) have the combined effect of accelerating aluminate reactions and retarding silicate reactions. The use of such an admixture may tip a marginally balanced cementitious system into incompatibility.

Some (Type A) water reducers accelerate aluminate reactions. A system that has just enough sulfate to control normal aluminate reactions, can therefore be thrown out of balance. Aluminate reactions are then uncontrolled and workability is reduced. Adding more admixture with the mixing water to boost workability likely exacerbates the problem, possibly leading to an overdose with its attendant problems (such as retardation of the silicate reactions).

One solution is to delay adding the water-reducing admixture until the early aluminate reactions are under control. The length of the delay will have to be determined for the specific mixture.

In addition, the same water-reducing admixtures retard the silicate reactions, delaying setting and slowing strength gain (figure 4-30).

It is therefore feasible that a system containing certain water reducers will exhibit classic early stiffening because of uncontrolled aluminate hydration, followed by severe retardation of final set because of slowed silicate reactions. This has been observed in the laboratory and in the field.

Cement Fineness. Cement fineness influences reaction rates. The finer the cement, the greater the rates of reaction and the greater the risk of an unbalanced system. Finer cements require a higher sulfate content and perhaps a higher plaster-to-gypsum ratio.

Gypsum ($C\bar{S}H_2$) is added to clinker while it is being ground to form cement. During grinding, the temperature is carefully controlled so that some gypsum dehydrates to plaster ($C\bar{S}H_{1/2}$) (but not too much). Trace amounts of sulfate in the form of anhydrite ($C\bar{S}$) may also be present in the clinker.

The primary difference among these types of calcium sulfate is the amount of water molecules attached to them, which accounts for their different rates of dissolution in water.

The proper balance of calcium sulfate forms is important. Cement manufacturers will normally target a 50/50 balance of plaster and gypsum and will optimize the total sulfate content of their products.

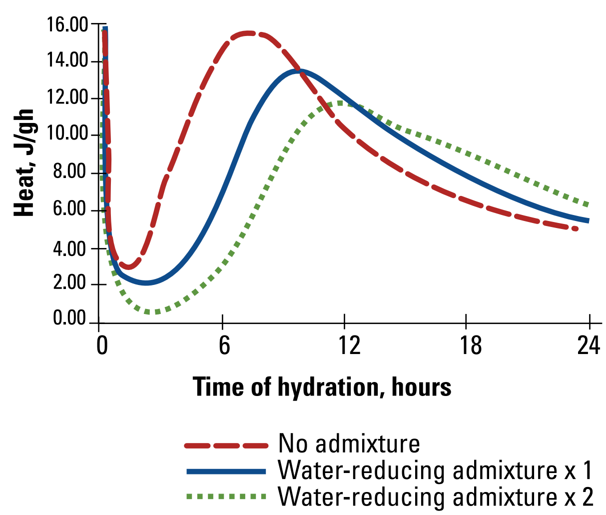


Figure 4-30. Plot of heat generated by cement hydration of cement pastes containing varying amounts of lignosulfonate-based water-reducing admixture (CTLGroup)

Temperature. The solubility and reactivity of all of the compounds are strongly influenced by temperature, with higher temperatures generally increasing solubility (except calcium) and accelerating reaction rates. Increasing temperature, on the other hand, decreases the solubility of calcium sulfate, thus reducing the amount of sulfate in solution available to control the accelerated aluminate reactions and thereby potentially making the system unbalanced. A change of as little as 6°C (10°F) can tip a mixture from being workable to exhibiting early stiffening. In warmer weather, more sulfate (plaster) is needed to control rapid tricalcium aluminate (C_3A) reactions.

Water-Cementitious Materials Ratio. The severity of these effects is also related to the ratio of water to cementitious materials. Lower water contents effectively mean that the cement grains are closer together; therefore, the early hydration products have to fill less space before stiffening results, so early stiffening may occur. The same mixture at a higher water-cementitious materials ratio, with greater particle spacing, may not exhibit the same problems.

Air-Void System Incompatibilities

There have also been reports of accumulations of air voids forming around aggregate particles, known as clustering (figure 4-31). This results in reduced strength and increased permeability.

Research has indicated (Kozikowski 2005) that this is most likely to occur with the use of non-vinsol air-entraining admixtures and when water is added to the mixture after initial mixing. Extended mixing will exacerbate the problem.

To avoid this problem, check the air-void system of hardened concrete in trial mixes prepared under field conditions, mimicking expected haul times.

Testing for and Prevention of Incompatibilities

The most reliable way to detect whether a mixture is likely to be problematic is to conduct a series of tests and trial batches on the materials at the field temperature. Laboratory tests must be run sometime before construction begins to prequalify materials planned for the project. Field tests (materials acceptance tests) should be run as materials are delivered to the site to ensure that site materials are similar to prequalified materials. Preferably, materials-acceptance tests should be run the day before batching is planned, although at the height of construction, results may be needed within a few hours.

What to Test. A suggested test protocol is summarized in table 4-5 (Taylor 2005).

In many cases. there is no single pass/fail limit because what is acceptable in one system or environment is not acceptable in another. It is recommended that test results be tracked over time, and a significant change in a test result will indicate potential problems. It is recommended that as many of these tests as practical be conducted at the prequalification stage so that a point of reference is available for comparison with tests conducted during construction. A test result that is out of the ordinary may be a problem with the testing or with the material. Such data should therefore be reviewed with an understanding of limitations and potential errors in testing. Interpreting the results can be complex and may need expert input.

The decision about how many of these tests to conduct will be based on the economics of the project, including the value of the project, probability of failure (i.e., is the cementitious system stable?), cost of testing, and cost of failure. Many problems will be avoided by regularly monitoring slump loss, unit weight, set time, and admixture dosages. Significant changes in any of these parameters will indicate the

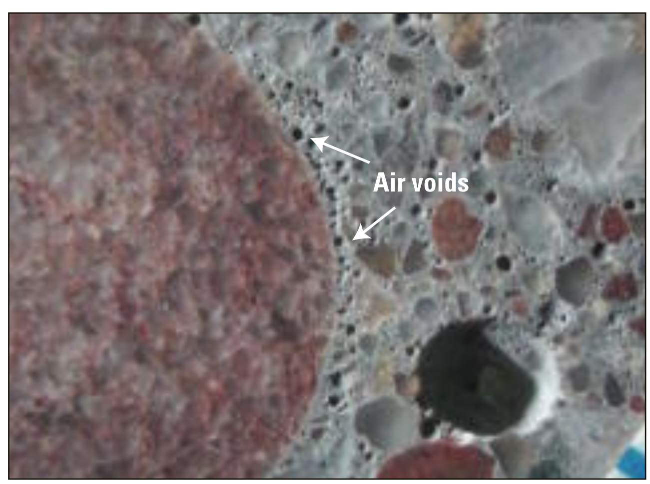


Figure 4-31. A typical example of air voids clustered around an aggregate particle

need for more intensive examination of the materials at hand.

Central Laboratory (Prequalification) Tests. Factors to monitor generally include minislump, temperature rise, shear stress, rate of stiffening, and early cracking.

Minislump

The minislump cone test monitors the area of small slump cone samples made using paste at selected time intervals. The test is effective at identifying systems prone to early hydration problems (Kantro 1981). The reproducibility between labs is reportedly low.

Isothermal Calorimetry

The energy required to maintain a hydrating paste mixture is monitored in an isothermal calorimeter. Changes in the timing or magnitude of the temperature rise, or the shape of the heat-energy-versus-time plot, will flag potential problems in the silicate reactions (Wadso 2004). ASTM is developing a practice for this application.

Shear Stress Increase

Measurement of the shear stress increase with time in a parallel plate rheometer using paste is showing promise as a method to monitor silicate hydration processes.

Rate of Stiffening

The ultrasonic P-wave test allows measurement of the rate of stiffening of a mixture in the lab and the field.

Early Stiffening

The method described in ASTM C 359 / AASHTO T 185 is being used in some laboratories to indicate potential problems in the early aluminate reactions (see Penetration Resistance (False Set) in chapter 9, page 255). Interpretation of the results must be undertaken with care and understanding. ASTM is developing a practice for this application.

Ring Rest

The ring test is a measure of when a fully restrained sample of concrete cracks. Earlier cracking may be considered an indicator of higher risk of cracking in the field.

Field Laboratory (Monitoring) Tests. Factors to monitor generally include the manufacturer's mill test x-ray data, semi-adiabatic temperature, concrete slump loss and setting time, uniformity of the air-void system, and air-void clustering.

X-Ray Data from Manufacturer's Mill Test Report or Mill Certificate (ASTM C 114, ASTM C 1365)

This test monitors the chemistry of the cement and fly ash. Changes in total calcium, tricalcium aluminate (C_3A), sulfate (SO_3), alite (C_3S) or belite (C_2S) may indicate potential problems.

Semi-Adiabatic Temperature Measurement

This test monitors the temperature of paste, mortar, or concrete mixtures in sealed containers (Dewar flasks or insulated cups). Changes in the timing or

Table 4-5. Recommended Tests and Their Applications

	Stiffening and setting	Cracking	Air-void system
Laboratory tests	• Materials chemistry • Calorimetry • Minislump • Rheometer • Time of set (ASTM C 191) • Stiffening (ASTM C 359)	• Materials chemistry • Ring test • Time of set	• Materials chemistry • Air-void analyzer • Hardened air (ASTM C 457) • Clustering index
Field tests	• Slump loss • Time of set (ASTM C 403) • Ultrasonic P-wave • Semi-adiabatic temperature measurement	• Time of set • Semi-adiabatic temperature measurement • Ultrasonic P-wave	• Foam index • Foam drainage • Unit weight (ASTM C 138) • Air content (ASTM C 231) • Air-void analyzer

magnitude of the temperature rise, or the shape of the heat-versus-time plot, will flag potential problems in the silicate reactions (figure 4-32) (see Heat Signature [Adiabatic Calorimetry Test] in chapter 9, page 259).

Concrete

For this test, make concrete batches and monitor slump loss with time as well as setting time (ASTM C 143).

Foam Index (Dodson 1990), Foam Drainage (Cross 2000), and Air-Void Analyzer (AASHTO 2003) Tests

These tests provide guidance on the uniformity and stability of the air-void system (see Air-Void System in chapter 5, page 133; and Air-Void Analyzer in chapter 9, page 265). Correlation with field concrete still has to be established.

Clustering Index Test (Kozikowski 2005)

This is a measure of the severity of air-void clustering around coarse aggregate particles. High values are associated with a reduction of strength.

Potential Solutions to Incompatibilities

If problems are observed in the tests or in the field, then one or more of the following actions may resolve them:

- Reduce the concrete temperature by cooling the materials and/or working at night.
- Seek a fly ash with lower calcium content.
- Reduce fly ash dosage.
- Delay admixture addition.
- Change the type of chemical admixture.
- Change the source of cement.
- Increase mixing time.

Seek expert advice to establish what the root cause of the problem is so that the correct remedial action can be taken.

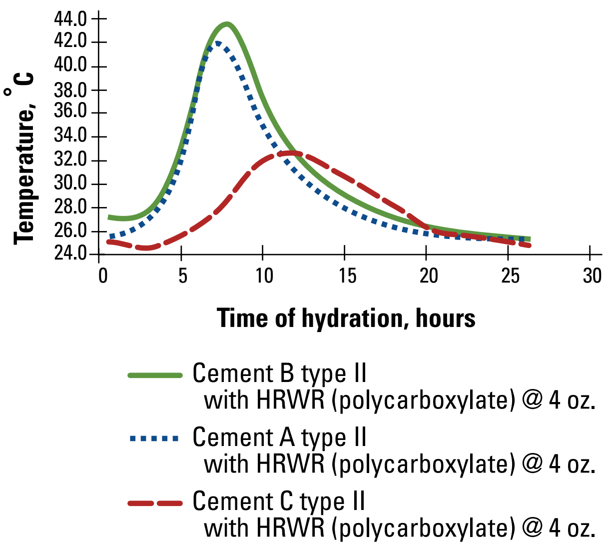


Figure 4-32. A set of field calorimetry data with three different cements and one high-range water-reducing admixture (HRWRA), including one set showing clear retardation and low heat output that was consistent with delayed setting and slow strength gain (Gary Knight, Holcim)

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ASTM C 143, Standard Test Method for Slump of Hydraulic-Cement Concrete

ASTM C 150/AASHTO M 85, Specification for Portland Cement

ASTM C 191/AASHTO T 131, Test Method for Time of Setting of Hydraulic Cement by Vicat Needle

ASTM C 231, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C 359, Standard Test Method for Early Stiffening of Hydraulic Cement (Mortar Method)

ASTM C 403/AASHTO T 197, Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance

ASTM C 457, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

ASTM C 1365, Standard Test Method for Determination of the Proportion of Phases in Portland Cement and Portland-Cement Clinker Using X-Ray Powder Diffraction Analysis

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Chapter 5

Critical Properties of Concrete

This chapter discusses critical properties of concrete that are needed to be able to mix, transport, place, finish, and maintain high-quality pavement. Some properties, like workability and materials segregation, are manifested only in the fresh or plastic stage of concrete, before it has hardened. Others, like frost resistance, are most important in the hardened concrete. Still others, like strength gain, begin early in the hydration process, remain critical during the first few days, and play a role in concrete for many months or even years. In general, the contractor is concerned about the fresh properties (how easy it is to get the concrete in place), and the owner is concerned about the long-term hardened properties (how long it will last).

Note that "durability" is not discussed as a property. Instead, the various properties that contribute to durability—permeability, frost resistance, sulfate resistance, alkali-silica reactivity, abrasion resistance, and early-age cracking—are covered.

At times, requirements for different properties in a specific mix may be mutually exclusive, meaning that compromises may need to be made. For example, high concrete strengths are often achieved by increasing cement content, which in turn increases shrinkage that can cause cracking. It is increasingly important for the designer, ready mix provider, contractor, and owner to understand how their decisions affect the other parties and to communicate among themselves about their decisions. This is the basis of the need for a pavement to be treated as an integrated system, not just a series of independent activities and materials.

For each concrete property, this chapter discusses the property's significance, factors that affect it, and tests used to measure it. (Chapter 6 discusses how the required properties can be achieved in the final concrete system. Chapter 9 discusses quality assurance and quality control testing and describes methods for a suite of specific tests.)

Uniformity of Mixture

Key Points

- The overarching goal is to make uniform concrete, even though the materials used to make the concrete may be variable.
- Materials and the environment at the batch plant are constantly changing. Despite these changes, it is important that the mixture properties be uniform from batch to batch to prevent problems in the paver and in the final pavement.
- Materials properties must be monitored regularly and proportions adjusted accordingly.
- Batching should be done by mass rather than by volume.
- Specifications: ASTM C 94 / AASHTO M 157, ASTM C 172 / AASHTO T 141.

Simple Definition

In uniform concrete, the concrete properties are consistently the same from batch to batch, even though the materials used to make the concrete may be variable.

Significance

Under economic or other pressures, experienced personnel can make a wide range of less-than-desirable materials work well. It is much harder to accommodate changes in concrete properties and performance (Scanlon 1994) that result from changes in materials from batch to batch. It takes time to adjust batching and paving equipment to allow for changing materials or environment. When such adjustments are regularly required between batches, there is a much higher risk of unsatisfactory finishes, low strengths, cracks, and durability problems. It is therefore of great importance for concrete and its materials to be uniform from batch to batch. (Chapter 9 discusses some of the implications of uniformity on quality management systems and testing.)

Factors Affecting Uniformity

Different aspects of concrete production—including the variability of raw materials (specifically, the aggregates and cement), batching operations, and mixing operations—can affect the uniformity of the final product.

Raw Materials. Aggregates should be tested for grading, density, and moisture content, and should be stored and handled in ways that minimize segregation. Preferably, cement should be from a single source and lot, or at least delivered in large enough quantities for several days of work.

Batching Operations. Batching is the process of measuring concrete mix ingredients by either mass or volume and introducing them into the mixer (Kosmatka, Kerkhoff, and Panarese 2002). Most specifications require that batching be done by mass rather than by volume (ASTM C 94 / AASHTO M 157), with the following typical levels of accuracy (see Batching in chapter 8, page 207):

- Cementitious materials: +1 percent
- Aggregates: +2 percent
- Water: +1 percent
- Admixtures: +3 percent

Mixing Operations. Thorough mixing is required to distribute all mixture ingredients evenly until the mix is uniform and to stabilize entrained bubbles (see Mixing Concrete in chapter 8, page 209, for information about mixing time). Mixers should not be loaded above their rated capacities and should be operated at the mixing speed recommended by the manufacturer. Mixing blades should be routinely inspected for wear or coating with hardened concrete, both of which can detract from effective mixing. ASTM C 94 provides details of requirements for mixing.

Uniformity Testing

Over the years, a variety of tests have been used to assess concrete uniformity (table 5-1). Commonly, unit weight (see Unit Weight in chapter 9, page 258), air content, slump, compressive strength, and coarse aggregate content are used as indicators of concrete uniformity (Scanlon 1994). ASTM C 94 / AASHTO M 157 set out the requirements for monitoring and accepting the uniformity of concrete.

The need for representative samples is critical for assessing concrete uniformity. Samples should be obtained in accordance with ASTM C 172 / AASHTO T 141.

Table 5-1. Requirements for Uniformity of Concrete (ASTM C 94 2004)

Test	Requirement, expressed as maximum permissible difference in results of tests of samples taken from two locations in the concrete batch	Applicable testing standard
Unit weight of fresh concrete, calculated to an air-free basis, lb/ft^3	1.0	ASTM C 138
Air content, volume % of concrete	1.0	ASTM C 138, ASTM C 173, or ASTM C 231
Slump		ASTM C 143
If average slump is 4 in. (10 cm) or less, in	1.0	
If average slump is 4 to 6 in. (10 to 15 cm), in	1.5	
Coarse aggregate content, portion by weight of each sample retained on # 4 sieve, %	6.0	Washout test (see ACI 1992)
Average compressive strength at 7 days for each sample, based on average strength of all comparative test specimens, %	7.5	ASTM C 39

Source: Bureau of Reclamation 1963

Workability

Key Points

- Workability is an indication of the ease with which concrete can be placed and compacted.
- Good workability benefits not only fresh concrete but hardened concrete as well, especially in its final density.
- Fresh concrete characteristics that affect workability include consistency, mobility, pumpability, compactability, finishability, and harshness.
- Concrete should have the right workability for the tools being used to place it.
- Changes in workability indicate that the raw materials, proportions, or the environment are changing.
- Water should not be added to concrete at the paver unless this can be done without exceeding the water-cementitious materials ratio of the mix design.
- Testing specifications:
  - Slump: ASTM C 143 / AASHTO T 119.
  - Penetration: ASTM C 360.

Simple Definition

As given in ACI 116R, workability is defined as that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished (ACI 2000).

Significance of Workability

Workability is an important property of fresh concrete because it affects the quality of several aspects of the construction process, including finishing. Workability is also a measure of uniformity. The benefits of good workability are often associated only with fresh concrete, in terms of the amount of mechanical work required to place and consolidate the concrete without segregation. However, good workability provides indirect benefits to the hardened concrete as well, because full consolidation (density) is easier to achieve. Workable mixtures that allow adequate consolidation greatly reduce the presence of large voids in the concrete, which can otherwise significantly reduce concrete strength (Neville 1996). Also, poor workability can make finishing difficult, causing tearing of the surface that can lead to cracking.

Do Not Add Water to Improve Workability

When paving crews experience problems with workability, they are often tempted to add water to the mix. However, water should not be added to concrete at the paver unless this can be done without exceeding the water-cementitious materials ratio of the approved mix design. (For a discussion of the water-cementitious materials ratio, see step 2 under the Absolute Volume Method in chapter 6, page 179.) Adding excess water will always lead to other problems, which may include reduced strength and increased permeability.

Requirements for workability will vary according to the techniques being used in the field. Therefore, contractors should be allowed to select their own workability requirements and to impose variability limits for quality assurance purposes.

The degree of workability required for proper placement and consolidation of concrete is governed by the type of mixing equipment, size and type of placing equipment, method of consolidation, and type of concrete (Scanlon 1994).

Factors Affecting Workability

In general, workability can be controlled through the proper proportioning of the mixture materials. However, workability depends on several factors, including the physical and chemical properties of the individual components (Scanlon 1994):

Water Content. The primary factor affecting the workability of a concrete mix is the water content. Increasing the water content will increase the flow and compactability of the mix, but can also reduce strength while increasing segregation, bleeding, and permeability (Mindess and Young 1981).

Aggregates. Several factors related to the aggregates in a mix have a significant effect on workability. The first is the amount of aggregate; increases in the aggregate-cement ratio result in a decrease in workability for a fixed water-cementitious materials ratio (Mindess and Young 1981).

Aggregate grading is critical. A deficiency of fine aggregate can lead to a harsh mix that is difficult to work, while an excess of very fine material will make the mix sticky (Scanlon 1994). A more uniform grading of aggregate particles may improve workability by filling the voids between larger particles and reducing the amount of locking between particles (see Aggregate Gradation in chapter 3, page 44).

Finally, the properties of the aggregate itself, including particle shape, texture, and porosity, are important. More spherical particles generally produce more workable mixtures than sharp, elongated, angular ones, while more absorptive, dry aggregates may reduce workability by removing water from the paste.

Entrained Air. Entrained air increases the paste volume while acting as a lubricant to improve the workability of concrete (Scanlon 1994). Entrained air is particularly effective in improving the workability of lean (low cement content) mixtures that otherwise might be harsh and difficult to work and of mixtures with angular and poorly graded aggregates (Kosmatka, Kerkhoff, and Panarese 2002). However, excessive amounts of entrained air can make a mixture sticky and difficult to finish and may reduce concrete strength.

Time and Temperature. Workability decreases with time as water from the mixture evaporates, is absorbed by the aggregate, and reacts with cement during the initial chemical reactions (Wong et al. 2000). Increases in ambient temperatures will accelerate these effects because higher temperatures increase both the evaporation and hydration rates (Mindess and Young 1981).

Cement. Although less important than other components' properties, the characteristics of the cement may also affect workability. For example, the increased cement fineness (therefore, the increased specific surface area) of Type III cements means they will have a lower workability at a given water-cementitious materials ratio than a Type I cement (Mindess and Young 1981).

Supplementary Cementitious Materials. Fly ash and ground granulated blast furnace (GGBF) slag have generally been found to improve concrete workability because of the fine spherical nature of fly ash and the glassy surface of GGBF slag particles. In hot weather, some fly ashes may cause early stiffening and loss of workability of the mixture (see Stiffening and Setting in chapter 6, page 186.)

Silica fume will markedly increase the water requirement and stickiness at dosages above five percent by mass of cement because of the high surface area. Less than five percent silica fume may improve workability because the silica fume particles tend to be spherical and assist with separating cement grains. (Silica fume is not typically used in concrete for pavements; see Supplementary Cementitious Materials in chapter 3, page 31.)

Admixtures. Water-reducing admixtures are used to increase workability, although the rate of slump loss may not be reduced, depending on the chemistry of the admixture (Kosmatka, Kerkhoff, and Panarese 2002). Set-retarding admixtures reduce the early rate of hardening and permit concrete to be handled and vibrated for a longer period of time (Scanlon 1994).

Workability Testing

Several characteristics of fresh concrete are related to workability. Some of these characteristics include the following (Mindess and Young 1981; Scanlon 1994):

- Consistency or fluidity.
- Mobility.
- Pumpability.

- Compactability.
- Finishability.
- Harshness (amount of coarse aggregate).

Unfortunately, no test method for assessing workability comprehensively measures all of these properties. And there is no single test that directly measures workability in terms of the fundamental properties of fresh concrete (Neville 1996). In addition, comparisons cannot be made among the different tests because each measures a different aspect of concrete behavior. The study of rheology (loosely, flow behavior) is ongoing to address this concern.

As a result, the measurement of workability is determined to a large extent by judgment and engineering experience (Scanlon 1994).

However, commonly available tests are useful as quality control measures (Koehler and Fowler 2003; Mindess and Young 1981). The following sections summarize common tests for measuring workability, with more detailed information provided by Mindess and Young (1981), Scanlon (1994), Neville (1996), and Wong et al. (2000). (See also chapter 9, page 250.)

Slump Test

The slump test (ASTM C 143 / AASHTO T 119) measures the consistency of the mix, that is, the ability of fresh concrete to flow. During flow, two events take place; one starts the movement and the other continues the movement. The slump test is an indicator of the former.

The slump test is valid for a range of results from 12 to 225 mm (0.5 to 9 in.) using coarse aggregate less than 38 mm (1.5 in.). The slump test measures concrete slump under the self-weight of the concrete only, and as such does not reflect the behavior and workability of the mixture under dynamic conditions like vibration or finishing (Neville 1996).

With different aggregates or mix properties, the same slump can be measured for concrete mixtures that exhibit very different workability. Nevertheless, the slump test is very useful as a quality control measure, with significant changes in the slump on a given job indicating that changes have occurred in the characteristics of materials, mixture proportions, water content, mixing, time of test, or the testing itself (Kosmatka, Kerkhoff, and Panarese 2002).

Compacting Factor Test

The compacting factor test is used to measure the compactability of concrete mixtures for a given amount of work. The test involves dropping fresh concrete through multiple heights and measuring the degree to which it compacts (Wong et al. 2000).

The degree of compaction, called the compacting factor, is expressed in terms of the ratio of the density actually achieved in the test to the density of the same concrete fully compacted (Neville 1996). The test is more sensitive at the low-workability end of the scale and is most appropriate for mixtures with a maximum aggregate size less than 38 mm (1.5 in.). (The test is standardized in Europe as EN 12350-4.)

Vebe Test

The Vebe test was developed in the 1940s and is particularly suitable for determining differences in the consistency of very dry mixes (Mindess and Young 1981). In this test, a sample of concrete is molded with the slump cone inside a larger cylinder. The slump mold is removed, a transparent disk is placed on top of the concrete, and the sample is then vibrated at a controlled frequency and amplitude until the lower surface of the disk is completely covered with grout (Mindess and Young 1981). The time in seconds for the disk to become covered is the Vebe time, and can commonly range from 5 to 30 seconds.

Although there is no ASTM standard for this test, there is a European standard test that is widely used throughout Europe (EN 12350-3).

Penetration Tests

Penetration-type tests can be used to assess concrete workability. These tests measure the penetration of some type of indenter into concrete under a variety of conditions.

The Kelly ball penetration test is described in ASTM C 360, which has been discontinued. In this test, a large, ball-shaped, steel probe is gently placed on the concrete surface and the depth of penetration is measured. This test can be conducted very quickly and can even be applied to concrete in the form (Neville 1996).

Segregation of Concrete Materials

Key Points

- Segregation of coarse aggregate from the mortar results in concrete with lower strength and poor durability.
- The primary way to prevent segregation is to use well-graded aggregate.
- If coarse aggregates advance in front of or behind the fine particles and mortar when the concrete is being placed, the mixture is segregating.

Simple Definition

Segregation is the tendency for coarse aggregate to separate from the mortar in a concrete mixture, particularly when the mixture is being transported or compacted.

Significance of Segregation

Segregation results in part of the batch having too little coarse aggregate and the remainder having too much. The former is likely to shrink more and crack and have poor resistance to abrasion, while the latter may be too harsh for full consolidation and finishing. The result is that effectively a number of different concrete mixtures are being placed (figure 5-1).

Segregation is especially harmful in placing concrete for pavement, as it results in problems such as strength loss, edge slump, spalling, blistering, and scaling.

Factors Affecting Segregation

Segregation is primarily prevented by using a well-graded aggregate system. A gap-graded aggregate system is more likely to segregate.

Segregation tends to decrease with increasing amounts of fine materials, including cement and supplementary cementitious materials, in the system. At the other extreme, poor mixture proportioning with excessive paste can also lead to segregation.

Segregation Testing

Many specifications require that segregation be prevented, although there is no standard test to measure it. However, segregation is readily visible and can be recognized easily when the concrete is being discharged from a chute or a pump. If the coarse particles advance in front of or behind the fine particles and mortar, the mixture is segregating. The batch plant should then be contacted to adjust the mix proportions.

Figure 5-1. Segregated concrete (Hanson, Iowa DOT)

Bleeding

Key Points

- Bleeding is the appearance of water at the surface of newly placed, plastic concrete due to settlement of the heavier particles.
- Some bleeding helps avoid plastic cracking in the surface, which can occur when water evaporating from the surface causes the surface to dry quickly.
- Excessive bleeding can result in voids under large aggregate particles and the formation of channels through the concrete. Excessive bleeding will also increase the effective water-cementitious materials ratio at the surface and soften the surface.
- Ideally, finishing and curing should occur when bleeding has finished and bleed water has evaporated.
- Bleeding is reduced with increasing fines content and with air-entraining and water-reducing admixtures.
- Specifications: ASTM C 232 / AASHTO T 158.

Simple Definition

Bleeding is the appearance of a layer of water at the top or the surface of freshly placed concrete after it has been consolidated and struck off, but before it has set (Mindess and Young 1981). Bleeding may also be referred to as water gain, weeping, or sweating.

Significance of Bleeding

Bleeding is caused by the settlement of solid particles (cement and aggregate) in the mixture and the simultaneous upward migration of water (Kosmatka, Kerkhoff, and Panarese 2002). A small amount of bleeding is normal and expected in freshly placed concrete.

In fact, some bleeding is actually helpful in controlling the development of plastic shrinkage cracking. If the rate of moisture evaporation at the surface exceeds the bleeding rate (Kosmatka 1994; Poole 2005), the surface will dry and crack. A lack of bleed water can also lead to a dry surface that can be very difficult to finish (Kosmatka 1994).

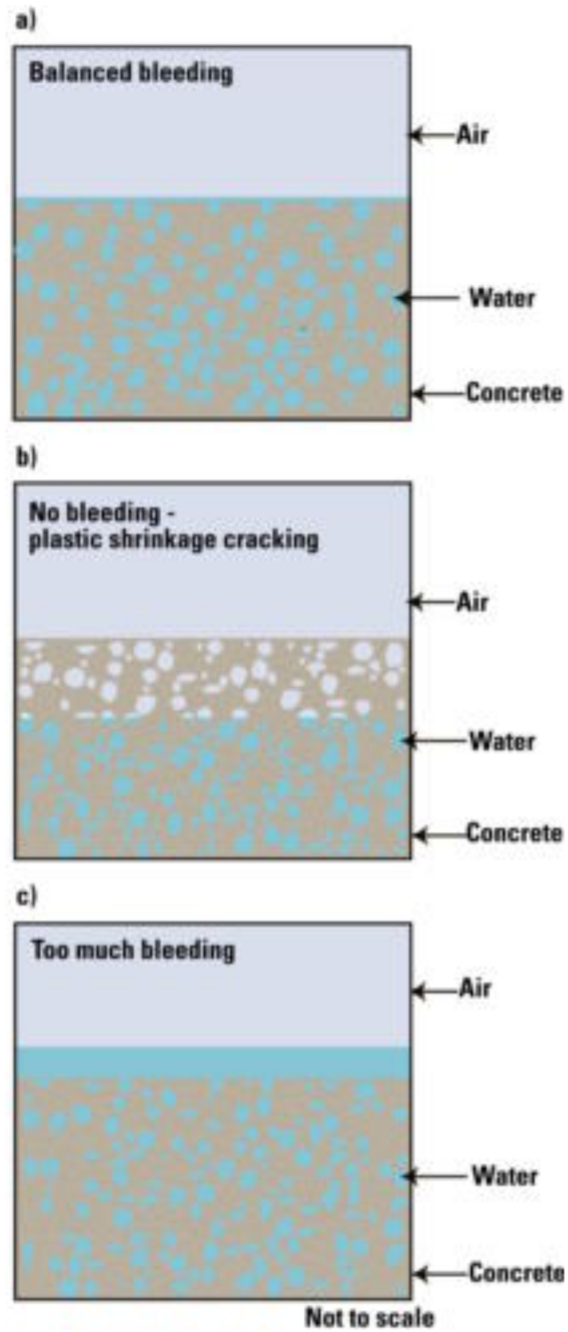


Figure 5-2. Bleeding (Ozyildirim)

However, excessive bleeding reduces concrete strength and durability near the surface. The rising water can carry with it a considerable amount of fine cement particles, forming a layer of weak and nondurable material, called laitance, at the surface (Neville 1996).

Excessive bleeding also may delay the finishing process, which in general should not proceed until the bleed water has evaporated from the surface (Kosmatka 1994). If the surface is finished with bleed water present, a thin and weak layer is created on the surface that is susceptible to scaling and delamination. In some cases, if the fresh concrete surface is prematurely sealed by troweling while the underlying concrete is still releasing bleed water, blisters (small hollow bumps beneath the concrete surface) can form.

Bleed water can also accumulate within the concrete mix itself, under large aggregate particles or reinforcing bars (Mindess and Young 1981). The former results in reduced concrete strength (due to decreased aggregate-paste bond). The latter may reduce the paste-steel bond, possibly promoting the corrosion of steel because the steel is not in contact with the corrosion-resistive paste (Kosmatka 1994).

Factors Affecting Bleeding

The initial bleeding process generally begins after agitation of the concrete mix ends, and bleeding continues until the cement paste has stiffened sufficiently to resist the settlement of the solid particles (Neville 1996). The duration of bleeding depends on the thickness of the concrete section as well as the setting properties of the cementitious materials, with thinner sections or faster setting concretes exhibiting less bleeding (Kosmatka 1994).

A number of different concrete mix constituents can affect the development of bleeding:

Water Content and Water-Cementitious Materials (W/CM) Ratio. Any increase in the amount of water or in the w/cm ratio results in more water available for bleeding (Kosmatka 1994).

Cement. As the fineness of cement increases, the amount of bleeding decreases, possibly because finer particles hydrate earlier and also because their rate of sedimentation (settlement) is lower (Neville 1996). Increasing cement content also reduces bleeding (Kosmatka 1994). Cement with a high alkali content or a high calcium aluminate (C_3A) content will exhibit less bleeding (Neville 1996).

Supplementary Cementitious Materials. Concrete containing fly ash generally exhibits a lower bleeding rate, but due to retarded setting the total bleed volume may be similar or greater than portland cement-only concrete. Ground, granulated blast-furnace slags have little effect on bleeding rates (Wainwright and Rey 2000). Silica fume has been found to greatly reduce, or often stop, bleeding, largely because of the extreme fineness of the particles (Neville 1996).

Aggregate. Ordinary variations in aggregate grading have little effect on the bleeding of concrete, provided that there is no appreciable change in the minus-75-µm material. However, concrete containing aggregates with a high amount of silt, clay, or other material passing the 75-µm (#200) sieve can significantly reduce bleeding (Kosmatka 1994), although there may be other adverse effects on the concrete, like increased water requirement and shrinkage.

Chemical Admixtures. Air-entraining agents have been shown to significantly reduce bleeding in concrete, largely because the air bubbles appear to keep the solid particles in suspension (Neville 1996). Water reducers also reduce the amount of bleeding because they release trapped water in a mixture.

Testing for Assessing Bleeding

When required, ASTM C 232 / AASHTO T 158 include two test methods for assessing bleeding. The first test method involves hand consolidating a sample of concrete by rodding in a container of standard dimensions and then covering the sample and leaving it undisturbed. The bleed water is drawn off the surface every 10 minutes during the first 40 minutes, and every 30 minutes thereafter, until the bleeding stops. The total bleeding and the rate of bleeding may then be determined.

The second test method in ASTM C 232 uses a sample of fresh concrete consolidated by vibration and, after covering the sample, intermittently vibrating it for a period of one hour to determine the total volume of bleed water.

Setting

Key Points

- Setting is when concrete loses its workability and becomes hard; it is influenced by the chemistry of the cementitious system.
- Class F fly ash and ground, granulated blast-furnace slag will generally retard setting time.
- Setting is accelerated when the concrete temperature increases.
- Set-accelerating and retarding chemical admixtures in the mixture can control set time.
- Setting affects the time available for placing and finishing, as well as the sawing window when joints can be sawed.
- Testing specifications: ASTM C 191 / AASHTO T 131, ASTM C 266 / AASHTO T 154 (rare), ASTM C 451 / AASHTO T 186, ASTM C 403 / AASHTO T 197.

Simple Definition

Setting is the stage when concrete changes from plastic to solid.

Significance of Setting

Over time, the chemical reactions of portland cement and water lead to stiffening, setting, and hardening—a continuous process. The time when setting occurs is important because it influences the time available to place and finish the concrete. The saw-cutting window is also indirectly related to setting. The setting time is an important characteristic because variation between batches may indicate issues with construction scheduling or materials compatibility.

Typically, initial set occurs between two and four hours after batching; final set occurs between four and eight hours after batching. Initial set and final set are arbitrarily determined based on the test methods available, but initial set generally occurs shortly after initiation of the silicate phase of cement hydration (see Portland Cement Hydration in chapter 4, page 88.)

False set and flash set are the stiffening of the mixture in the first few minutes after mixing and are due to uncontrolled reactions of the aluminate/sulfate compounds in the cement (see Potential Materials Incompatibilities in chapter 4, page 97). False set is temporary and can be worked through with continued mixing, but flash set means that the mixture will have to be discarded.

Factors Affecting Setting

A number of factors affect concrete setting time:

Temperature/Weather. Increasing temperature reduces set time. Decreasing temperature increases set time. Hydration will stop when the temperature is close to 0°C (32°F). Exposure to sunlight and windy conditions also influence setting, especially at the surface, largely due to the effects of heating and evaporative cooling.

Water-Cementitious Materials (W/CM) Ratio. A lower w/cm ratio reduces set time.

Cement Content. Increasing cement content reduces set time.

Cement Type. Cement chemistry will strongly influence set time (see Reactions of Supplementary Cementitious Materials and Potential Materials Incompatibilities in chapter 4, pages 94 and 97.)

Chemical Admixtures. Accelerating and retarding admixtures are used deliberately to control the setting time (Dodson 1994). Overdose of some water reducers may result in set retardation (see Potential Materials Incompatibilities in chapter 4, page 97.)

Timing of Addition of Admixtures. Delayed addition of some water reducers may prevent early stiffening or retardation.

Mixing. Improved mixing influences hydration by improving the homogeneity and dispersion of the reactants and, thus, also accelerates setting.

Supplementary Cementitious Materials. Class F fly ash and ground, granulated blast-furnace slag will generally retard the setting time of concrete. Class C fly ash may accelerate or retard setting, depending on the chemistry of the fly ash and the other components in the system.

Testing for Setting Time

Setting time is both a characteristic of cement (tested as a standard paste) and of concrete (tested as a mortar extracted from the concrete).

Cement specifications typically place limits on setting time using the Vicat apparatus (ASTM C 191 / AASHTO T 131). This test is run on paste made to a standard consistency and measures the time at which different indicators penetrate the surface. An optional test using the Gillmore needle (ASTM C 266 / AASHTO T 154) is rarely used.

Cements are tested for early stiffening (flash set/ false set) using ASTM C 451 / AASHTO T 186 (paste method) and ASTM C 359 / AASHTO T 185 (mortar method), which use the penetration techniques of the Vicat apparatus. The test records the depth of penetration after remixing at fixed intervals.

Concrete setting is determined using ASTM C 403 / AASHTO T 197. Mortar is separated from the concrete through a 4.75 mm (#4) sieve, and the penetration resistance is recorded as a function of time. The initial and final setting times are defined as the time the mortar achieves a penetration resistance of 3.4 MPa (500 lb/in^2) and 27.6 MPa (4,000 lb/in^2), respectively (figure 5-3).

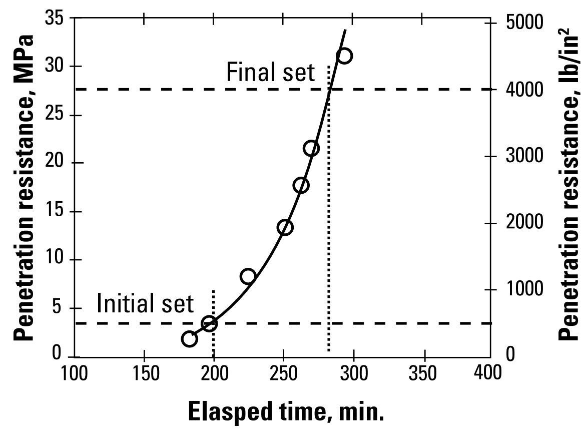


Figure 5-3. Penetration resistance of mortar sieved from concrete as a function of time, per ASTM C 403. Initial and final setting times are defined as shown. (Dodson 1994)

Strength and Strength Gain

Key Points

- Concrete strength is often used to measure concrete quality, although this can be a false assumption.
- Sufficient concrete strength is needed to carry the loads.
- Strength increases with a decreasing w/cm ratio.
- Strength gain is accelerated at higher temperatures and decelerated at lower temperatures.
- Strength decreases as air content increases.
- Strength is measured in compression or in flexure (bending). In general, concrete has significantly more compressive strength than flexural strength.
- Early strength can be assessed in the field using maturity (time and temperature) measurements.

Simple Definition

Strength is a measure of the ability of concrete to resist stresses or forces at a given age.

Significance of Strength and Strength Gain

Strength is the most commonly measured property of concrete and is often used as the basis for assessing concrete quality. This is partly because strength measurements give a direct indication of concrete's ability to resist loads and partly because strength tests are relatively easy to conduct. The age at which a given strength is required will vary depending on the need. Contractors may want early strength (rapid strength gain) in order to put construction traffic on the pavement, while the owner may be interested only in the strength at a later age. The rate of strength development will also influence the risk of cracking (see Early-Age Cracking in this chapter, page 148.)

Some people rely on strength measurements as indicators for other concrete properties, such as abrasion resistance or potential durability. A word of caution: This correlation between strength and other properties is not necessarily accurate. In many cases, strength alone is not sufficient to determine the suitability of a concrete for a specific application. Specific properties should be tested according to relevant standards, not correlated to strength measurements. For instance, high early strength achieved by chemical admixtures or heating will often result in a poorer microstructure, higher permeability, and loss of potential durability.

Concrete is generally strong in compression, meaning it can resist heavy loads pushing it together. However, concrete is much weaker in terms of tension, meaning that the concrete is relatively weak in resisting forces pulling it apart.

Most loads on pavements (see figure 5-4) result in bending (or flexure), which introduces compressive stresses on one face of the pavement and tensile stresses on the other. The concrete's compressive strength is typically much greater than the compressive stresses caused by the load on the slab. However, the tensile strength is only about 10 percent of the compressive strength. Most slab failures are in flexure rather than in compression. Consequently, the flexural stress and the flexural strength (modulus of rupture) of the concrete are used in pavement design to determine required slab thickness. Slab failures after the first few weeks are often due to a loss of support under the slab, which results in excessive stresses.

Another key strength parameter of concrete for pavements is fatigue, or the concrete's ability to carry repeated loading and unloading. Under fatigue, a small crack develops in the concrete that then grows with every cycle.

Factors Affecting Strength and Strength Gain

Fundamentally, strength is a function of the volume of voids in the concrete. Voids provide a shortcut for cracks growing through the system to propagate. These voids may be large, such as air voids due to poor consolidation, or small, such as capillary voids left after excess water has evaporated from the paste.

The primary factors that influence strength in well-compacted concrete, therefore, are the water-cementitious materials ratio (a direct influence on capillary volume) and the extent to which hydration has progressed. These and other factors are discussed below (table 5-2):

Water-Cementitious Materials (W/CM) Ratio. Strength increases as the w/cm ratio decreases because the capillary porosity decreases. This observation holds for the entire range of curing conditions, ages, and types of cements considered. Remember, however, that although there is a direct relationship between w/cm ratio and strength, concretes with the same w/cm ratio but different ingredients are expected to have different strengths.

Degree of Hydration. Hydration begins as soon as cement comes in contact with water and continues as long as favorable moisture and temperature

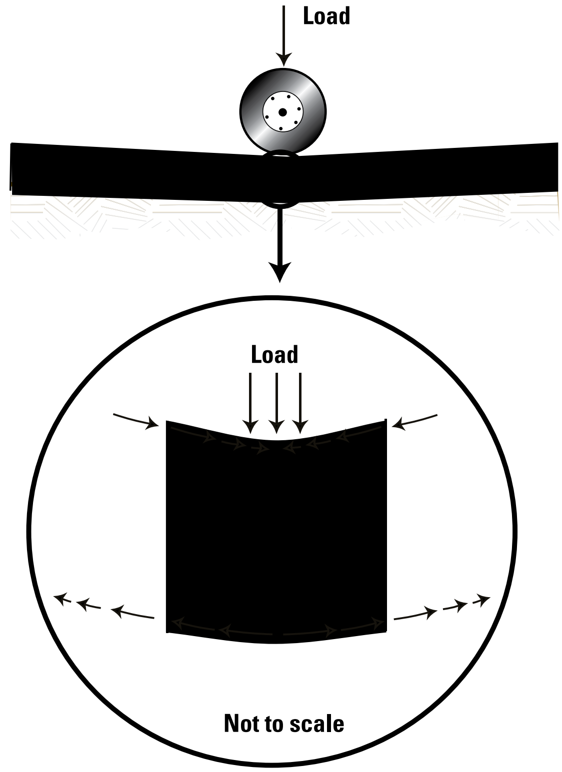


Figure 5-4. Loads on a pavement induce flexural stresses in the concrete slab. (ACPA 1994)

Table 5-2. Factors Affecting Compressive and Flexural Strength

Areas	Factor	Pavement impact	Testing impact
Construction	Change in w/cm ratio	Higher w/cm=lower strength	Higher w/cm= lower strength
	Poor consolidation	Low strength	Lower strength if cores are tested
	Excessive vibration	Segregation may result in lower strength	Lower strength if cores are tested
	Improper curing	Lower strength	Lower strength if cores are tested
	Reduced air content	Higher strength	Higher strength if cores are tested
	Increased air content	Lower strength	Lower strength if cores are tested
Sampling	Nonrepresentative, segregated sample	Lower strength	Lower strength
Specimen casting	Poor consolidation	Low strength and high permeability	Lower strength
	Poor handling	Low strength and high permeability	Lower strength
Specimen curing	Specimen freezes or dries out	Higher strength than indicated	Lower strength
Specimen breaking	Rapid rate	Lower strength than indicated	Higher strength
	Poor end preparation	Higher strength than indicated	Lower strength

conditions exist and space for hydration products is available (although hydration slows significantly after a few days). As hydration continues, concrete becomes harder and stronger. Hydration proceeds at a much slower rate when the concrete temperature is low and accelerates when the temperature rises. Hydration (and thus strength gain) stops when there is insufficient water in the system.

Cement. Concrete strength is influenced by the composition and fineness, and perhaps by the amount, of the cement. The silicate alite (C_3S) hydrates more rapidly than belite (C_2S) and contributes to early strength. Belite (C_2S) hydrates more slowly but continues hydrating longer, thus increasing later strengths (see Portland Cement Hydration in chapter 4, page 88). Finer cements hydrate faster than coarser cements and tend to have a limited later strength development because of a poorer quality microstructure (figure 5-5).

Supplementary Cementitious Materials (SCMs). SCMs contribute to the strength gain of concrete. However, the amount or rate of this contribution will depend on the chemistry, fineness, and amount of the SCM. Generally, with Class F fly ash and ground, granulated blast-furnace slag, early strengths are lower than those of similar mixtures with portland cement only, and ultimate strengths are higher. The effect of Class C fly ash will go either way, depending on the specific fly ash used. Silica fume normally increases strengths at both early and later ages (although silica fume is not generally used in concrete for pavements). Mix proportions can be selected to achieve the required strengths with or without the presence of SCMs, but the majority of concrete mixtures include one or more SCMs.

Air Content. As air content is increased, a given strength generally can be maintained by holding the ratio of voids (air and water) to cement constant. To accomplish this, the cement content may need to be increased or the w/cm ratio reduced. Air-entrained as well as non-air-entrained concrete can readily be proportioned to provide moderate strengths.

Aggregate Bond. Rough and angular (including crushed) aggregate particles exhibit a greater bond with cement paste than aggregates with smooth and rounded surfaces. Large aggregates generally provide improved aggregate interlock at the joints and cracks, increasing flexural strength.

Handling and Placing. Improper mixing, handling, and placing will affect concrete strength and strength gain. The later addition of water can markedly reduce strength (see Water-Cementitious Materials (w/cm) Ratio, on the previous page). Concrete must be thoroughly compacted in order to reduce the void content of the mixture.

High Early-Strength Concrete

The period in which a specified concrete strength is achieved may range from a few hours to several days. High early-strength concrete, used in fast-track concrete, achieves its specified strength at an earlier age than normal concrete. (It is notable that concrete considered normal today performs the same as high early-strength concrete of only a few years ago.)

High early-strength can be obtained by using one or more of the following:

- Type III or HE high-early-strength cement.
- High cement content (400 to 500 kg/m^3 or 675 to 850 lb/yd^3).

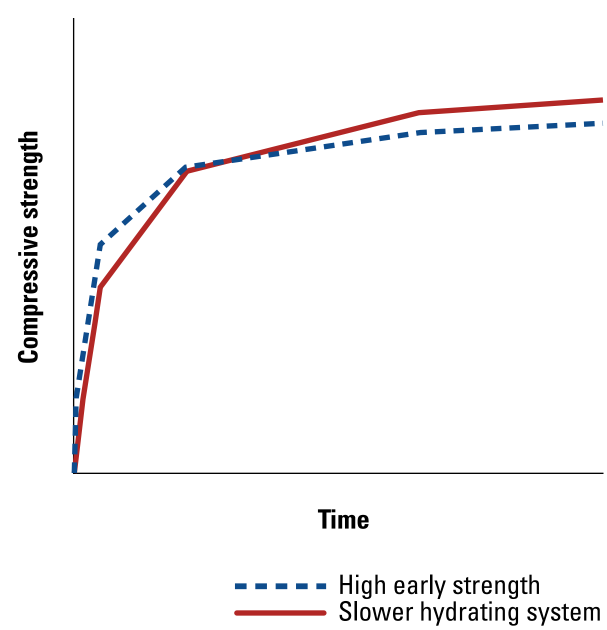


Figure 5-5. Cementitious systems that produce high early-strengths (blue line) tend to have lower strengths in the long term when compared to slower hydrating systems (red line). (CTLGroup)

- Low water-cementitious materials ratio (0.35 to 0.45 by mass).
- Higher freshly mixed concrete temperature.
- Higher curing temperature.
- Accelerating admixtures.
- Insulation to retain heat of hydration.
- Hydraulic non-portland cements that have rapid strength gain.

High early-strength concrete can be used for several applications, including cold-weather construction, rapid repair of pavements to reduce traffic downtime, fast-track paving, and several others. In fast-track paving, using high early-strength mixtures allows traffic to open within a few hours after concrete is placed. See Kosmatka, Kerkhoff, and Panarese (2002) for an example of a fast-track concrete mixture used for a bonded concrete highway overlay.

When designing early-strength mixtures, strength development is not the only criteria that should be evaluated; durability, early stiffening, autogenous shrinkage, drying shrinkage, temperature rise, and other properties should also be evaluated for compatibility with the project. For more information on high early-strength concrete, consult ACPA (1994).

Strength Testing: Mix Design Stage

Concrete strength is not an absolute property. Results obtained from any given concrete mixture will depend on specimen geometry and size, preparation, and loading method (Carrasquillo 1994). Specifications therefore need to set out the test methods as well as the value to be achieved at a given age. Variability is inherent in the test methods and materials. Therefore, trial mixes should yield strengths somewhat higher than the minimum specified (see Sequence of Development in chapter 6, page 172; Quality Control in chapter 9, page 242; and ACI 214 [2002]).

Strength is generally expressed in megapascals (MPa) or pounds per square inch (lb/in^2) at a specified age. Seven-day strengths are often estimated to be about 75 percent of the 28-day strength, and 56-day and 90-day strengths are about 10 to 15 percent greater, respectively, than 28-day strengths.

Compressive strength is normally measured by loading a cylinder of concrete at its ends (ASTM C 39). Testing the tensile strength of concrete is difficult; it is normally determined indirectly by using a bending test on a beam (ASTM C 78) or by using a split tensile test (ASTM C 496), in which a line load is applied on opposite sides of a cylinder.

Fatigue is normally tested by cyclically loading a concrete beam with a maximum load somewhat less than the concrete's ultimate capacity. The number of cycles before the beam fails then indicates the specimen's fatigue.

Mix Design Testing: Flexural Strength

The primary parameter used in assessing pavement strength is flexural strength, or modulus of rupture (MOR), because that is the critical mode of loading. Flexural strength is determined in accordance with ASTM C 78 / AASHTO T 97 (third-point loading) (figure 5-6a). Some agencies use the center-point flexural strength test (ASTM C 293 / AASHTO T 177) (figure 5-6b), particularly to assess whether the pavement can be opened to traffic.

For AASHTO thickness design, it is important that the third-point loading, 28-day flexural strength be used in the AASHTO equation. If strength values are measured using some other test method, the results must be converted to the third-point loading, 28-day strength. (See www.pavement.com/PavTech/Tech/FATQ/fatq-strengthtests.html for strength correlations and conversions. Published conversion factors are necessarily generic, and it is advisable to develop the relationships for a specific mix if they are to be used in a contract.)

Specimens for flexural strength testing are large and somewhat difficult to handle. Measurements of flexural strength are more sensitive than measurements of compressive strength to variations in test specimens and procedures, especially the moisture condition during testing. For these reasons, a relationship should be developed between flexural strength and compressive strength by laboratory testing for a given mix.

Mix Design Testing: Compressive Strength

The compressive strength of concrete cylinders or cores (ASTM C 39 / AASHTO T 22) can be used as an alternative to flexural strength testing if so specified.

Usually, a correlation is established between flexural and compressive strengths. Compressive strength is the parameter normally used in structural concrete specifications.

Mix Design Testing: Splitting Tensile Strength Tests

The splitting tensile test involves compressing a cylinder or core on its side (ASTM C 496) until a crack forms down the middle, causing failure of the specimen (figure 5-7). The loading induces tensile stresses on the plane containing the applied load, causing the cylinder to split.

Strength Testing: Field Tests

Strength tests of hardened concrete can be performed on the following:

- Cured specimens molded in accordance with ASTM C 31 or C 192 / AASHTO T 23 and T 126 from samples of freshly mixed concrete.
- In situ specimens cored or sawed from hardened concrete in accordance with ASTM C 42 / AASHTO T 24.

Samples prepared and cured in the field are likely to show a different (often lower) strength than samples prepared and cured in the laboratory because of the greater variability in the field. Even then, the resulting strength reported is the specimen strength and not that of the in-place pavement.

Laboratory-cured specimens are used to determine the specified concrete strength within a designated time period. Test specimens cast in the field at the time of concrete placement are normally used to determine when the concrete has gained enough strength to be opened to traffic. In situ cores taken after the pavement has hardened are often used to verify the in-place concrete strength.

Cylinder size can be 150 x 300 mm (6 x 12 in.) or 100 x 200 mm (4 x 8 in.), provided that the diameter of the mold is at least three times the maximum size aggregate.

Tests results are greatly influenced by the conditions of the cylinder ends and cores. Therefore, for compression testing, specimens should be ground or capped. ASTM C 617 / AASHTO T 231 outline methods for using sulfur mortar capping. ASTM C 1231

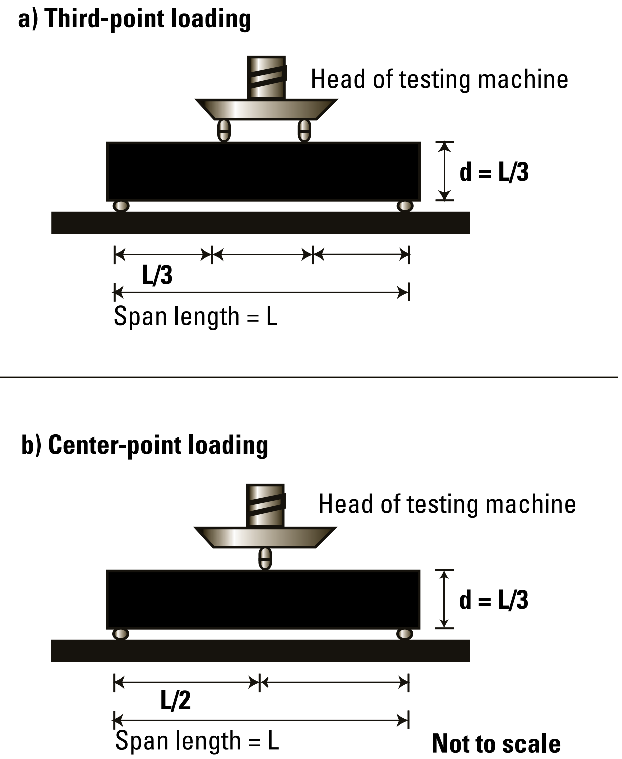


Figure 5-6. (a) In third-point loading, the entire middle one-third of the beam is stressed uniformly, and thus the beam fails at its weakest point in the middle one-third of the beam. (b) By forcing the beam to fail at the center, the center-point loading flexural test results are somewhat higher than the third-point test results. Typically, center-point results are about 15 percent greater than third-point results and vary widely, depending on many concrete mix properties. (PCA)

Figure 5-7. Splitting tensile strength (PCA)

describes the use of unbonded neoprene caps that are not adhered or bonded to the ends of the specimen.

Testing of specimens should be performed in accordance with the following specifications:

- ASTM C 39 / AASHTO T 22 for compressive strength.
- ASTM C 78 / AASHTO T 97 for flexural strength using third-point loading.
- ASTM C 293 / AASHTO T 177 for flexural strength using center-point loading.
- ASTM C 496 / AASHTO T 198 for splitting tensile strength.

The moisture content of the specimen has a considerable effect on the resulting strength. Beams for flexural tests are especially vulnerable to moisture gradient effects. A saturated specimen will show lower compressive strength and higher flexural strength than those for companion specimens tested dry. This is important to consider when cores taken from hardened concrete in service are compared to molded specimens tested as taken from the moist-curing room or water storage tank.

Maturity Testing

In recent years, maturity methods have been used extensively to predict the in-place strength and strength gain of concrete. The basis for this method is simple: The strength and modulus of elasticity (see Modulus of Elasticity in this chapter, page 123) of a concrete specimen are directly related to the quantity of heat developed from the hydrating cement.

The practical benefit of this method is that field evaluations of in-place strength can be predicted from simple measurements of the concrete temperature over time. Maturity testing can be effective when making decisions about opening pavements to traffic.

The theoretical benefit is the ability to accurately predict both the strength and modulus of elasticity of concrete over a wide range of conditions based simply on the temperature development in the modeled pavement.

Maturity testing is most useful in estimating the in-place properties of concrete. However, it is also useful in developing concrete mixes. When insufficient time is available to adequately test a concrete mix before it is used on a project, maturity tests can be used to predict later-age strengths. In this regard, concrete specimens can be cured at elevated temperatures and, using an assumed or empirically determined maturity constant, the measured strength development can be correlated back to the strength development if the concrete were cured at standard conditions.

The basis of maturity testing is that each concrete mix has a unique strength-time relationship. Therefore, a mix will have the same strength at a given maturity no matter what conditions (time or temperature) occur before measurement. Maturity testing entails developing a maturity curve that correlates the development of particular concrete properties for a specific concrete mix to both time and temperature. After the maturity curve is developed, development of the concrete property can be estimated from a measured time-temperature record of the concrete. The maturity function is a mathematical expression to account for the combined effects of time and temperature on the strength development of concrete. The key feature of a maturity function is the representation of the way temperature affects the rate of strength development.

ASTM C 918 uses the maturity method of monitoring the temperature of cylinders cured in accordance with standard methods outlined in ASTM C 31 / AASHTO T 23. Cylinders are tested at early ages beyond 24 hours, and the concrete temperature history is used to compute the maturity index at the time of test. Using historical data, a prediction equation is developed to project the strength at later ages based on the maturity index and early-age strength tests. See Carino (1994) for more information.

ASTM C 1074 provides procedures for using the measured in-place maturity index to estimate in-place strength (figure 5-8) (see chapter 9, page 261). This practice describes two maturity functions. The first, and most popular for use with concrete pavements, is the Nurse-Saul function. The other (preferred) maturity equation is the Arrhenius function. This function presents maturity in terms of the equivalent age of curing at standard laboratory conditions. Although the equivalent-age maturity function presents results in a more understandable format (the equivalent age), the complexity of its equation is likely why this method is less popular than the time-temperature factor method.

Equivalent age is expected to provide more accurate results when large temperature changes occur in the field. However, the time-temperature method is easier to apply and has been successfully used for estimating the in-place strength of paving concrete. Each of these functions requires preliminary testing to relate to the strength of concrete. Each method has a constant that can be assumed or, for accuracy, determined for the specific mix (ASTM C 1074). In the time-temperature factor, a datum temperature below which hydration is minimal can be determined experimentally. In the equivalent-age method, an activation energy is calculated.

Maturity can be determined with commercially available test equipment or with standard temperature logging equipment and an understanding of maturity (see Concrete Maturity in chapter 9, page 261). In either case, temperature sensors must be placed at the critical locations in the concrete. For most pavements, this will be either at the top or bottom surface. When in doubt, use the lower of the maturities from sensors at the top and bottom surfaces.

Commercially available maturity meters log the concrete temperature as a function of time and present the current maturity (time-temperature factor or equivalent age) of the concrete. There are two primary types of maturity meters. The first type uses temperature sensors in the concrete with logging equipment outside the concrete. The second type combines the temperature sensor and logging equipment in a single package, which is embedded in the concrete. Wires extend from the sensor outside the concrete. These wires must be periodically connected to a hand-held reader so that the maturity data from the sensor can be read. Wireless equipment is also available.

Maturity can also be calculated from temperature sensors (like thermocouples, thermometers, or thermistors) embedded in the concrete. The time interval should be selected to adequately resolve temperature changes in the concrete. Some States require twice daily readings, although more frequent intervals would improve accuracy.

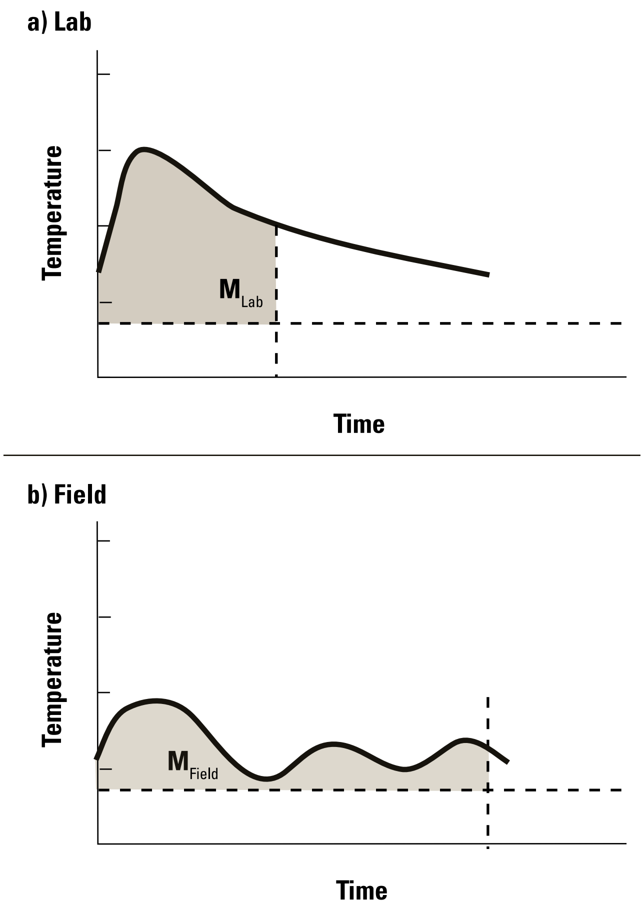


Figure 5-8. Maturity of the field concrete is equivalent to maturity of the laboratory concrete when the area under the curves is the same. (CTLGroup)

Modulus of Elasticity and Poisson's Ratio

Key Points

- Concrete's modulus of elasticity generally correlates with the strength of the concrete and the type and amount of the aggregate.
- Modulus of elasticity is used in structural design of concrete pavement and for modeling the risk of cracking in concrete pavement.
- Poisson's ratio is normally about 0.2 in hardened concrete.
- Similar to the prediction of concrete strength, maturity methods can be used to predict the modulus of elasticity.
- Testing specifications: ASTM C 469 (dynamic modulus: ASTM C 215)

Simple Definition

The modulus of elasticity (E), or stiffness, of concrete is a measure of how much the material will deflect under load and indicates risk of cracking. Poisson's ratio is a measure of deflection that is perpendicular to the load.

Significance

The modulus of elasticity (E) parameter is used in the structural design of the pavement and for modeling the risk of cracking. Strictly defined, the modulus of elasticity is the ratio of stress to corresponding strain for loads up to about 40 percent of the ultimate strength (figure 5-9). (Dynamic modulus is the response of concrete to dynamic rather than static loading. The dynamic modulus of concrete is normally about 10 percent higher than the static modulus.)

Normal-density concrete has a modulus of elasticity of 14,000 to 41,000 MPa (2,000,000 to 6,000,000 lb/in^2), depending on factors like compressive strength and aggregate type. For normal-density concrete with compressive strengths between 20 and 35 MPa (3,000 and 5,000 lb/in^2), the modulus of elasticity can be estimated as 5,000 times the square root of strength (57,000 times the square root of strength in lb/in^2). Several formulas have been suggested for high-strength concrete (Farny and Panarese 1993). Like other strength relationships, the relationship of modulus of elasticity to compressive strength is specific to mix ingredients and should be verified in a laboratory (Wood 1992).

Poisson's ratio is a measure of the deflection that is perpendicular to the direction of the load. A common value used for concrete is 0.20 to 0.21, but the value may vary from 0.15 to 0.25 depending on the aggregate, moisture content, concrete age, and compressive strength. Poisson's ratio is generally of little concern to the designer; however, it does play a role in predicting early-age concrete pavement behavior and is required in some numerical models for concrete performance. It is a design input in the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements* (M-E PDG) (NCHRP 2004).

Factors Affecting Elasticity

Modulus of elasticity increases with an increase in compressive strength and is influenced by the same factors that influence strength.

It is primarily affected by the modulus of elasticity of the aggregate and by the volumetric proportions of the aggregate in concrete (Baalbaki et al. 1991). If an

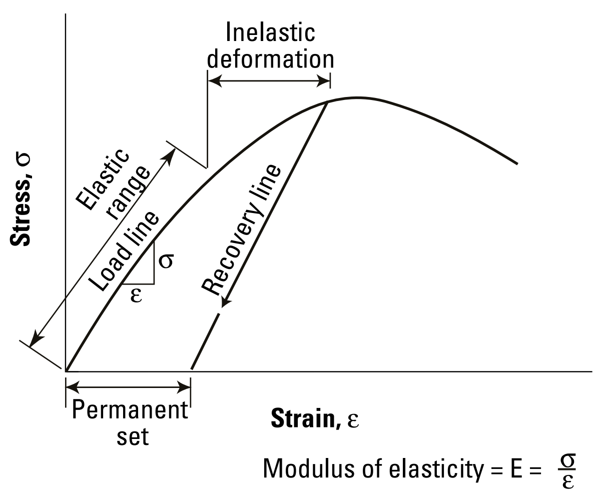


Figure 5-9. Generalized stress-strain curve for concrete (PCA)

aggregate has the ability to produce a high modulus, then the highest modulus in concrete can be obtained by using as much of this aggregate as practical while still meeting workability and cohesiveness requirements.

Testing for Modulus of Elasticity and Poisson's Ratio

Static modulus of elasticity and Poisson's ratio of concrete in compression are tested according to ASTM C 469. Specimens can be concrete cylinders or cores. In the ASTM C 469 test procedure, the cylinder is loaded to 40 percent of the concrete compressive strength. In order to determine the 40 percent load, it is first necessary to determine the concrete compressive strength on companion specimens. This requires a machine with adequate capacity to break the cylinders.

Dynamic modulus can be determined by using ASTM C 215, in which the fundamental resonant frequency is recorded in a sample struck with a small hammer. The dynamic modulus is calculated from the recorded frequency.

Similar to the prediction of concrete strength, maturity methods can be used to predict the actual modulus of elasticity.

Shrinkage

Key Points

- Concrete shrinkage occurs due to a number of mechanisms starting soon after mixing and continuing for a long time.
- Shrinkage primarily increases with increasing water (paste) content in the concrete.
- Testing specifications: ASTM C 157 / AASHTO T 160.

Simple Definitions of Shrinkage

Shrinkage is a decrease in length or volume of the concrete due to moisture loss.

Significance

Starting soon after mixing and continuing for a long time, concrete shrinks due to several mechanisms. Because concrete shrinkage is generally restrained in some way, concrete almost always cracks. Uncontrolled cracks that form at early ages are likely to grow due to mechanical and environmental stresses that would otherwise be of no concern. Therefore, minimizing uncontrolled early shrinkage cracking can prolong the service life of the concrete.

Factors Affecting Shrinkage

Soon after concrete is placed, it shrinks due to chemical changes and loss of moisture:

- Autogenous shrinkage is the amount of chemical shrinkage that can be measured in a sample. (Chemical shrinkage occurs because the volume of the hydration products of cement occupies less space than the original materials.) Autogenous shrinkage is normally insignificant in concrete with a high water-cementitious materials (w/cm) ratio, but it becomes important when the w/cm ratio is below 0.40. The difference is observed as microcracking in the matrix.
- Concrete shrinks as moisture is lost from the system, largely due to evaporation.
  - Plastic shrinkage occurs before the concrete sets and is primarily due to loss of moisture from the surface of fresh concrete. It can result in plastic cracking in the surface.
  - Drying shrinkage occurs after the concrete has set. If the shrinkage is restrained, drying shrinkage cracking will occur (see Early-Age Cracking in this chapter, page 148.)

In addition, concrete shrinks somewhat as it settles and contracts as it cools (see Temperature Effects in this chapter, page 127). All of these shrinkage effects are additive; therefore, reducing any one of them will reduce the risk of cracking (figure 5-10).

The most important controllable factor affecting drying shrinkage is the amount of water per unit volume of concrete (figure 5-11). Total shrinkage can be minimized by keeping the water (or paste) content of concrete as low as possible. The higher the cement content of a mixture, the greater the magnitude of likely drying shrinkage. The paste content can be minimized by keeping the total coarse aggregate content of the concrete as high as possible while achieving workability and minimizing segregation.

Drying shrinkage may also be reduced by avoiding aggregates that contain excessive amounts of clay in their fines. Quartz, granite, feldspar, limestone, and dolomite aggregates generally produce concretes with low drying shrinkages (ACI Committee 2001).

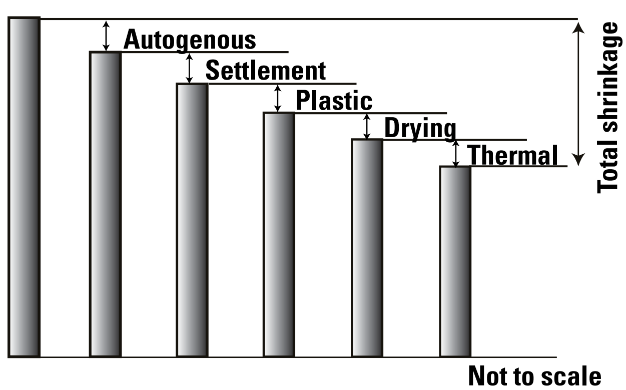


Figure 5-10. Total shrinkage is a sum of all individual shrinkage mechanisms. Minimizing any or all of the mechanisms will reduce the risk of cracking. (CTLGroup)

Weather—air temperature, wind, relative humidity, and sunlight—influences concrete hydration and shrinkage. These factors may draw moisture from exposed concrete surfaces with resultant slowing of hydration and increased warping (see Curling and Warping: A Variation of Volume Change in this chapter, page 150).

Cement types and supplementary cementitious materials usually have little direct effect on shrinkage.

Testing for Shrinkage

Limits to changes in volume or length are sometimes specified for concrete pavements. Volume change should also be tested when a new ingredient is added to concrete to make sure that there are no significant adverse effects.

ASTM C 157 / AASHTO T 160 are commonly used to determine length change in unrestrained concrete due to drying shrinkage. Since the rate and magnitude of shrinkage are influenced by specimen size, any specification based on ASTM C 157 must include the specimen size. The standard procedure is to take an initial length measurement at 24 hours. The specimens are then stored in lime-saturated water for 27 days, when another length measurement is taken. All specimens are then stored in air at a constant temperature until 64 weeks. (Since most projects cannot wait 64 weeks, an alternative set of initial reading, drying age, and final reading age are sometimes specified.)

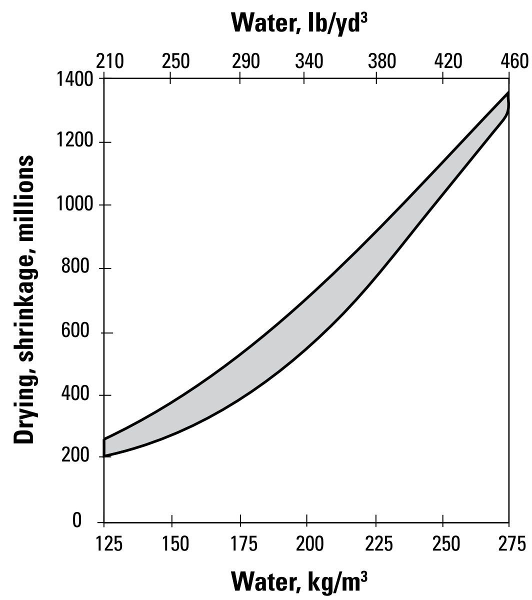


Figure 5-11. Relationship between total water content and drying shrinkage. Several mixtures with various proportions are represented within the shaded area of the curves. Drying shrinkage increases with increasing water contents. (PCA)

Temperature Effects

Key Points

- Concrete hydration generates heat.
- The risk of cracking is increased with increasing placement temperature.
- Concrete expands with increasing temperature and contracts (shrinks) with decreasing temperature. The amount of this expansion and contraction is governed primarily by the aggregate type (see Aggregates in chapter 3, page 39.)
- Concrete hydration rate is accelerated with increasing temperature and with increasing cement fineness. This can accelerate setting time and reduce the sawing window.
- Supplementary cementitious materials typically have lower heat of hydration.
- In cold-weather concreting, the challenge is to maintain the concrete temperature to prevent freezing while gaining strength.
- Testing specifications: ASTM C 186, ASTM C 1064 / AASHTO T 309, AASHTO TP 60.

Simple Definition

The hydration of cement and water in concrete generates heat (see the time-heat curve in figure 4-13, page 74). Monitoring the temperature is a useful means of estimating the degree of hydration of the system. In turn, the temperature of the concrete will influence the rate of hydration (strength development) and the risk of cracking.

Significance of Thermal Properties

An optimal temperature for freshly placed concrete is in the range of 10 to 15°C (50 to 60°F), and it should not exceed 30 to 33°C (85 to 90°F) (Mindess et al. 2003). Problems associated with high concrete temperatures include increased water demand to maintain workability, decreased setting time, increased danger of plastic shrinkage cracking, reduction in the effectiveness of the air-void system, increased risk of incompatibility (see Potential Materials Incompatibilities in chapter 4, page 97), and lower ultimate strength. During the winter, the primary danger is that low temperatures may slow hydration, and thus strength gain, and in extreme cases may permanently damage the concrete if it freezes early in its life (Mindess et al. 2003).

Other thermal effects that may be of interest include solar reflectance, specific heat, and thermal diffusivity. These properties affect the amount of solar energy absorbed by concrete, the corresponding temperature change of the concrete, and the rapidity with which the concrete dissipates this temperature to its surroundings.

Effects on Hydration

The rate of hydration of concrete is significantly accelerated with increasing temperatures and slowed at lower temperatures, affecting placement and consolidation due to early stiffening, as well as the timing of saw cutting. The early strength of a concrete mixture will be higher with an elevated temperature, but the strength may be lower at later ages than the same mix kept at a lower temperature. All chemical reactions are faster at higher temperatures; therefore, setting times will be reduced as the temperature of the concrete rises. With increasing temperature, the potential for an imbalance in the cementitious paste system will be exacerbated, possibly leading to problems with unexpected stiffening of the mixture before the mixture can be consolidated. It has been observed that water may be added to such a mix to restore workability, but with the effect of reducing strength and durability. Water should not be added to the mix in excess of the specified maximum water-cement ratio.

Effects on Cracking

Concrete expands as temperature rises and contracts as temperature falls. These movements can contribute significantly to the risk of cracking in concrete, particularly within the first 24 hours. If the concrete sets when it is hot, then it will contract a significant amount when it cools later, thus significantly increasing the risk of cracking. When a cold front passes over concrete that has been placed in the middle of a hot day, the risk of cracking is greater because the temperature drop is large (see Early-Age Cracking in this chapter, page 148).

Factors Affecting Thermal Properties

Primary factors that affect a concrete pavement's thermal properties are the following:

Heat of Hydration of Cementitious Materials. Type III cements, which are typically used in applications where early strength is a goal, generate more heat and at a faster rate than Type I cements. Table 5-3 shows the typical ranges of chemical compounds in cement, and the heat evolution associated with these compounds. This table is useful in predicting the relative heat generation of similar cements.

Cement fineness affects the rate of heat generation. Finer cements (smaller particle sizes) hydrate faster and generate heat at a faster rate. The total heat evolution is not affected by the fineness, but the peak temperature of the concrete may be higher, as the heat is evolved more quickly.

Pozzolans also generate heat during hydration but, generally, less than portland cement. (The benefit of a lower heat of hydration is to reduce thermal shrinkage and the possibility of resultant cracking. When blended with cement, Class F fly ash has a heat of hydration that is typically 50 percent of cement. Class C fly ash generally has a heat of hydration in the range of 70 to 90 percent of that of cement. The heat of hydration of both silica fume and metakaolin are approximately 125 percent of cement. The heat of hydration in concrete is affected by the amount and grade of ground, granulated blast furnace (GGBF) slag. The heat of hydration of grade 100 GGBF slag is typically 80 percent.

Initial Temperature. As mentioned previously, multiple strategies can be employed during construction to reduce the initial temperature heat. A common practice is to conduct paving only at night and/or to use pre-cooled materials in the batch. Pre-cooling can be achieved by shading and wetting the aggre-

Table 5-3. Chemical Composition and Heat Evolution of Typical Portland Cements

Cement type		Potential phase composition*, % C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Blaine fineness, m^2/kg
Type I	Range	45–65	6–21	6–12	6–11	333–431
	Mean	57	15	9	8	384
Type II	Range	48–68	8–25	4–8	8–13	305–461
	Mean	56	17	7	10	377
Type III	Range	48–66	8–27	2–12	4–13	387–711
	Mean	56	16	8	9	556
Type V	Range	47–64	12–27	0–5	10–18	312–541
	Mean	58	18	4	12	389
Heat evolution**, kJ/kg		a	b	c	d	
(kilojoules/kg)	3 d	243	50	887	289	
	7 d	222	42	1556	494	
	13 yr	510	247	1356	427	

* Source: Tennis and Bhatty (2006)
** Cement paste with water/cement ratio 0.4 at 21˚C (70˚F).
Values represent coefficients in the equation:
Heat evolution (kJ/kg) = $a(C_3S) + b(C_2S) + c(C_3A) + d(C_4AF)$ (Taylor 1997)

gates and using chilled water or ice in the mixture. A white-pigmented curing compound should always be applied immediately after final finishing while the surface is still damp to alleviate evaporation and reduce heat buildup from solar radiation (Kosmatka et al. 2003).

Environmental Factors. The rate of heat loss to the environment is influenced by the thickness of the concrete, the temperature of the environment, and the degree of insulation provided by the materials surrounding the concrete. Thinner concrete sections will not get as hot as thicker sections.

In cold-weather concreting, the challenge is to maintain the concrete temperature to prevent freezing while the concrete gains strength. Strategies that may be employed include heating one or more of the materials, warming the jobsite environment, and/or covering the slab with insulation to hold in the heat produced as the cement hydrates.

Thermal Expansion/Contraction. Thermal expansion and contraction of concrete (that is, expansion and contraction related to temperature change) vary with factors such as aggregate type, cement content, water-cementitious materials ratio, temperature range, concrete age, and relative humidity. Of these, aggregate type has the greatest influence, as aggregates account for about 60 to 75 percent of concrete by volume.

A material's coefficient of thermal expansion (CTE) is a measure of how much it changes in length (or volume) for a given change in temperature. Typically, an increase in temperature will result in lengthening (expansion) and a decrease will result in shortening (contraction). Because aggregates make up a majority of a concrete's volume, the CTE of the aggregate particles will dominate the CTE for a concrete. Table 3-12 in chapter 3, page 48, shows some typical values of the linear CTE of several aggregates, as well as those for concrete and other concrete ingredients. Typically, limestone aggregates have lower coefficients than siliceous aggregates, and concretes made with them have lower values. CTE values are considered in design calculations for pavements and are used in durability modeling of concretes.

An average value for the CTE of concrete is about 10×10^{-6}/°C (5.5×10^{-6}/°F), although values ranging from 6 to 13 × 10^{-6}/°C (3.2 to 7.0 × 10^{-6}/°F) have been observed. In practical terms, this amounts to a length change of around 5 mm for 10 m of concrete (2/3 in, for 100 ft of concrete) subjected to a rise or fall of 50°C (90°F). Temperature changes may be caused by environmental conditions or by the heat of hydration.

Testing for Thermal Properties

If specific information is needed about the actual heat of hydration of the cementitious materials, the heat of hydration should be measured. Testing should be conducted using the proportions that will be used in the concrete mix, rather than using the individual components.

The heat of hydration can be measured in accordance with ASTM C 186 or in a conduction calorimeter. Heat evolution of the concrete can also be measured directly by a calibrated calorimeter. Several such instruments are commercially available. They consist of a calibrated insulated container that measures the heat flow out of a cylinder of fresh concrete.

The adiabatic (without loss or gain of heat from the surroundings) temperature rise of the concrete can be measured directly by Army Corps Method CRD-C 38 (figure 5-12). It should be noted that the actual temperature rise of a concrete pavement is only a fraction of that of the adiabatic temperature rise because the

Figure 5-12. A typical field semi-adiabatic temperature monitoring system for mortar (W.R. Grace & Company)

large surface-to-volume ratio of a pavement allows heat to escape almost as rapidly as it is generated.

Pavement temperatures and the associated risk of cracking can be estimated with finite element software or by the Schmidt method (a finite difference method) described in ACI 207. FHWA's HIPERPAV software (www.hiperpav.com) is a helpful analysis tool to determine early-age properties and the potential for cracking. Pavement temperatures measured with embedded sensors (ASTM C 1064 / AASHTO T 309-99) and environmental conditions monitored with aportable weather station (see Concrete Temperature, Subgrade Temperature, and Project Environmental Conditions in chaper 9, page 260) are HIPERPAV data inputs.

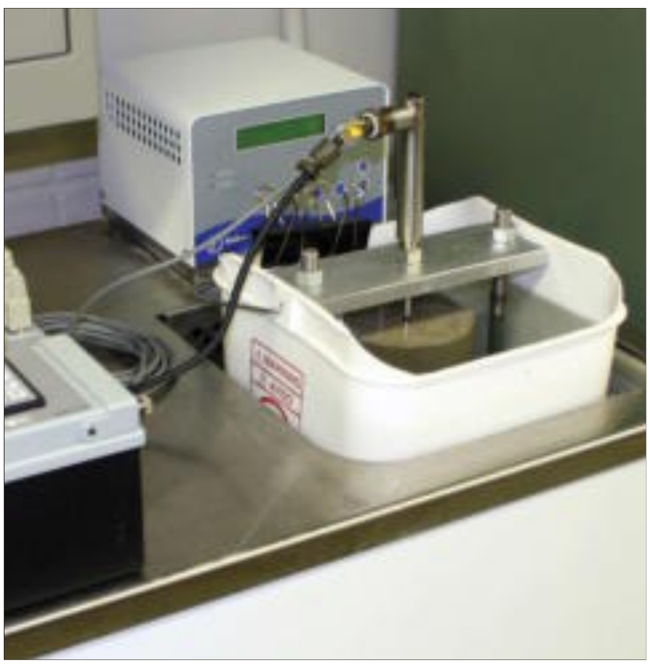


Figure 5-13. Measuring the coefficient of thermal expansion

Coefficient of thermal expansion can be measured using the method described in AASHTO TP 60 (figure 5-13) (see Coefficient of Thermal Expansion in chapter 9, page 269). The test involves measuring the length change of a specimen observed due to a change in temperature of 40°C (72°F) controlled using a water bath.

Concrete Durability is Affected by Many Concrete Properties

The rest of this chapter discusses concrete properties that can affect concrete durability.

Durability is the ability of concrete to resist chemical attack while in service. It is a critical characteristic of long-life pavements but, in itself, is not generally considered a property of concrete.

Durability is environment-specific; that is, a concrete pavement that is durable in a snow environment is probably not going to be durable in the desert. Therefore, concrete properties that contribute to durable concrete may include any (but not necessarily all) of the following:

- Low permeability.
- Frost resistance.
- Sulfate resistance.
- Low alkali-silica sensitivity.
- Abrasion resistance.

Cracking also affects concrete permeability. Note, however, that concrete strength is not necessarily a good measure of potential durability.

Permeability

Key Points

- Concrete durability is improved by improving concrete's ability to prevent fluids from penetrating, that is, by reducing concrete permeability.
- Permeability is reduced by reducing cracking, reducing the number of connected pores in the paste system, and improving the interface between the paste and aggregate.
- Therefore, permeability can be reduced by reducing the water-cementitious materials ratio, increasing the degree of hydration, using supplementary cementitious materials, and using good curing practices.
- Strength is not necessarily a good measure of potential permeability.
- Testing specifications include ASTM C 1202 / AASHTO T 277, AASHTO TP 64, ASTM C 1543 and 1556, and ASTM C 1585.

Simple Definition

Permeability is the ease with which fluids can penetrate concrete. (Permeability is different from porosity, which is a measure of the number of [possibly disconnected] voids in concrete.)

Significance

Almost all durability-related distresses in pavements can be slowed or stopped by reducing the concrete's permeability. This is because most durability-related distress mechanisms involve the transport of harmful substances into the concrete:

- Water that expands on freezing, leaches calcium hydroxide, and/or carries dissolved ions that attack the concrete.
- Salts that crystallize on wetting and drying or exert osmotic pressure during freezing and thawing, causing surface damage.
- Alkalis that release hydroxyls that react with alkali-reactive aggregates.
- Sulfates that attack the aluminate compounds.
- Carbon dioxide that reduces the alkalinity (pH).
- Oxygen and moisture that contribute to the corrosion of steel bars or reinforcement.
- Chlorides that promote corrosion of steel bars.

Factors Affecting Permeability

Permeability is primarily controlled by the paste system in concrete and the quality of the interfacial zone between the paste and the aggregate. If there are a large number of pores and they are connected (percolated), then the concrete will be permeable. Reducing the porosity and the likelihood that pores will be connected is key to achieving low permeability (Detwiler 2005). The following activities will help:

- Reducing the water-cementitious materials ratio as low as is consistent with other requirements of the concrete, including cracking.
- Using appropriate supplementary cementitious materials for the environment.
- Ensuring adequate consolidation and curing.
- Minimizing cracking.

Testing

Some specifications use compressive strength as an indicator of low permeability. This approach is not always valid, which is why tests are being developed to directly assess concrete permeability.

The so-called "rapid chloride" test (ASTM C 1202 / AASHTO T 277) is most commonly used (see Chloride Ion Penetration in chapter 9, page 268). However, the test does not measure permeability directly but measures conductivity, which may or may not be related to permeability. The data can be used for comparison purposes between concrete mixtures.

AASHTO TP 64 is an alternative method to assess the rate of chloride penetration into concrete. ASTM C 1543 and 1556 are two new ponding tests useful in determining the chloride resistance of concrete. Another new method, ASTM C 1585, determines the capillary absorption of concrete and offers a useful tool for assessing the relative performance of different concrete systems.

Frost Resistance

Key Points

- Problems related to low frost resistance include freeze-thaw damage, salt scaling, D-cracking, and popouts.
- Concrete frost resistance can be improved through several good practices:
  - Maintaining a proper air-void system to provide space for freezing and expanding water to move into.
  - Attaining adequate strength.
  - Using sound aggregate.
  - Paying careful attention to good mixing, placement, and curing practices.
  - Protecting concrete so that it gains sufficient strength and dries before it is exposed to freezing temperatures or deicing salts.
- Specifications include the following:
  - Aggregates: ASTM C 666 / AASHTO T 161, ASTM C 88 / AASHTO T 104, Iowa Pore Index Test.
  - Air-void system: ASTM C 231 / AASHTO T 152, ASTM C 173 / AASHTO T 196, ASTM C 138 / AASHTO T 121, ASTM C 457.
  - Freeze-thaw: ASTM C 666.
  - Salt scaling: ASTM C 672.

Simple Definition

Frost resistance is a concrete's ability to resist damage during winter weather conditions.

Significance

Concrete that is exposed to cold weather can experience several kinds of damage: freeze-thaw damage, salt scaling, D-cracking, or popouts.

- Freeze-thaw damage is due to the expansion of water in the capillaries as it freezes, causing cracking that can be as deep as several inches into the concrete. Cycles of freezing and thawing can eventually cause severe surface loss (figure 5-14).
- Deicing salts can aggravate freeze-thaw damage and cause cracking, scaling, and disintegration.
- When aggregates with a critical pore size are saturated, they expand and fracture when the water freezes, causing D-cracking and/or popouts.

Freezing and Thawing Damage

Water expands about nine percent when it freezes. If the capillaries and voids in a concrete are saturated (filled with water), this expansion can set up pressures greater than the strength of the concrete (Newlon and Mitchell 1994; Janssen and Snyder 1994; Cordon 1966), and the concrete will crack, increasing concrete permeability.

For resistance to freezing and thawing damage, water-saturated concretes must have a proper air-void system, sound aggregates, and a strength of at least 28 MPa (4,000 lb/in^2) to be able to resist the stresses that are set up. Concrete that will be exposed to freezing conditions should be allowed to dry before it is exposed to the first freeze, thus reducing the degree of saturation (Verbeck and Klieger 1957).

Figure 5-14. Air-entrained concrete (bottom bar) is highly resistant to damage from repeated freeze-thaw cycles. (PCA)

Salt Scaling

Scaling (figure 5-15) is a physical deterioration mechanism aggravated by the use of deicing salts and freezing and thawing. Salts that are used to melt snow and ice go into solution and penetrate concrete's pore structure, aggravating hydraulic pressures when the solution freezes. In addition, as the water freezes to ice, the salts are concentrated at the freezing site. Unfrozen water migrates toward the site due to osmosis (the tendency for imbalances in salt concentrations to seek balance). These osmotic pressures also cause cracking, scaling, and disintegration.

In addition to hydraulic and osmotic pressures, which are the primary cause of deicer scaling, salts may also crystallize upon drying, creating expansive pressures.

Research has shown that relatively low concentrations of sodium chloride (two to four percent) cause greater damage than greater concentrations of sodium chloride (Klieger 1957).

The best way to control deicer scaling is to ensure that the concrete has a proper air-void system, sound aggregates, and a strength of at least 28 MPa (4,000 lb/in^2), and has been allowed to dry before it is exposed to deicing salt.

Figure 5-15. Scaled concrete surface resulting from lack of air entrainment, use of deicers, and poor finishing and curing practices (PCA)

D-Cracking

D-cracking is damage that occurs in concrete due to expansive freezing of water in some aggregate particles (see Aggregate Durability in chapter 3, page 47). The damage normally starts near joints to form a characteristic D-shaped crack (see chapter 3, figure 3-11, page 48).

This problem can be reduced either by selecting aggregates that are less susceptible to freeze-thaw deterioration or, where marginal aggregates must be used, by reducing the maximum aggregate size. Also, providing drainage for carrying water away from the base may prevent saturation of the pavement.

Popouts

A popout is a conical fragment that breaks out of the surface of concrete, leaving a shallow, typically conical, depression (see chapter 3, figure 3-12, page 48). Generally, a fractured aggregate particle will be found at the bottom of the hole. Unless numerous, popouts are considered a cosmetic detraction and do not generally affect the service life of the concrete.

Aggregates containing appreciable amounts of shale or other shaly rocks, soft and porous materials (clay lumps for example), and certain types of chert have low resistance to weathering and should be avoided (see Aggregate Durability in chapter 3, page 47). Weak, porous particles in the aggregate can be reduced by various methods of aggregate beneficiation such as jigging, heavy-media separation, or belt picking.

Factors Affecting Frost Resistance

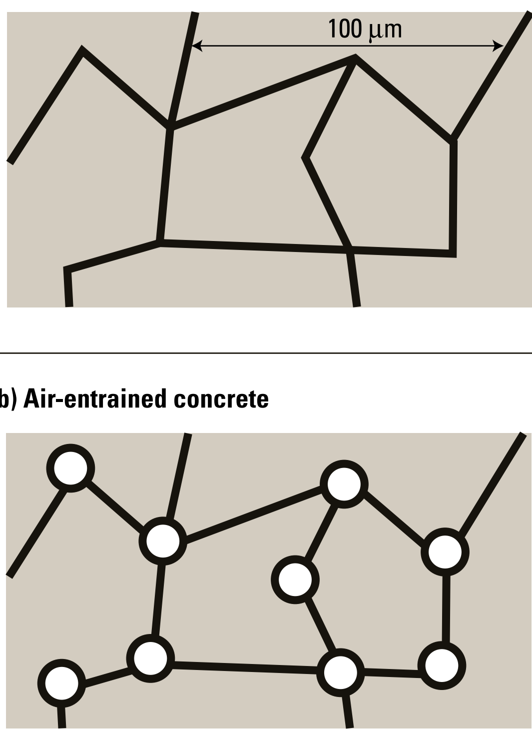
Many factors influence the resistance of concrete to frost-related damage, each of which is discussed briefly below. The most important means of preventing damage in critically saturated concrete is to ensure that it has an adequate air-void system and adequate strength to resist the stresses. Some high-strength mixtures may not need as much (or any) air to be frost resistant, but the addition of air will provide additional protection for relatively little cost.

Air-Void System

Concrete's susceptibility to freeze-thaw damage may be reduced by entraining a number of small, closely spaced air bubbles in the paste (see Function of Air Entrainment in Concrete in chapter 3, page 56). The air voids provide space for freezing, expanding water in the pores to move into, thus relieving the pressure (Mielenz et al. 1958). A proper air-void system contains small air bubbles uniformly dispersed throughout the cement paste (figure 5-16).

Powers (1949) introduced the concept of a spacing factor, which indicates the distance water must travel to reach an air void. It is generally accepted that a spacing factor of 0.20 mm (0.008 in.) or less will be adequate to protect concrete (Mielenz et al. 1958; ACI 201.2R 2001; ACI 318 2002). Increasing the total air content will reduce the spacing factor, which is why many specifications place a limit on the minimum amount of air in a mixture. For a given air content, small, closely spaced air voids provide better protection than larger, more distant voids (Klieger 1994). For equal protection, larger bubbles would require a larger volume of air. This is undesirable,

a) Non-air-entrained concrete



b) Air-entrained concrete

Figure 5-16. Air voids provide a place for expanding water to move into as it freezes. (CTLGroup)

since an increase in air content can result in a decrease in strength. Optimally, the air content of the mortar should be about nine percent.

The amount of air, as well as the size and spacing of the voids, are influenced by the following factors (Whiting and Nagi 1998):

Type and Dosage of Air Entrainer. Newer, non-vinsol admixtures produce smaller air bubbles than older products. Air-entraining admixtures are also available formulated specifically for low slump mixtures like those used for paving. Increasing the dosage will increase the total air content of a mixture.

Grading and Amount of Aggregate. Air is most easily entrained in concrete that contains increasing amounts of sand in the 150 to 600 µm (#100 to #30 sieve) range. Increasing the total aggregate in the concrete means that there is less paste that has to be protected with entrained air.

Chemical Composition of the Cementitious Materials. More alkalis in the cement will result in more entrained air. High loss-on-ignition (LOI) fly ash (that is, loss of mass when heated to 1,000°C [1,830°F]) will require greater dosages of admixture to achieve the same air content. Variable LOI in a fly ash source may cause large jumps in the concrete air content. Such a fly ash should be monitored using the foam index test with every delivery to prevent problems in the batch plant.

Fineness and Amount of Cementitious Materials. Mixtures with finer cement and increasing cement content will require a higher dosage of admixture to achieve the same air content.

Chemical Characteristics of Water; Water-Reducing or Retarding Admixtures. Other admixtures may interfere with the air-entraining admixture. Possible incompatibilities should be evaluated in trial batches early in the selection of materials and proportions.

Water-Cementitious Materials (W/CM) Ratio and Slump of the Concrete. A higher w/cm ratio means that there is more free water in the mixture, which assists air entrainment. It is easier to entrain air in a high slump mixture than in a low slump mixture.

Type of Plant and Production Procedures. This includes the sequence of materials addition, mixer capacity, and mixing time and speed. The later the air-entraining admixture is added to the mixture, the less entrained air there will be. Depending on the type of mixture, the nominal suggested mix time is approximately 60 seconds (Cable and McDaniel 1998). Some mixtures lose air during transport from the plant to the site and during placement. Therefore, it is recommended that air be checked before and after placement to ensure that the target air content is met.

Temperature of the Concrete; Construction Practices. These include transport, delivery, and retempering; and placement, consolidation, and finishing. Higher temperatures require more air-entraining admixture to achieve the same air content. Late addition of water to a mix will cause the air content to increase and possibly exacerbate air-void clustering. Handling of the concrete after initial mixing will tend to reduce the air content.

Strength

According to ACI 201.2R, dry, air-entrained concrete needs a compressive strength of 3.5 MPa (500 lb/in^2) to withstand the effects of freezing. For repeated cycles of freezing and thawing under saturated conditions, a minimum strength of 28 MPa (4,000 lb/in^2) is recommended.

Aggregates

Aggregates should be selected that are resistant to freeze-thaw damage. This can be determined from records of the performance of the aggregate in the past or by testing, as discussed below. If damage-prone aggregate has to be used, the smallest possible size should be used, and preferably it should be diluted with sound materials.

Cementitious Materials

A moderate amount of cementitious material is needed to achieve the strengths discussed above. A minimum of 335 kg/m^3 (564 lb/yd^3) is recommended (Kosmatka et al. 2002) unless testing and field experience indicate otherwise. Scaling resistance may be reduced with increasing amounts of supplementary cementitious materials (SCMs); however, concrete containing SCMs can be expected to exhibit good scaling resistance if the concrete is properly designed, placed, and cured. ACI 318 limits the amount of pozzolans or ground, granulated blast-furnace slag (maximum 25 percent fly ash, 50 percent slag, and 10 percent silica fume) in concrete to minimize deicer scaling. Higher dosages of SCMs can be used if adequate durability is demonstrated by testing and/or field performance.

Finishing

In general, concrete surfaces should be finished after the disappearance of the bleed water (Kosmatka 1994). Working bleed water into concrete weakens the top surface and can cause a crust to form with water accumulation underneath, which could easily scale off. Over-finishing should be avoided because it may cause loss of air at the surface.

Curing

Good curing practices ensure that hydration reactions progress and that cracking is minimized, enabling the desired properties and performance (ACI 308R). Liquid-membrane curing compounds are widely and successfully used on pavements, provided that the proper curing material is applied in the right amount as the water sheen disappears. In cold weather, insulating blankets, multiple layers of burlap or straw can be used to maintain the favorable temperature for hydration and to minimize temperature differentials.

Testing

D-Cracking

The performance of aggregates under exposure to freezing and thawing can be evaluated in two ways: past performance in the field and laboratory freeze-thaw tests of concrete specimens. If aggregates from the same source have previously given satisfactory service when used in concrete under similar conditions, they generally may be considered acceptable.

Aggregates not having a service record can be tested in freezing and thawing tests, such as ASTM C 666 / AASHTO T 161. In these tests, air-entrained concrete specimens made with the aggregate in question are alternately frozen and thawed in water (procedure A) or frozen in air and thawed in water (procedure B). Deterioration is measured by (1) the reduction in the dynamic modulus of elasticity, (2) linear expansion, and (3) weight loss of the specimens. An expansion failure criterion of 0.035 percent in 350 freeze-thaw cycles or less is used by a number of State departments of transportation to help indicate whether an aggregate is susceptible to D-cracking. Different aggregate types may require different criteria (Vogler and Grove 1989).

An additional test that evaluates aggregates for potential D-cracking is the rapid pressure release method. An aggregate sample is placed in a pressurized chamber. The pressure is rapidly released, causing aggregates with questionable pore systems to fracture (Janssen and Snyder 1994). The amount of fracturing relates to the potential for D-cracking.

Another test for determining the freeze-thaw potential of carbonate aggregates is the Iowa pore index test. The apparatus measures the large or primary pores and the secondary or capillary pore system. Aggregates with large primary pores correlate to good durability, while those with large secondary pores correlate to poor durability. Studies that correlate pore index results with durability tests indicate that the Iowa pore index test can quickly and accurately determine aggregate durability.

Specifications may require that resistance to weathering, or freeze-thaw durability, be demonstrated by a sodium sulfate or magnesium sulfate test, ASTM C 88 / AASHTO T 104. This test consists of immersing a sample of the aggregate in a sulfate solution for a number of cycles. Pressure is created through salt crystal growth in the aggregate pores similar to that produced by freezing water. The sample is then oven dried, and the percentage of weight loss is calculated. Unfortunately, this test is sometimes misleading, due at least in part to the fact that the mechanisms of attack are not the same as in freezing and thawing in concrete.

Air-Void System

The most common test procedure to determine the air content is the pressure method, ASTM C 231 / AASHTO T 152 (see Air Content [Plastic Concrete, Pressure Method] in chapter 9, page 266). Air in the fresh concrete and the aggregates is measured. It is applicable to dense, normal-weight aggregates with the appropriate aggregate correction factor. Another test method applicable to dense, cellular, or lightweight aggregate is the volumetric method (Rollameter), ASTM C 173 / AASHTO T 196. The volumetric method takes longer to complete and is more physically demanding; therefore, it is not widely used for concrete with normal-weight aggregates. The air content of the freshly mixed concrete can also be determined by the gravimetric method, ASTM C 138 / AASHTO T 121.

These methods determine the total air content. However, for satisfactory frost resistance, an air-void system with closely spaced small bubbles is needed. The average size of the bubbles and their spacing is characterized by the specific surface and the spacing factor. These parameters must be determined on hardened concrete (ASTM C 457), although the air-void analyzer shows promise in determining spacing factors for fresh concrete.

The gravimetric method for determining unit weight (ASTM C 138 / AASHTO T 121) also gives an indication of air content, provided the specific gravities of other ingredients are known. The method is especially helpful for determining when something has gone wrong with the air system, because significant changes in the unit weight would signal a change in the mixture's air content.

The air-void analyzer (AVA) (figure 5-17) was developed in Europe in the late 1980s. It measures the size and spacing of entrained air bubbles in fresh concrete. The AVA has the advantage of providing the air-void parameters of fresh concrete in less than 30 minutes, so that adjustments can be made during construction (see Air-Void Analyzer in chapter 9, page 265).

With the AVA, a mortar sample containing air voids is introduced into a liquid of a certain viscosity and placed at the bottom of a riser column filled with water. Immediately after injection, a magnetic stirring rod breaks up the mortar sample, releasing air bubbles into the analysis liquid. The proper selection of the liquid enables the air voids to retain their quantity and size during the transfer. Air voids rise in the column to the surface, according to Stokes' law. The large bubbles rise faster than the small bubbles. The air bubbles rising in the liquid are collected under a bowl attached to a balance. The buoyancy of the bowl is recorded over time, from which the air content, specific surface, and spacing factor of freshly mixed concrete are determined.

Since the entrapped air voids are not measured, AVA air content is approximately 1.5 to 2 percent less than the air content as determined by the pressure meter and by ASTM C 457. The spacing factor is about the same for AVA and ASTM C 457 (Magura 1996). An AVA is sensitive to vibration and uses a small sample; therefore, it should be used with care.

The air content of concrete is generally measured before it reaches the paver. However, measurement of the air-void system after placement and vibration would provide more useful information. Some reduction in air is expected as it is vibrated; however, this loss does not necessarily imply that freeze-thaw protection is compromised.

ASTM C 457 has two microscopical procedures for determining the air-void parameters in lapped sections of hardened concrete samples: the linear traverse method and the modified point count method, the former being the most widely used (see Air Content [Hardened Concrete] in chapter 9, page 267). Some States are using image analysis techniques to determine air content of lapped sections of hardened concrete samples; see, for example, the Portland Cement Association's CT021. There is, as yet, no standard method for such an approach.

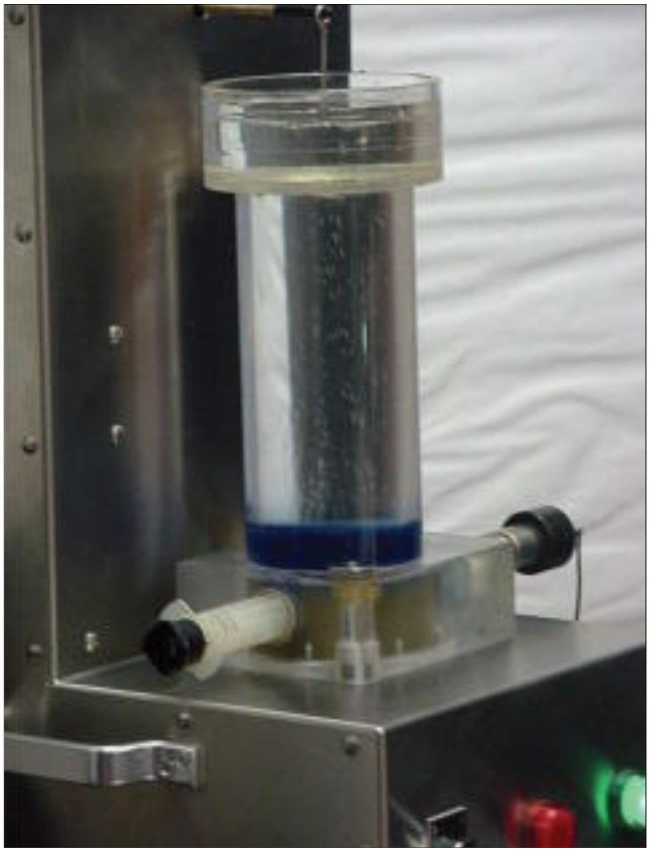


Figure 5-17. Air bubbles rising in the AVA (FHWA)

Rapid Freezing and Thawing

Resistance to freezing and thawing of a concrete is normally determined using the procedures (A or B) described in ASTM C 666. Procedure A involves rapid freezing and thawing of samples of concrete in water. Procedure B requires rapid freezing in air and thawing in water.

The fundamental transverse frequency of the samples is measured periodically and used to determine the relative dynamic modulus of elasticity, from which a durability factor is calculated (ASTM C 666). As damage increases in the sample, the dynamic modulus will decrease. For adequate performance, specimens tested to 300 cycles are expected to exhibit a durability factor of 60 or more. Length change and mass loss can also be monitored.

Procedure A is the more severe test. Concretes performing well in this test have done well in field applications. Concretes failing the test may also have satisfactory field performance, but such performance must be proven in the field. Procedure B is not as severe as procedure A, since the specimens are allowed to dry during testing.

In Virginia, ASTM C 666 procedure A is conducted with specimens immersed in two percent NaCl solution (Newlon 1978). Prior to exposure, specimens are moist-cured for 14 days and air-dried for 7 days.

Salt Scaling

Resistance to salt scaling is determined using the ASTM C 672 test. Specimens are moist-cured for 14 days and air-dried for an additional 14 days. A dike is placed around the top surface of the specimens, and the surface of the concrete is covered with four percent calcium chloride solution. The specimens are placed in a freezing environment for 16 to 18 hours, then thawed in laboratory air for 6 to 8 hours. The surface is flushed at the end of each five cycles and a visual examination is made. The solution is replaced and the test repeated for 50 cycles. Concretes with a rating of three or less are considered satisfactory. (A rating of three indicates moderate scaling with some coarse aggregate showing.) Some States also monitor the mass loss of the samples and require a value of less than 0.3 lb/ft^2 after 50 cycles.

This test is also considered to be severe, with concretes performing satisfactorily in the field despite failing ASTM C 672. The Bureau De Normalisation du Québec has published an alternative method that is reportedly less severe (BNQ NQ 2621-900). This method sets out slightly different finishing and curing requirements for the samples.

Sulfate Resistance

Key Points

- Sulfates damage concrete by reacting with products of hydrated tricalcium aluminate (C_3A) in hardened cement paste and by infiltrating and depositing salts. The resulting expansive crystals damage the cement paste, causing cracking.
- Sulfate problems are more severe where concrete is exposed to wet and dry cycles than where it is continuously wet.
- Concrete can be designed to resist sulfate attack:
  - Achieve low permeability (see Permeability in this chapter, page 131).
  - Use a mixture with a low water-cementitious materials ratio, sulfate resistant cements, and proper proportions of suitable supplementary cementitious materials.
- Testing specifications: ASTM C 452 and ASTM C 1012.

Simple Definition

Sulfate resistance is concrete's ability to resist attack by, and damage from, sulfates penetrating from outside the concrete system.

Significance

Excessive amounts of sulfates in soil or water can, over a period of years, attack and destroy concrete pavements and other structures (figure 5-18).

Sulfates damage concrete by reacting with hydrated tricalcium aluminate (C_3A) compounds in the hardened cement paste and by infiltrating and depositing salts. Due to crystal growth pressure, these expansive reactions can disrupt the cement paste, resulting in cracking and disintegration of the concrete.

Preventive measures are well accepted, and concrete can be designed to resist sulfate attack. This is done primarily by reducing permeability and reducing the amount of reactive elements in the concrete system needed for expansive sulfate reactions.

Factors Affecting Sulfate Attack

Prevention of sulfate attack depends on protecting the concrete from infiltration by sulfate ions. For the best defense against external sulfate attack, consider the following:

- Design concrete with a low water-cementitious materials (w/cm) ratio (around 0.4 or lower).
- Use cements specially formulated for sulfate environments, such as ASTM C 150 / AASHTO M 85 Type II or V cements, ASTM C 595 / AASHTO M 240 moderate sulfate-resistant cements, or ASTM C 1157 Types MS or HS.

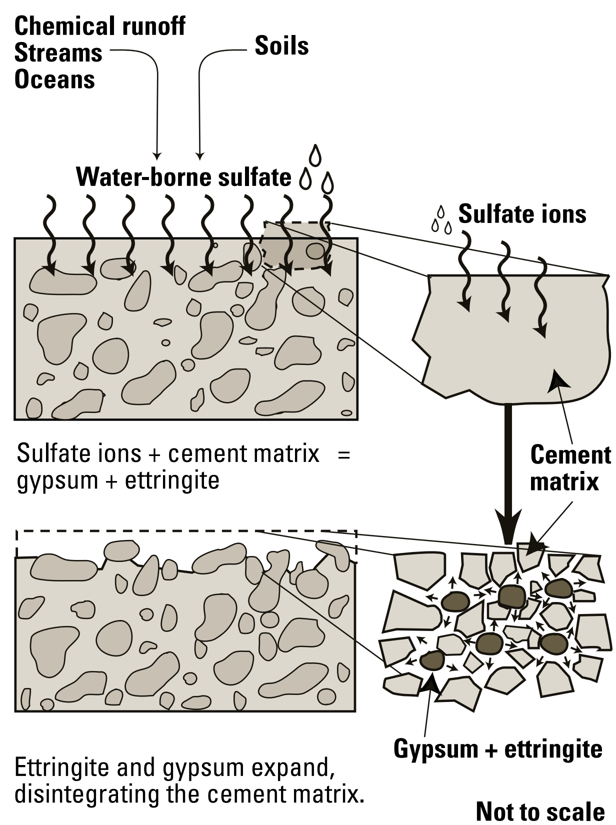


Figure 5-18. Sulfate attack is a chemical reaction between sulfates and the calcium aluminate (C_3A) in cement, resulting in surface softening. (Emmons 1994)

Note that, although the use of sulfate-resistant cements is beneficial, it may not be sufficient to protect concrete against sulfate attack. Table 5-4 provides recommendations for concrete in various sulfate exposures. It is important to use the test method described in the table to assess the sulfate content to prevent misleading data.

- Use supplementary cementitious materials (SCMs) with proper proportioning and material selection. SCMs improve sulfate resistance by reducing permeability of the concrete and by diluting the C_3A content of the system. Concretes with Class F ashes are generally more sulfate resistant than those made with Class C ashes. Some Class C ashes have been shown to reduce sulfate resistance at normal dosage rates.
- Specify a minimum cementitious materials content (hydraulic cement plus SCM) of 335 kg/m^3 (564 lb/yd^3) and only enough mixing water to achieve the desired consistency without exceeding the maximum w/cm ratio shown in table 5-4. The maximum w/cm ratio should not exceed 0.40 and may need to be lower in more severe sulfate exposures.
- Extend wet curing to increase concrete's strength development and decrease its permeability, thus improving its sulfate resistance.

Sulfate attack is more severe at locations where the concrete is exposed to wetting and drying cycles than at locations where there is continuously wet exposure due to salt deposition. However, if the sulfate exposure is severe enough, even continuously moist sections can be attacked by sulfates with time.

Testing

Tests on the sulfate resistance of cements are usually performed on mortars: ASTM C 452 is used for portland cement and ASTM C 1012 is used for hydraulic cements, including blended cements.

There are currently no well-accepted tests for sulfate resistance of concrete in the United States. Most laboratory investigations use concrete prisms immersed in sulfate solutions and try various methods to evaluate damage. More severe tests incorporate a wetting/drying regime into the testing.

Table 5-4. Requirements for Concrete Exposed to Sulfates in Soil or Water

Sulfate exposure	Sulfate (SO_4) in soil, % by mass*	Sulfate (SO_4) in water ppm*	Cement type **	Maximum w/c ratio, by mass	Minimum strength f' MPa (lb/in^2)
Negligible	Less than 0.10	Less than 150	No special type required	_	_
Moderate***	0.10 to 0.20	150 to 1,500	II, MS, IP(MS), IS(MS), P(MS), I(PM)(MS) , I(SM)(MS)	0.50	28 (4,000)
Severe	0.20 to 2.00	1,500 to 10,000	V, HS	0.45	31 (4,500)
Very severe	Over 2.00	Over 10,000	V, HS	0.40	35 (5,000)

Source: Adapted from ACI 318 (2002)

* Tested in accordance with ASTM 1580, the method for determining the quantity of soluble sulfate in solid (soil and rock) and water samples, Denver, Colorado, 1977.

** Cement types II and V are in ASTM C 150 / AASHTO M 85, types MS and HS are in ASTM C 1157, and the remaining types are in ASTM C 595 / AASHTO M 240. Pozzolans or GGBF slags that have been determined by test or service record to improve sulfate resistance may also be used.

*** Sea water.

Alkali-Silica Reaction

Key Points

- The presence of alkali-silica reaction (ASR) gel does not always coincide with concrete distress.
- Damaging expansion and cracking due to ASR can be controlled in several ways:
    - Using nonreactive aggregates.
    - Blending sufficient nonreactive aggregate with reactive aggregate.
    - Using supplementary cementitious materials in proper proportions.
    - Using low-alkali cements.
    - Using blended cements.
    - Using lithium compounds.
- Testing specifications:
    - Aggregates and concrete: See table 5-5 on page 144.
    - Mitigation measures: ASTM C 1293, ASTM C 1567, ASTM C 441

Simple Definition

Alkali-silica reaction (ASR) is a potentially harmful condition in concrete resulting from a chemical reaction between some aggregate minerals (see Aggregate Durability and Alkali-Silica Reactivity in chapter 3, pages 47 and 48, including tables 3-12 and 3-13) and the high alkaline (pH) pore solutions found in concrete. Over time, the product of these chemical reactions, a gelatinous alkali-silicate referred to as ASR gel, can absorb water and expand, leading to concrete cracking and reduced service life (figure 5-19).

Significance

The amount of gel formed in the concrete depends on the amount and type of silica in the aggregate and the alkali hydroxide concentration in the concrete pore solution. The presence of gel does not always coincide with distress. The reactivity is potentially harmful only when it produces significant expansion. For more information, see Farny and Kosmatka (1997) and Folliard, Thomas, and Kurtis (2003).

Typical indicators of deleterious ASR include a network of cracks that are perpendicular to joints, closed or spalled joints, or relative displacements of adjacent slabs. Because ASR is slow, deterioration often takes

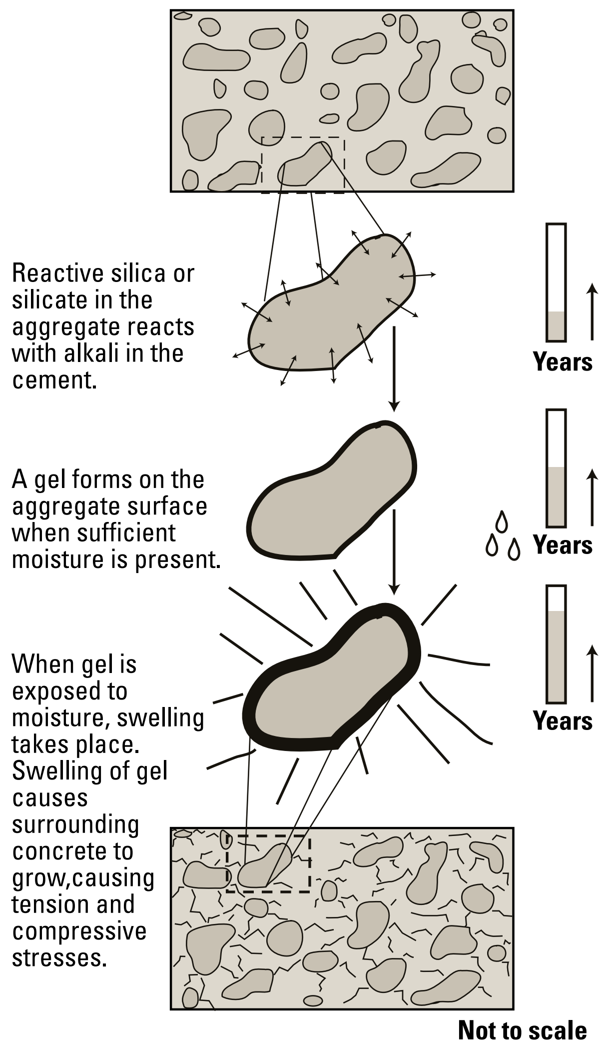


Figure 5-19. Alkali-silica reaction is an expansive reaction of reactive aggregates, alkali hydroxides, and water that may cause cracking in concrete. (Emmons 1994)

several years to develop. Alkali-silica reactions can cause serviceability problems and can exacerbate other deterioration mechanisms, such as those that occur in frost, deicer, or sulfate exposures.

For most reactive aggregates, the reaction can be mitigated or controlled through proper concrete materials selection or other means. In fact, even though potentially reactive aggregates exist throughout North America, ASR distress in concrete is no longer a common problem. There are a number of reasons for this:

- Many aggregates are not reactive.
- Known reactive aggregates are avoided.
- Some forms of ASR do not produce significant deleterious expansion.
- The appropriate use of certain pozzolans or slags controls ASR.
- In many concrete mixtures, the alkali content of the concrete is low enough to limit the reaction.
- The concrete in service is dry enough to limit the reaction.

Factors Affecting Alkali-Silica Reaction

For ASR to occur, three conditions must be present:

1. Reactive forms of silica in the aggregate.
2. High-alkali (pH) pore solution (water in the paste pores).
3. Sufficient moisture.

If any one of these conditions is absent, ASR gel cannot form and deleterious expansion from ASR cannot occur. Therefore, the best way to avoid ASR is through good mix design and materials selection.

Design mixes specifically to control ASR, preferably using locally available materials. Use nonreactive aggregates, if possible, or a mix of nonreactive and active aggregate (see tables 3-12 and 3-13 in chapter 3, pages 48 and 49, respectively).

If you must use some reactive aggregate, use supplementary cementitious materials or blended cements proven by testing to control ASR or limit the alkali content of the concrete. Where applicable, different amounts of pozzolan or slag should be tested to determine the optimum dosage. Too low a dosage of fly ash may exacerbate the problem. Low-calcium (typically Class F) fly ashes are generally better at mitigating ASR than high-calcium (typically Class C) fly ashes. Ground, granulated blast-furnace slag and natural pozzolans also generally effective in mitigating ASR when used in the proper dosages. Expansion usually decreases as the dosage of the pozzolan or slag increases.

Using portland cement with an alkali content of not more than 0.60 percent (equivalent sodium oxide) can often (but not always) control ASR. Its use has been successful with slightly reactive to moderately reactive aggregates. However, low-alkali cements are not available in all areas and are not effective against all reactive aggregates.

Lithium compounds may also be useful in reducing or preventing expansion (Folliard, Thomas, and Kurtis 2003). Typically, a solution of lithium-bearing compound (usually lithium nitrate) is added when batching concrete. Caution is warranted, as this technology is new and field performance data are still being evaluated. An additional concern is that no standardized test method is able to evaluate the ability of lithium compounds to prevent ASR, although guidance has been provided by Folliard, Thomas, and Kurtis (2003) in using ASTM C 1293 and a version of ASTM C 1260, in which lithium is added to the storage solution.

Testing

Aggregate should be evaluated for its susceptibility to ASR. When ASR-susceptible aggregates must be used, mitigation measures should be evaluated. There are also test for hardened concrete to determine whether ASR is a cause of distress in concrete. See table 5-5.

Aggregate Testing

Field performance history is the best method of evaluating the susceptibility of an aggregate to ASR. For the most definitive evaluation, the existing concrete must have been in service for at least 15 years. Comparisons should be made between the existing and proposed concretes for mixture proportions, ingredients, and service environments. This process will indicate whether special requirements or testing of the aggregate is needed. The use of quick methods provides for initial screening. Where uncertainties arise, lengthier tests can be used to confirm results. If the aggregate is not reactive by historical identification or testing, no special requirements are needed.

ASTM C 295 (petrographic analysis) and ASTM C 1260 (accelerated mortar-bar test, similar to AASHTO T 303) are the quickest indicators of the potential reactivity of an aggregate. ASTM C 1260 is an extremely severe test, and is intended to be an aggregate screening test. If the quick methods indicate potential reactivity, ASTM C 1293 (concrete prism test) can be run over the period of a year (two years with SCMs in the concrete) to help resolve uncertainties about results from the screening tests. When reactivity is indicated by either field history or testing, special requirements must be used to control ASR. When these methods indicate no potential for reactivity, no special requirements are needed.

Use of ASTM C 289 (chemical method) is not recommended, as it may fail aggregates with good field performance history. Likewise, use of ASTM C 227 is not considered reliable, as it may pass reactive aggregates or measure expansion that may not be due to ASR.

Mitigation Measures Testing

When reactive aggregates are used, the efficacy of mitigation measures such as the use of SCMs, blended cements, or low-alkali cements should be evaluated in preventing deleterious expansion due to ASR. ASTM C 1293 is the recommended procedure. However, this test, although an accelerated test, requires up to two years to obtain results.

ASTM C 1567 is similar to ASTM C 1260 but allows combinations of cementitious materials to be tested so that the efficacy of mitigating ASR can be assessed. This method appears to correlate well with concrete prism testing (Thomas et al. 2005; Thomas and Innis 1999; Bérubé, Duchesne, and Chouinard 1995) and is widely used for this purpose.

ASTM C 441 uses a reactive crushed glass to make a “mortar” and has been used to compare the effectiveness of SCMs or blended cements for preventing expansion. However, no absolute limiting values on expansion are provided; mitigation is gauged by expansions of similar mortar bars made with low-alkali portland cements. Some aggregates are too reactive to be controlled by low-alkali portland cement; therefore, this test should be used with caution.

Concrete Testing

A petrographic examination (ASTM C 856) is the most positive method for identifying ASR gel in concrete. A network of internal cracks connecting reacted aggregate particles is a good indication that ASR is responsible for cracking. Prepared sections of concrete are examined under a microscope by an experienced petrographer to determine the presence and location of reactive aggregates and gel. Petrography can confirm the presence of reaction products and verify ASR as an underlying cause of deterioration. Visual indicators of ASR can be found in Stark (1991); however, petrographic examination is required for confirmation, as distress caused by ASR can look similar to that caused by other deterioration mechanisms.

The presence of ASR gel can also be detected by the uranyl acetate test (AASHTO T 299, also found in the annex to ASTM C 856); however, small amounts of radioactive materials are used, which require special handling. A relatively new technique, the Los Alamos staining method (Powers 1999; Guthrie and Carey 1999), provides confirmation of the presence of ASR gel. Both the Uranyl Acetate Test and the Los Alamos staining test only provide indications of ASR gel’s presence and do not provide conclusions as to whether ASR is the cause of concrete deterioration.

Table 5-5. Test Methods for Potential Alkali-Silica Reactivity (ASR) and Mitigation Measures

Test method	Purpose	Type of test	Type of specimen	Measurement	Duration	Criteria	Comments
ASTM C 227, Potential alkali reactivity of cement-aggregate combinations (mortar bar method)	To test the susceptibility of cement-aggregate combinations to expansive reactions involving alkalies	Mortar bars stored over water at 38°C (100°F) and high relative humidity	At least 4 mortar bars standard dimensions: 25 x 25 x 285 mm (1 x 1 x 11¼ in.)	Length change	First measurement at 14 days, then 1, 2, 3, 4, 6, 9, and 12 months and every 6 months after that as necessary	Per ASTM C 33 maximum 0.10%, expansion at 6 months, or if not available for a 6-month period, maximum of 0.05% at 3 months	Test may not produce significant expansion, especially for carbonate aggregate. Long test duration. Expansions may not be from AAR.
ASTM C 289 Potential reactivity of aggregates (chemical method)	To determine, potential reactivity siliceous aggregates	Sample reacted with alkaline solution at 80°C (176°F)	3 25-gram samples of crushed and sieved aggregate	Drop in alkalinity and amount of silica solubilized	24 hours	Point plotted on graph falls in deleterious or potentially deleterious area	Quick results. Some aggregates give low expansions even though they have high silica content. Not reliable.
ASTM C 295, Petrographic examination of aggregates for concrete	To outline petrographic examination procedures of aggregates—an aid in determining their performance	Visual and microscopic examination of prepared samples—sieve analysis, microscopy, scratch or acid tests	Varies with knowledge of quarry: cores 53 to 100 mm in diameter (2 1/8 to 4 in.), 45 kg (100 lb) or 300 pieces, or 2 kg (4 lb)	Particle characteristics, like shape, size, texture, color, mineral composition, physical condition	Short duration—visual examination does not involve long test periods	Not applicable	Usually includes optical microscopy; may include XRD analysis, differential thermal analysis or infrared spectroscopy. See ASTM C 294 for descriptive nomenclature.
ASTM C 441, Effectiveness of pozzolans or GGBF slag in preventing excessive expansion of concrete due to the alkali-silica reaction	To determine effectiveness of mineral admixtures in controlling expansion from ASR	Mortar bars—using Pyrex glass as aggregate—stored over water at 38°C (100°F) and high relative humidity	At least 3 mortar bars and 3 mortar bars for control mixture	Length change	First measurement at 14 days, then 1, 2, 3, 4, 6, 9, and 12 months and every 6 months after that as necessary	Per ASTM C 989 / AASHTO M 302, minimum 75% reduction in expansion or 0.020% maximum expansion or per ASTM C 618 / AASHTO M 295, comparison against low-alkali control	Highly reactive artificial aggregate may not represent real aggregate conditions.
ASTM C 856, Petrographic examination of hardened concrete	To outline petrographic examination procedures of hardened concrete—useful in determining condition or performance	Visual and microscopic examination of prepared samples	At least one 150 mm (6 in.) diameter by 300 mm (12 in.) long core	Is the aggregate known to be reactive? Orientation and geometry of cracks. Is there any gel present?	Short duration—includes preparation of samples and visual and microscopic examination	See measurement. This examination determines if ASR reactions have taken place and their effects upon the concrete. Used in conjunction with other tests.	Specimens can be examined with stereo-, microscopes polarizing microscopes, metallographic microscopes, and SEM.

Table 5-5. Test Methods for Potential Alkali-Silica Reactivity (ASR) and Mitigation Measures, continued

Test method	Purpose	Type of test	Type of specimen	Measurement	Duration	Criteria	Comments
ASTM C 856, (Annex) / AASHTO T 299 Uranyl acetate treatment procedure	To identify products of ASR in hardened concrete	Staining of freshly exposed concrete surface and viewing under UV light	Varies: core with lapped surface, core with broken surface	Intensity of fluorescence	Immediate results	Lack of fluorescence	Identifies small amounts of ASR gel whether they cause expansion or not. Opal, a natural aggregate, and carbonated paste can glow—interpret results accordingly. Tests must be supplemented by petrographic examination and physical tests for determining concrete expansion.
Los Alamos staining method*	To identify products of ASR in hardened concrete	Staining of a freshly-exposed concrete surface with two different reagents	Varies: Core with lapped surface, core with broken surface	Color of stain	Immediate results	Dark pink stain corresponds to ASR gel and indicates an advanced state of degradation	
ASTM C 1260 / AASHTO T 303, Potential alkali reactivity of aggregates (mortar-bar method)	To test for potential ASR of aggregate in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	At least 3 mortar bars	Length change	16 days	If greater than 0.10%, use supplementary test procedures; if greater than 0.20%, indicative of potentially deleterious expansion	Very fast alternative to ASTM C 227. Useful for slowly reacting aggregates or ones that produce expansion late in the reaction.
ASTM C 1293, Determination of length change of concrete due to alkali-silica reaction (concrete prism test)	To determine the potential ASR expansion of cement-aggregate combinations	Concrete prisms stored over water at 38°C (100°F)	Three prisms per cement-aggregate combination; standard dimensions: 75 x 75 x 285 mm (3 x 3 x 11¼ in.).	Length change	First measurement at 7 days, then 28 and 56 days, then, 3, 6, 9, and 12 months and every 6 months after that as necessary	Potentially deleteriously reactive if expansion equals or exceeds 0.40% at one year	Long test duration for meaningful results. Use as a supplement to ASTM C 227, ASTM C 295, ASTM C 289, and ASTM C1260.
Modified ASTM C 1293, Accelerated concrete prism test	To determine the potential ASR expansion of cement-aggregate combinations	Concrete prisms stored over water at 60°C (140°F)	Three prisms per concrete-aggregate combination; standard dimensions: 75 x 75 x 285 mm (3 x 3 x 11¼ in.)	Length change	91 days	Potentially deleteriously reactive if expansion exceeds 0.04% at 91 days.	Fast alternative to ASTM C 227; good correlation with ASTM C 227 for carbonate and sedimentary rocks.
ASTM C 1567, Potential alkali-silica reactivity of combination of cementitious materials and aggregate (accelerated mortar bar method)	To test the potential for deleterious alkali-silica of cementitious materials and aggregate combinations in mortar bars	Immersion of mortar bars in alkaline solution at 80°C (176°F)	At least 3 mortar bars for each cementitious material and aggregate combination	Length change	16 days	If greater than 0.10%, indicative of potential deleterious expansion; use ASTM C 1293 to confirm	Very fast alternative to ASTM C 1293. Useful for assessing effects of supplementary cementitious materials.

Source: Adaped from Farny and Kosmatka, (1997)
*** Powers (1999)**

Abrasion Resistance

Key Points

- Abrasion resistance is important for maintaining adequate texture and skid resistance on the concrete pavement surface.
- For satisfactory abrasion resistance, consider the following procedures:
  - Select strong and hard aggregates.
  - Use high compressive strength concrete.
  - Provide proper finishing and curing.
- Testing specifications: ASTM C 418, ASTM C 779, ASTM C 944, ASTM C 1138.

Simple Definition

Abrasion resistance is concrete's ability to resist surface wear.

Significance

Pavement surfaces must maintain adequate texture and skid resistance for proper vehicular control. It is therefore important for concrete pavements to have a high abrasion resistance. Abrasion resistance is generally related to concrete's compressive strength and to the type of aggregate in the concrete; harder aggregates resist wear better than softer aggregates.

Skid resistance is affected by both the concrete's microtexture (provided by the type and hardness of fine aggregate particles) and the macrotexture (primarily provided by grooves formed on freshly mixed concrete or cut in the hardened concrete [ACI 325 1988]). Wear of pavement surfaces occurs due to the rubbing action from the wheels of vehicular traffic. The rubbing action is greatly increased by the presence of abrasive particles, such as fine aggregates mixed with deicing chemicals (ACI 201.2R 2001; Liu 1994).

Wear is usually minimal with concrete pavements unless vehicles with studs, chains, or metal wheels travel on the pavement or unless poor aggregates and concrete are used. Even with minimal wear, polished surfaces can occur unless proper aggregates are selected. With more wear, loss of texture and loss of thickness can occur.

Factors Affecting Abrasion Resistance

The main factors affecting abrasion resistance are the type of aggregate, compressive strength, surface finishing, and curing methods (ACI 201.2R 2001; Liu 1994).

Aggregate Type. Coarse aggregate has a large influence on abrasion resistance, and the use of hard aggregates, such as granite and traprock, is preferred (Laplante et al. 1991). Soft limestone has poor abrasion resistance, but dolomitic limestone may have very good resistance.

To provide good skid resistance on pavements, the siliceous particle content of the fine aggregate should be at least 25 percent. Certain manufactured sands produce slippery pavement surfaces and should be investigated for acceptance before use.

Compressive Strength. A high concrete compressive strength improves abrasion resistance. High strength is achieved by having strong paste and strong bond between the aggregate and paste, thus preventing dislodging of aggregates out of the paste. The water-cementitious materials ratio has a large effect on the abrasion resistance, since it relates to the compressive strength. The compressive strength at the surface is important and is improved by avoiding segregation, eliminating bleeding, and using proper finishing and curing procedures (ACI 201.2R 2001). Supplementary cementitious materials do not affect the abrasion resistance, provided that strength levels are maintained.

Surface Finishing. Finishing techniques that densify the surface will increase abrasion resistance (Kettle and Sadegzadeh 1987).

Curing Methods. Increased curing promotes cement hydration, thus improving abrasion resistance.

Testing

The most common test for abrasion resistance of aggregate is the Los Angeles abrasion test (rattler method) performed in accordance with ASTM C 131 or ASTM C 535 / AASHTO T 96. In this test, a specified quantity of aggregate is placed in a steel drum containing steel balls, the drum is rotated, and the percentage of material worn away is measured. Specifications often set an upper limit on this weight loss. However, a comparison of the results of aggregate abrasion tests with the abrasion resistance of concrete made with the same aggregate do not show a clear correlation.

The wear resistance of concrete is determined more accurately by abrasion tests of the concrete itself. Four standard tests measure the abrasion resistance of concrete under various conditions.

ASTM C 418 subjects the concrete surface to air-driven silica sand, and the loss of volume of concrete is determined.

In ASTM C 779, three procedures simulate different abrasion conditions:

- Procedure A: sliding and scuffing of revolving steel disks in conjunction with abrasive grit (figure 5-20).
- Procedure B: impact and sliding friction of steel dressing wheels riding in a circular path.
- Procedure C: a rapidly rotating ball-bearing under load on a wet concrete surface, causing high contact stresses, impact, and sliding friction.

In all three procedures, the depth of wear of the specimen is used as a measure of abrasion.

In ASTM C 944, a rotating cutter abrades the surface of the concrete under load. Loss of mass or depth of wear is measured. This test is similar to procedure B of test method ASTM C 779 (figure 5-21); however, ASTM C 944 can be performed on cores. ASTM C 944 is included in the FHWA's definition of high-performance concrete for highway structures (table 5-6).

In ASTM C 1138, concrete is subjected to waterborne particles, which simulates the condition of hydraulic structures.

Figure 5-20. Test apparatus for measuring abrasion resistance of concrete to ASTM C 779 (PCA)

Figure 5-21. Rotating cutter with dressing wheels for the ASTM C 944 abrasion resistance test (Goodspeed 1996)

Table 5-6. FHWA High-Performance Concrete Performance Grades for Abrasion

	Grade 1	Grade 2	Grade 3
Average daily traffic (ADT)	< 50,000	50,000 to 100,000	≥ 100,000
Specified depth of wear* (studded tires allowed)	1 and 2 mm (0.04 to 0.08 in.)	0.5 to 1 mm (0.02 to 0.04 in.)	≤ 0.5 mm (0.02 in.)

Source: Goodspeed et al. (1996)
* As tested in ASTM C 944.

Early-Age Cracking

Key Points

- Concrete shrinks and expands due to moisture and temperature changes and will crack when the stress from restrained shrinkage exceeds the concrete's strength.
- The number and location of shrinkage cracks can be controlled by the timely construction of joints at optimum spacing and depth.
- Good practices by designers and contractors will help ensure that cracks develop only at joints and that little, if any, random cracking occurs.
- Good curing practices can reduce or prevent random cracking because curing helps delay the onset of stresses until the concrete is strong enough to avoid cracking.
- Good support is essential for preventing cracking due to loads.
- If concrete sets at a high temperature, the stresses and risk of cracking are increased.
- Standard test methods to determine shrinkage potential include ASTM C 1581 / AASHTO PP 34, ASTM 157.

Simple Definition

Basically, concrete cracks when tensile stresses exceed tensile strength. For the purposes of this manual, early-age cracks are defined as those that occur before the concrete pavement is opened to public traffic.

Later-age cracks are caused by a number of mechanisms, including traffic loading and materials-related distress (see Frost Resistance, Sulfate Resistance, D-Cracking, and Alkali-Silica Reaction in this chapter, pages 132, 139, 135, and 141, respectively).

Significance

While cracking is not strictly a property of concrete, concrete always cracks. A certain amount of early-age, full-depth cracking to relieve tensile stresses is inevitable and normally does not pose a problem. However, the challenge is to control the number and location of these cracks, generally by constructing joints in the concrete, using good curing practices, and/or reinforcing the concrete. Ideally, the concrete will crack along the joints down through the depth of the slab.

Controlled cracks at joints are aesthetically acceptable and can be sealed to prevent the ingress of aggressive fluids and incompressible materials. Joints can also help delineate lanes. Undesirable slab movement at joints can be controlled by installing dowels across transverse joints (to prevent vertical movement) or tiebars across longitudinal joints (to prevent horizontal movement).

Random (uncontrolled) cracks, however, are undesirable. They can reduce ride quality and lead to reduced durability. Although some random cracks are at first only cosmetic flaws or are even invisible to the naked eye, these cracks can grow and become problematic due to mechanical and environmental stresses that would otherwise be of no concern.

Early-age cracking occurs during the first few days of a pavement's life. This cracking is generally due to a combination of several factors, primarily thermal contraction and drying shrinkage (see the sections on Temperature Effects and on Shrinkage earlier in this chapter). Thermal-related cracks are normally observed in the first day, while drying-related cracks may appear over a longer period.

To control early-age cracks and prevent random cracks, designers and construction personnel need to understand the mechanisms that cause them.

Factors Affecting Early-Age Cracking

The primary factors affecting early-age concrete pavement cracking include the following:

- Volume change (drying shrinkage, thermal contraction) and restraint.
- Curling and warping.
- Strength and stiffness.

- Base condition and support.
- Early loadings (including the weight of the concrete itself).

These factors are affected by decisions made during pavement design, mixture design and proportioning, and construction. Cracking rarely occurs as a result of just one of these factors, but rather is generally a cumulative effect of several factors. In addition, weather conditions can greatly affect the magnitude and/or impact of each factor.

Volume Change and Restraint

Concrete always changes in volume (expands or shrinks) due to the effects of changing temperature and moisture (see Shrinkage and Temperature Effects in this chapter, pages 125 and 127, respectively).

Volume change can occur due to moisture loss before or after setting (plastic shrinkage and drying shrinkage, respectively), or due to a temperature drop after the concrete has set (thermal contraction). Thermal contraction can be 140 to 350 microstrains (0.17 to 0.42 in./100 ft) for a 22°C (40°F) temperature change, depending on the aggregate type (see Temperature Effects in this chapter, page 127; Aggregate Durability and Coefficient of Thermal Expansion in chapter 3, page 47).

Drying shrinkage can be significantly greater (400 to 800 microstrains, or 0.48 to 0.96 in./100 ft), but will take several months to achieve these levels.

In general, an object can shrink or contract freely, without any stress to the system, as long is it is not restrained. Theoretically, in homogeneous, elastic, unrestrained concrete systems (for example, in space where there is no gravity or friction), shrinkage is not a problem; the whole slab simply gets smaller (figure 5-22a).

The magnitude of drying shrinkage stresses (and the width of resulting cracks) is likely to be several times larger than thermal contraction stresses.

Several Mechanisms Cause Cracking

Random cracks often get blamed on a single mechanism, when in fact they generally result from a combination of several stresses.

For example, two new pavements using the same materials and mix design are placed on the same day only a few miles apart. On the day after placement, one pavement experiences random cracking; the other does not. What is the difference?

The first pavement was placed early in the morning. Its peak heat of hydration coincided with the hottest part of a summer day, resulting in a peak temperature of 49°C (120°F).

The second pavement was placed late in the afternoon. Its peak heat of hydration occurred during the cooler night, resulting in a peak temperature of 32°C (90°F). As a result of its higher set temperature and peak temperature, the first pavement experienced significantly more stress during the following hours due to cooling and thermal contraction.

In addition, a spotty summer storm passed through the region during the first night. A cold rain fell on the first pavement, but not on the second.

The rain cooled the first pavement surface quickly, increasing the temperature differential throughout the slab. Thus, the first pavement experienced more early curling-induced stress than the second pavement experienced.

Together, the increased contraction-related stress and the increased curling-related stress caused the first pavement to crack randomly.

Preventing random cracking, therefore, requires being aware of all cracking-related variables during pavement design, mix design, materials selection, and construction, and then balancing and/or mitigating the variables' effects.

Sometimes, compensating for the effects of one variable may exacerbate the effects of another. It is important to balance all cracking-related variables.

If the concrete pavement is restrained, however (for example, if there is bonding or friction between a slab and the base), tensile stresses develop in the concrete in proportion to the concrete stiffness and the degree of restraint (figure 5-22b). As noted earlier in this chapter, concrete's tensile strength, its ability to resist being pulled apart, is much smaller than its compressive strength. When the stress from restraint of shrinkage exceeds the concrete's tensile strength at any point in the slab, a crack will form. This is generally called shrinkage cracking.

Both internal and external restraint can cause stress. Internal restraint can arise, for example, if the outer concrete shrinks while the core does not. External restraint can arise not only from friction with the grade, but also from abrupt changes in the slab's cross section.

Curling and Warping: A Variation of Volume Change

Volume change can also cause curling and/or warping. (The term curling is sometimes used, incorrectly, for both phenomena.)

Curling. Curling is caused by differences in temperature between the top and bottom of the slab.

During cooler weather (e.g., at night or when a cold front comes through), the top surface of the slab cools more quickly than the bottom of the slab, which is insulated by the soil. The top part of the slab shrinks more quickly than the bottom, causing the slab to curl up at the edges (figure 5-23a).

During hot weather conditions (typically, during the daytime), the top of the slab may be warmer than the bottom, resulting in curling in the opposite direction (figure 5-23b).

Warping. Warping of concrete pavements is caused by differences in moisture content between the top and bottom of the slab.

During cool, moist weather (e.g., at night), the bottom of the slab may be drier than the top surface. The bottom of the slab therefore shrinks more quickly than the top, causing the slab edges to warp down (see figure 5-23c).

During warm, dry weather conditions (typically, during the daytime), the top of the slab dries and shrinks while the bottom remains moist, resulting in warping in the opposite direction (figure 5-23d).

Curling and warping actions may offset each other or augment each other. During summer days, for example, curling may be counteracted by warping (figure 5-23e). During summer nights, however, the curling and warping actions may compound each other (figure 5-23f). Along the joints, the pavement edges tend to curl upward when the surface of the concrete is drier and cooler than the bottom.

The curled edges then become a cantilever. Traffic passing over the joints causes a repetitive vertical deflection that creates a large potential for fatigue cracking in the concrete (figure 5-24).

Strength and Stiffness

The ability of concrete to resist stresses introduced by volume change depends on the mixture's strength and the stiffness.

Strength. The greater the concrete strength, the greater the stress the concrete will be able to carry. This is why most early-age cracking occurs soon after the concrete has been placed, when strength is still developing but stresses related to thermal contraction and drying shrinkage are high (see Strength and Strength Gain in this chapter, page 116).

Stiffness. The stiffer the concrete (as indicated by modulus of elasticity), the greater the stresses resulting

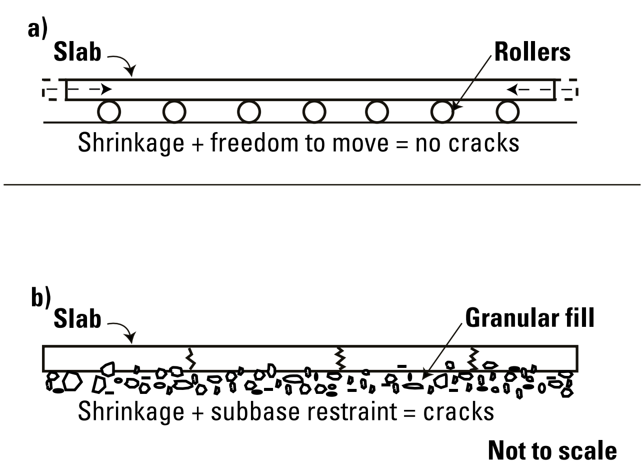


Figure 5-22. (a) Cracks generally do not develop in concrete that is free to shrink. (b) In reality, slabs on the ground are restrained by the subbase or other elements, creating tensile stresses and cracks. (ACPA)

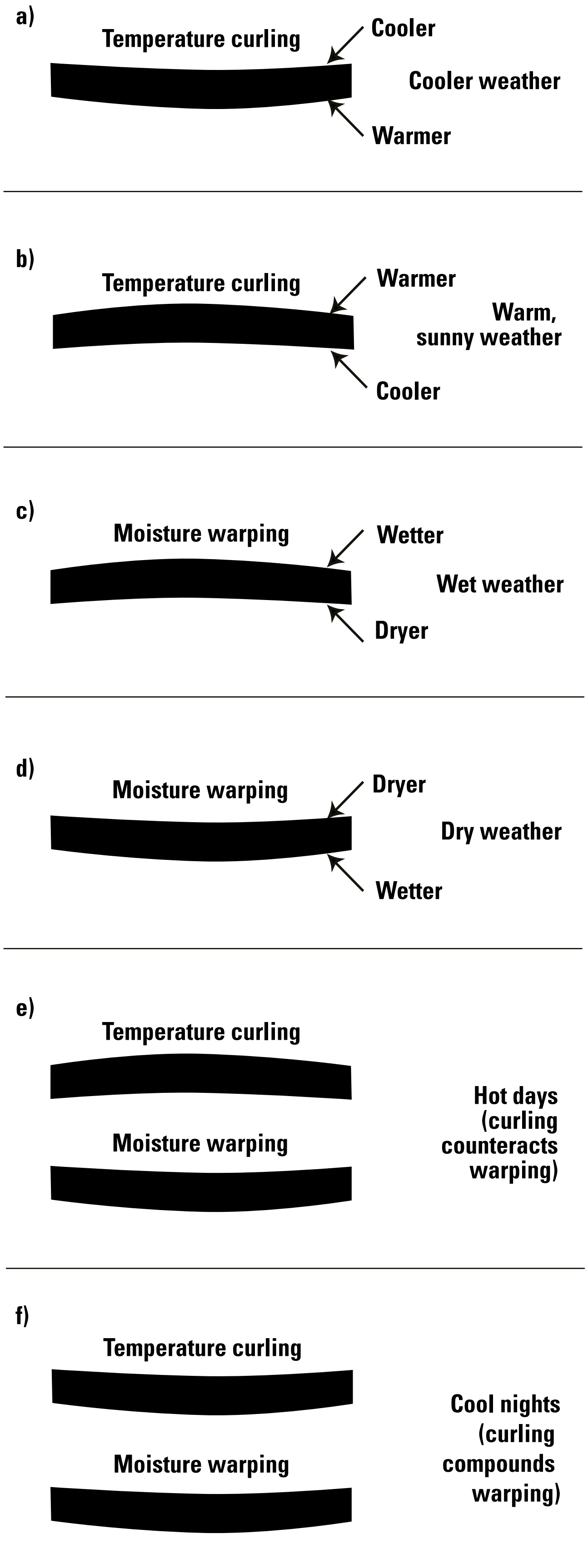


Figure 5-23. Curling and warping of slabs

from volume change. Unfortunately, stiffness increases faster than strength for the first few hours after setting, increasing the risk of cracking if the concrete is allowed to experience significant temperature variations or moisture loss (see Modulus of Elasticity in this chapter, page 123).

Lack of Support

If the concrete slab is not supported on a continuous, uniform base, then very high bending (and therefore tensile) stresses will be introduced, resulting

Strength and Cracking

The solution to cracking is not necessarily to focus on increasing concrete strength. Design strength must be balanced with other factors that affect cracking, such as volume changes, curling and warping, loading, weather, and level of support.

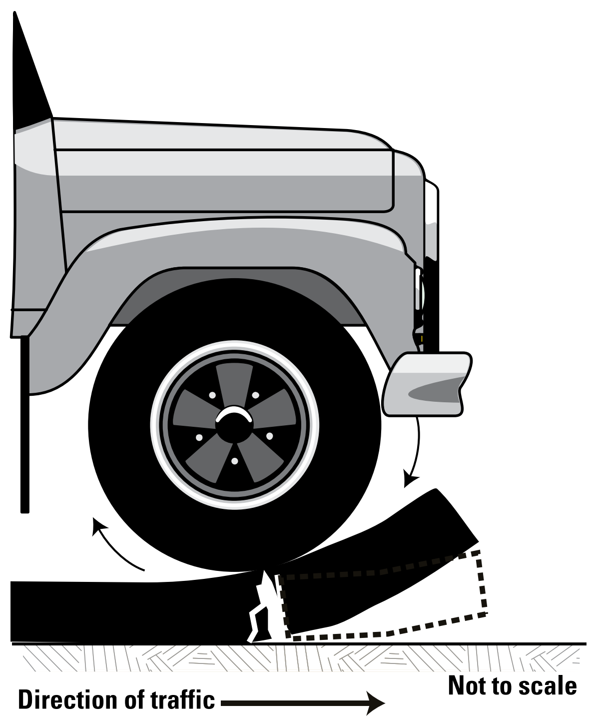


Figure 5-24. Exaggerated illustration of pavement curling. The edge of the slab at a joint or a free end lifts off the base, creating a cantilevered section of concrete that can break off under heavy wheel loading. (PCA)

in cracking. The loss of support may be due to the base material's lack of stability and uniformity or the erosion of the material over time (figure 5-25).

Early Loading

Load is distributed through a concrete slab over a wide area, meaning that the base layer does not have to be particularly strong or stiff. However, at the edges and corners of a slab, there is less area to carry the load, resulting in higher loads and deflections in the base. This indicates that the edges and corners of a slab are particularly sensitive to loading (i.e., susceptible to cracking) before the concrete has gained sufficient strength.

It is therefore recommended that construction equipment be kept away from the edges of a fresh slab until a minimum strength of 3 MPa (450 lb/in^2) is achieved. When construction equipment (e.g., a sealing truck) is allowed on the slab, protect the slab edges with cones or other temporary barricades.

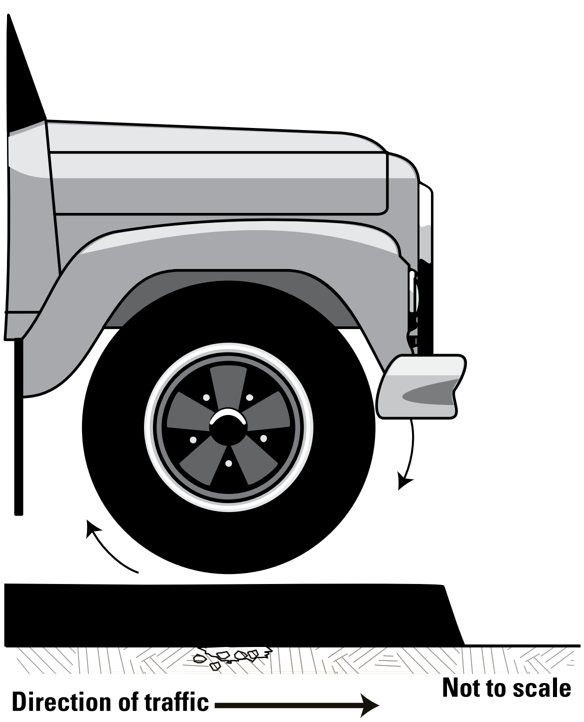


Figure 5-25. An eroded base can lead to high tensile stresses, resulting in cracking.

Controlling Early-Age Cracks

As noted earlier, concrete cracks because stresses develop in the concrete more quickly than the concrete's tensile strength develops. The goal is to control the number and location of cracks as much as possible and to prevent random cracks. This requires using good design and construction practices.

Controlling Early-Age Cracks with Joints

In jointed pavements (the majority of concrete pavements), the number, location, and size of early-age cracks is controlled by constructing (forming or sawing) contraction joints. The joints create planes of weakness where cracks form (figure 5-26) (see Joint Sawing in chapter 8, page 233).

To control cracking adequately, joints must be constructed correctly. In the case of sawed joints, this means that joints must be sawed at the correct time, at the correct spacing, and to the correct depth.

Timing: The Sawing Window. Joints are usually constructed by saw-cutting the concrete a few hours after placing. The optimum period of time to saw contraction joints is known as the sawing window.

The sawing window for conventional saws generally begins when concrete is strong enough not to ravel excessively along the saw cut. The window ends when significant shrinkage occurs that induces

Figure 5-26. A saw cut that has cracked through as planned (PCA)

uncontrolled cracking (Voigt 2000) (figure 5-27). Good practice generally dictates that, if the slab begins cracking in front of the saw, sawing should be stopped at that joint.

The beginning, duration, and end of the sawing window for any given concrete system are unique to that system. The sawing window is governed by the rate of hydration of the system and the environment to which it is exposed.

Higher early-strength concrete will be able to withstand more tensile stress when it first cools and undergoes temperature differentials. However, the sawing window for concrete mixtures that gain strength rapidly may begin sooner and be shorter than for normal mixtures.

The use of lightweight, early-entry saws allows joints to be sawed earlier without raveling, within an hour or two of paving, and may reduce the risk of random cracking (see Implications of Cement Hydration for Construction Practices in the Stages of Hydration chart in chapter 3, page 80; and Saw Timing in chapter 8, page 233).

For early-entry saws, the sawing window begins at final set and ends when the shallower early-entry cut no longer creates an effective plane of weakness.

It can be difficult to know when shallow cuts are no longer effective because the resulting random cracks are generally not visible until much later. Getting a good "feel" for the duration of early-entry sawing windows comes with experience.

Joint Spacing. When transverse joints are too far apart, the concrete may still crack randomly at locations other than the joints.

An optimal joint spacing exists for each specific project, depending on the slab thickness, base stiffness, and concrete strength. Most state agencies specify transverse contraction joints in plain (unreinforced) pavement at intervals between 4.5 and 6.1 m (15 and 20 ft).

For concrete pavements placed on granular subbase, the American Concrete Pavement Association recommends a maximum spacing of 24d, where "d" is the pavement depth; for concrete pavements placed on stabilized materials, a maximum spacing of 21d is recommended.

Why are Controlled Cracks at Contraction Joints Preferable to Random Cracks?

Properly constructed contraction joints have many benefits:

- Joints are more aesthetically pleasing than random transverse and longitudinal cracks.
- Joints can be sealed more efficiently to limit infiltration of harmful materials.
- Joints prevent the slab from randomly cracking into small, weak pieces.
- Joints can be constructed with dowel bars and tiebars to prevent slab deflection at the joints and to allow proper transfer of vehicle loads between pavement sections (panels).
- Joints help designate lanes.
- Joints generally provide a smoother ride than random cracks.

Figure 5-27. This joint was cut too late, resulting in random transverse cracking. (ACPA)

Joint Depth. The design depth of saw cuts is the minimum depth required to create a properly functioning joint. Cuts that are too shallow may not relieve stresses adequately, allowing random cracks to occur. Cuts that are unnecessarily deep require additional effort (require more time), cause unnecessary equipment wear, and reduce aggregate interlock.

In general, the depth of conventional saw cuts is one-third of the pavement thickness. However, unless a State specifies otherwise, early-entry cuts can generally be approximately 25 mm (1 in.) deep, regardless of pavement thickness. Because early-entry saw cuts are made before the concrete has developed significant strength or stresses, this shallower cut will create an effective plane of weakness where a crack should form (see Saw Timing in chapter 8, page 233).

Controlling Early-Age Cracks with Curing

To help ensure that cracks form only at the joints, use the moisture control and temperature control techniques discussed on the following pages. Curing helps delay the onset of shrinkage stresses until the concrete is stronger.

Note: In plain (unjointed) continuously reinforced concrete pavements, the reinforcing material causes cracks to develop within an acceptable spacing. The reinforcing material also holds the cracks tightly together, limiting the infiltration of aggressive fluids and other materials that can reduce durability.

Preventing Early-Age Cracks

The following cracks are, at least theoretically, preventable:

- Random transverse and/or longitudinal cracks.
- Plastic shrinkage cracks (short, shallow surface cracks that occur when the surface of the concrete dries too quickly).
- Map cracks (crazing). These occur primarily in hand pours.
- Corner and edge cracks.

These cracks are described in more detail beginning on page 158. They can be prevented by constructing joints, by controlling drying shrinkage and thermal contraction through good practices and a well-designed mix, and by providing a uniform, stable base.

Using Joints to Prevent Uncontrolled Early-Age Cracks

Under normal conditions, constructing an adequate system of joints in unreinforced concrete pavement will prevent the formation of random transverse and/or longitudinal cracks.

Selecting Materials to Prevent Early-Age Cracks

Another mechanism for controlling shrinkage is careful mix design/materials selection.

- Minimize the mix water content required for workability by avoiding the excessive use of cementitious materials, optimizing the size and amount of coarse aggregate, and minimizing the use of dusty aggregate.
- Consider using a water-reducing admixture to reduce drying shrinkage (see figure 5-29).
- Avoid calcium chloride admixtures, which can significantly increase drying shrinkage.
- Reduce the aggregate absorption of mix water (see Stockpile Management and Batching in chapter 8, pages 206 and 207, respectively).

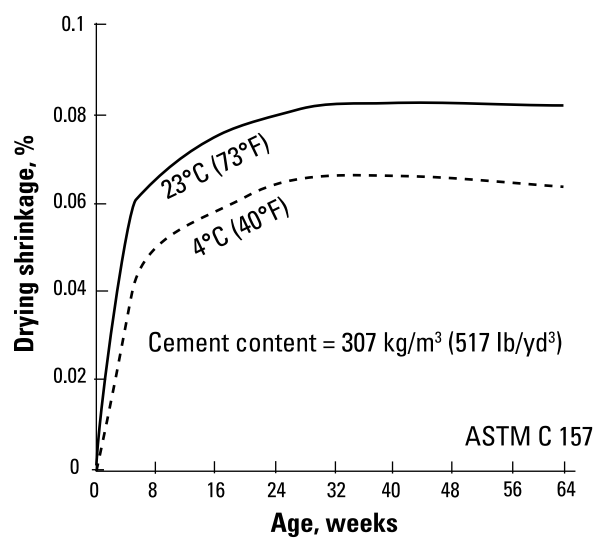


Figure 5-28. Effect of initial curing on drying shrinkage of portland cement concrete prisms. Concrete with an initial 7-day moist cure at 4°C (40°F) had less shrinkage than concrete with an initial 7-day moist cure at 23°C (73°F). Similar results were found with concretes containing 25 percent fly ash as part of the cementitious material.

Note: Some bleeding of the concrete may help reduce the rate of surface moisture loss, but a mixture should not be designed to bleed excessively simply to avoid plastic shrinkage cracking.

Preventing Early-Age Cracks with Moisture Control

If the concrete surface dries too rapidly before initial set, the surface will experience plastic shrinkage cracking. Significant drying shrinkage after the concrete hardens may contribute to map cracking and random transverse or longitudinal cracking if the concrete is not strong enough for the stresses.

Even if is the concrete is strong enough, early drying will exacerbate warping and thus contribute to fatigue cracking (see Shrinkage earlier in this chapter, page 125). Therefore, controlling moisture is essential.

A critical mechanism for controlling moisture (and thus plastic shrinkage, drying shrinkage, and warping) is good curing (FHWA 2005).

- Apply curing compound as soon as possible after finishing.
- Apply curing compound early if no additional finishing is to be conducted.
- If the evaporation rate is high, apply an evaporation retarder to the surface of the concrete before the final finishing activities. (Evaporation retarders are not curing compounds and should not be used as finishing aids, although they can be reworked into the

Summary of Tips to Reduce Early-Age Concrete Cracking

Random cracking in concrete can be reduced significantly or eliminated by observing the following practices:

1. Prepare the subgrade and base properly to provide stable, uniform support with adequate moisture content.
2. Use a mix with a low water-cementitious materials ratio, optimize the size and amount of coarse aggregate, and use low-shrinkage aggregate to minimize shrinkage that may cause cracking.
3. Consider using a water-reducing admixture to reduce paste content.
4. Use appropriate supplementary cementitious materials and minimize the amount of fine cementitious materials to reduce the set temperature and the temperature peak due to hydration. This will in turn reduce thermal shrinkage.
5. Consider using a set-retarding admixture to reduce thermal shrinkage.
6. Avoid calcium chloride admixtures, which can significantly increase drying shrinkage.
7. Time concrete placement so that the temperature peak due to hydration does not coincide with the hottest time of day.
8. Prevent rapid loss of surface moisture while the concrete is still plastic. For example, consider using spray-applied evaporation retarders. If the weather is sunny, hot, and/or dry, slow evaporation from the surface with wet curing methods, such as fog curing or covering with wet burlap.
9. Limit tensile stress from external restraint by making sure there are no abrupt changes in the slab's cross section.
10. Construct contraction joints at appropriate intervals, at the appropriate depth, and at the appropriate time to relieve tensile stresses.
11. Construct isolation joints to prevent restraint on the concrete from the adjoining elements of a structure.
12. If the ambient temperature is likely to drop significantly, slow heat loss and prevent extreme differentials in temperature through the slab by covering the surface with blankets.
13. Properly place, consolidate, finish, and cure the concrete and protect the curing compound from equipment and traffic for a minimum of 72 hours.

surface of the concrete if applied in accordance with the manufacture's recommendations.)

- In hot, dry, and/or windy conditions when evaporation is high, use wet curing methods, such as fog spray to increase the relative humidity of the air above the surface, or covering the surface with wet burlap.

Preventing Early-Age Cracks with Temperature Control

Changes in concrete temperature will result in thermal contraction and/or curling, which can contribute to random transverse or longitudinal cracking (see Temperature Effects earlier in this chapter, page 127).

Therefore, it is important to control changes in temperature.

First, reduce set temperature. Generally, this involves controlling the heat of hydration through the following activities:

- Use supplementary cementitious materials in the mix that reduce the heat and rate of hydration.
- Avoid or limit the use of fine cementitious materials.
- Consider using a set-retarding admixture in the mix.
- Reduce the temperature of fresh concrete by using chilled water, ice, or cooled aggregates.
- Avoid placing concrete during the hottest part of the day.

Second, use good curing practices:

- Apply curing compound as soon as possible after finishing.
- Protect the concrete from significant changes in ambient temperatures. For example, if a drop in temperature is likely soon after placement (e.g., if a cold front is expected, or at night), insulate the concrete with blankets or polyethylene sheets. This will reduce heat loss from the concrete surface. It will also moderate differences in temperature throughout the depth of the slab, reducing the risk of curling.

Preventing Early-Age Cracks with Uniform Support

Edge and corner breaks due to loss of base support can be prevented by good design and detailing and by careful preparation of the subgrade and base. In particular, the base must be uniform and stable (see Structural Performance in chapter 2, page 12; Subgrades and Bases in chapter 7, pages 192 and 196, respectively).

Testing for Cracking Risk

There are no tests that assess the risk of cracking for a given concrete mixture in a given environment. However, the risk of cracking in a given construction site can be estimated using modeling tools such as HIPERPAV (see Crack Prediction with HIPERPAV in chapter 8, page 231). In addition, two types of standard tests in North America can be used to compare the relative risks of different mixture combinations during prequalification and mix design.

One type of test, ASTM C 1581 / AASHTO PP 34, uses restraint to determine the effects of concrete variations on cracking tendency. Concrete is cast around a steel ring (figure 5-29), and strain gages on the ring allow stress measurements to begin as soon as the samples are cast. This method is useful for (and limited to) determining the relative susceptibility of different concrete mixtures to early-age cracking due to early drying shrinkage. With this test, drying can be started at any required age. This is an advantage over the other type of test (ASTM C 157), in which the first reading is taken after 24 hours.

Figure 5-29. A ring shrinkage specimen marked where a crack has occurred (CTLGroup)

ASTM C 157 uses an unreinforced concrete prism with pins cast in the ends. The samples are kept in water for a fixed period (28 days in the standard method), then allowed to dry for some time (64 weeks in the standard method). Several state authorities use different time intervals for wet storage (7 days is typical) and for taking readings (28 or 56 days). The change in length of the sample is then recorded as it dries.

The sample is unrestrained during drying, but is not a truly "unrestrained" test because the sample is kept in the mold for 24 hours after casting. This test is useful for comparing the risk of cracking due to the long-term drying shrinkage behavior of different concrete mixtures.

ASTM C 1581 and ASTM C 157 measure different properties of the concrete, and data from both methods can be useful in assessing the potential risk of cracking in a given mixture.

The Japan Concrete Institute has reported an autogenous shrinkage test (Tazawa 1999), and a restrained test was described by Springenschmidt (1995). Both are being investigated in the United States.

What about Later-Age Cracks? (After the Pavement is Opened)

Several mechanisms can contribute to cracking problems for years after the pavement is place:

- Load-associated issues, including loss of support.
- Expansive chemical reactions, such as alkali-silica reaction, salt crystallization, and freezing and thawing, all of which may cause durability problems later in a concrete pavement's life.
- Long-term drying shrinkage.

For more information about these mechanisms, see the section on Shrinkage, as well as the discussion of properties related to concrete durability (specifically, Frost Resistance, Sulfate Resistance, Alkali-Silica Reactions, and Shrinkage), earlier in this chapter.

Summary of Preventable Early-Age Cracks:

Plastic Shrinkage Cracks

Time of Occurrence

Before set, while the concrete is plastic.

Description

- One to three ft apart (figures 5-30 and 5-31).
- Usually short (a few in. to several ft long).
- Relatively shallow (one to two in. deep).
- Discontinuous.
- Generally perpendicular to wind direction.
- May occur throughout the panel surface.
- Rarely intersect the slab perimeter.

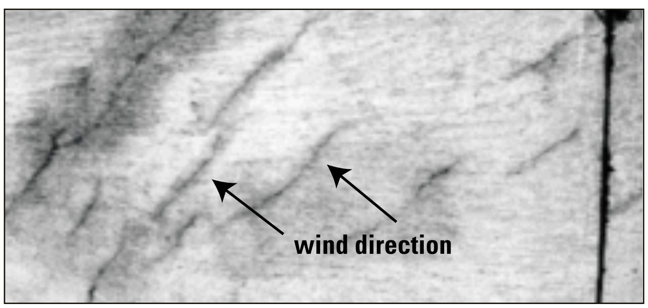


Figure 5-30. Typical plastic shrinkage cracks

Figure 5-31. Deep plastic shrinkage cracks

Cause

Plastic shrinkage cracks are caused when rapid evaporation of moisture from the concrete surface causes the surface to dry while the concrete is still plastic (before initial set). As the surface dries, it begins to form a crust. Shrinkage of the fast-drying surface crust is restrained by the plastic concrete underneath it, resulting in surface cracks.

Weather conditions such as the following increase surface evaporation and thus the formation of plastic shrinkage cracks:

- Low relative humidity during concrete placement.
- High concrete or air temperatures.
- Wind blowing across the pavement surface (at any temperature).
- A sudden cold front or rain.

Note that excessive evaporation can occur in cool but windy weather conditions.

Combinations of these weather conditions will increase surface moisture evaporation and the likelihood of plastic shrinkage cracking.

Plastic shrinkage can also be exacerbated by the following:

- Delayed set of the concrete.
- Dry aggregate, which absorbs moisture and thus reduces the available bleed water.
- Gap-graded aggregate, which requires more paste than other aggregate types.
- Too-fine sand, which reduces bleeding.
- Delayed finishing, which prevents application of protective curing methods.

Plastic shrinkage cracks should not be confused with pre-hardening cracks caused by concrete settlement on either side of reinforcing steel or the movement of concrete forms.

Effect

Plastic shrinkage cracks are somewhat unsightly, but they generally do not pose a structural problem unless they are very deep. However, plastic shrinkage cracks do permit water and chemicals to enter the concrete, so extensive plastic shrinkage cracking can result in long-term durability problems.

If the concrete is still plastic, plastic shrinkage cracks can be closed by revibrating the concrete (ACI 305R). Tight, hairline cracks do not require repair. Deep or very wide cracks should be sealed.

Prevention

When evaporation is expected to be high, i.e., when conditions are hot, windy, sunny, and/or the humidity is low, take appropriate precautions to prevent plastic shrinkage cracking:

1. Perhaps most important, protect the new concrete surface with adequate curing. Possible protective measures include the use of evaporation retarders, liquid membrane-forming curing compounds, fogging the area over the newly placed concrete, and wet curing with wet burlap (see Curing Compounds in chapter 3, page 64; Curing in chapter 8, page 224).
2. If possible, plan to place concrete during conditions that are less likely to cause shrinkage cracking. For example, during the hot summer place concrete in the late afternoon, early evening, or at night when ambient temperatures are cooler and relative humidity is higher.
3. Cool the concrete mixture.
4. Reduce aggregate absorption of mix water (see Stockpile Management and Batching in chapter 8, pages 206 and 207, respectively).
5. Dampen dry, absorptive subgrade.
6. Consider applying evaporation-retarding material before finishing.
7. Finish the concrete surface promptly, then apply curing early.
8. Some bleeding of the concrete may help reduce the rate of surface moisture loss, but do not design a mixture to bleed excessively simply to avoid plastic shrinkage cracking.

Excessive Evaporation Rates

When the evaporation rate approaches values between 0.5 and 1.0 kg/m^2/hr (0.1 and 0.2 lb/ft^2/hr), some specifications require action to prevent plastic shrinkage cracking. The evaporation rate depends on air temperature, concrete temperature, relative humidity, and wind velocity. The likely rate of evaporation can be estimated from a monograph published by the Portland Cement Association (2002) (see Weather Considerations in chapter 8, specifically figure 8-16 on page 227).

Summary of Preventable Early-Age Cracks:

Map Cracking (Crazing)

Time of Occurrence

After concrete has set; usually apparent the day after placement or by the end of the first week.

Description

- Network of fine fissures on the concrete surface that enclose small (12 to 20 mm [½ to ⅜ in.]) and irregular hexagonal areas (figure 5-32).
- Shallow; often only 3 mm (⅛ in.) deep.
- May occur throughout the panel surface.

Figure 5-32. Map cracking

Cause

Map cracking generally occurs on hand pours with significant hand finishing and/or inadequate curing. This type of cracking is caused by restrained drying shrinkage of the surface layer after set. It is often associated with the following:

- Overfinishing the new surface or finishing while there is bleed water on the surface.
- Mixes with high water-cementitious materials ratios (mixes that are too wet).
- Late or inadequate curing.
- Spraying water on the surface during finishing.
- Sprinkling cement on the surface to dry bleed water.

Effect

Some map cracking cannot be seen unless the pavement surface is wet. Visible crazing is somewhat unsightly but generally does not pose a structural problem. However, map cracks do permit water and chemicals to enter the concrete surface, so extensive map cracking may result in long-term durability problems.

Prevention

Take appropriate precautions to prevent map cracking:

1. Use moderate slump mixtures (generally, with a low water-cementitious materials ratio). Higher slump mixtures may be acceptable if they do not produce excessive bleeding. Bleeding can be controlled by using water-reducing admixtures in the mix.
2. Do not spray water on the slab to facilitate finishing.
3. Do not finish the surface while bleed water is present, and do not sprinkle dry cement on the surface to dry the bleed water.
4. Do not overwork or overfinish the surface.
5. Begin curing as soon as possible. Cover the surface thoroughly with curing compound.
6. Use wet curing methods, i.e., fog spraying and/or wet burlap, and keep the surface moist for at least three days.

Repair

Map cracks generally do not require repair. To improve aesthetics, they may be removed by diamond grinding the surface.

Summary of Preventable Early-Age Cracks:

Random Transverse Cracks (Drying Shrinkage Cracks)

Time of Occurrence

After concrete has set but before the pavement is opened to traffic.

Description

- Perpendicular to centerline (figure 5-33).
- Usually evenly spaced and continuous from the centerline to the edge of the pavement.
- May fork into a "Y" shape.
- Extend into the full depth of slab.
- May be hairline (and nearly invisible) or open.
- Normally appear within the first 72 hours.

Cause

Random transverse cracking occurs after the concrete sets but before it has gained enough strength to resist tensile stresses. The stresses are generally caused by restrained, cumulative shrinkage of the slab and by curling and warping (see Shrinkage and Temperature Effects in this chapter. pages 125 and 127, respectively). Stress may be increased by the following factors:

- Early drying.
- High-shrinkage mixes.
- High setting temperature, which increases the amount of cooling after set.
- Dry aggregate, which absorbs moisture and thus increases shrinkage.
- Gap-graded aggregate, which requires more paste.
- Early loads from construction equipment.
- Change in weather that increases shrinkage.

Figure 5-33. Random transverse crack

Effect

In jointed pavements without continuous reinforcement (the majority of concrete pavements), random transverse cracks can permit water and chemicals to enter the concrete, resulting in long-term durability problems. "Working" transverse cracks (that is, cracks in which vertical movement or displacement along the cracks is detectable) can cause structural failure.

Random transverse cracks do not cause problems in plain (unjointed), continuously reinforced concrete pavements. The reinforcing material causes cracks to develop within an acceptable spacing and holds the cracks tightly together. These tight cracks do not diminish the pavement's initial structural performance and do not allow the infiltration of aggressive fluids and other materials.

Random Transverse Cracks (Drying Shrinkage Cracking) continued

Prevention

To prevent random transverse cracking in unreinforced concrete, use the following good practices:

1. Minimize drying shrinkage by using a mix with a low paste content.
2. Maximize the size and amount of coarse aggregate while leaving a workable mix.
3. Keep aggregate piles moist.
4. Wet the grade prior to paving.
5. Minimize the temperature at which concrete sets to minimize the amount of cooling (and thermal contraction) after final set. Generally, this involves controlling the heat of hydration through careful selection of cementitious materials, using pre-cooled materials in the mixture, etc. (see Temperature Effects in this chapter, page 127).
6. Make sure the joints are constructed at the proper time, spacing, and depth.
7. Protect the concrete surface from sudden temperature changes, from moisture loss, and from excessive curling and warping through proper curing (see Curing Compounds in chapter 3, page 64; and Curing in chapter 8, page 224).
8. Keep construction traffic off the pavement as long as possible.

A certain amount of full-depth cracking to relieve tensile stresses is inevitable in concrete pavements. In unreinforced concrete, the number and location of these random cracks can be controlled with contraction joints.

Construct contraction joints to create planes of weakness where cracks will form and thus relieve stresses. To completely control these cracks, joints must be cut at the proper time, the proper depth, and the proper spacing (see Joint Sawing in chapter 8, page 233).

Repair

Random transverse cracks that are not working (that is, cracks in which there is no detectable vertical movement or displacement along the cracks) should be sawed and sealed. However, random transverse cracks that are working or near a joint or another crack generally require a full-depth repair to prevent structural failure.

Summary of Preventable Early-Age Cracks:

Random Longitudinal Cracks

Time of Occurrence

After concrete has set but before the pavement is opened to traffic.

Description

- Parallel to centerline (figure 5-34).
- Run through the full depth of the slab.
- May be hairline (and nearly invisible) or open.
- May appear within the first 24 hours or after several months.

The causes, effects, control, prevention, and repairs for random longitudinal cracks are similar to those for random transverse cracks. The following additional information is specific to longitudinal cracks.

Cause

Random longitudinal cracking can occur after the concrete sets but before it has gained enough strength to resist tensile stresses. The stresses are generally caused by restrained, cumulative shrinkage of the slab and by curling and warping (see Shrinkage and Temperature Effects in this chapter, pages 125 and 127, respectively).

The stress of restrained thermal contraction and drying shrinkage may be increased by the following factors:

- Nonuniform base support caused by frost heaving, soil setting, or expansive soils.
- A slab that is too wide, i.e., longitudinal joints that are too far apart.
- Restraint from an adjoining tied slab.
- A joint cut that is too shallow.

Figure 5-34. Random longitudinal crack

Control

If more than one lane width of unreinforced concrete is placed at once, cut or form longitudinal joints between lanes where cracks will form (see Joint Sawing in chapter 8, page 233).

Prevention

Use the same good practices for preventing random transverse cracking, as listed on the previous page. In addition, take care to do the following:

1. Place concrete on a stable, uniform base not prone to frost heaving, settling, or expansion.
2. Prevent early loading by keeping construction equipment off the pavement, particularly along the free slab edges.
3. Do not tie too many lanes together with tiebars.
4. Tie lanes together when the weather is not too hot or too cold (extreme temperatures will increase contraction).
5. If the slab is 23 cm (9 in.) thick or less, the slab width should be no more than 3.5 m (12 ft) wide without a longitudinal joint. If the slab is 25 cm (10 in.) thick or more, the slab should typically be no wider than 4 m (14 to 15 ft) without a longitudinal joint.

Summary of Preventable Early-Age Cracks:

Corner Breaks

Time of Occurrence

Corner breaks can occur after set, before pavement is opened to the public. However, corner breaks can continue to form for years, anytime the pavement loses support due to soil settling, erosion, frost heaving, expansive soils, or excessive curling and warping.

Description

- Cracks intersecting the adjacent transverse and longitudinal joints at approximately a 45-degree angle (figure 5-35).
- From 0.3 m (1 ft) long to half the slab width on each side.
- Full depth.

Cause

Corner cracks occur when a pavement carries loads that are heavier than its current strength can support and/or when there is loss of base support. For instance, early loading with heavy construction equipment can cause corner cracking.

Furthermore, curled or warped slabs lose base support where the slab lifts away from the grade. When loads are applied, the pavement will crack in the areas that have reduced support.

If the base is not uniform, the slab will similarly lose support where the base is less stable than in the surrounding areas.

Repeated loadings may also create voids under slab corners, and when loads are applied the pavement may crack where the support is weakened.

Figure 5-35. Corner break

Effect

Corner cracks usually represent structural failures.

Prevention

To prevent corners cracking, consider the following measures:

- Make sure the base is uniformly stable over time.
- Keep construction traffic off the new pavement as long as possible.
- Properly cure the concrete as long as possible to help prevent or reduce curling and warping.

Repair

Corner cracks generally require full-depth repair of the slab and perhaps stabilization of the base.

References

AASHTO standards may be found in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 24th Edition, and *AASHTO Provisional Standards*, 2004 Edition, HM-24-M. https://www.transportation.org/publications/bookstore.nsf.

AASHTO M 85, Standard Specification for Portland Cement

AASHTO M 157, Standard Specification for Ready-Mixed Concrete

AASHTO M 240, Blended Hydraulic Cement

AASHTO T 22, Compressive Strength of Cylindrical Concrete Specimens

AASHTO T 23/AASHTO M201, Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes

AASHTO T 24, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

AASHTO T 96, Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

AASHTO T 97, Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)

AASHTO T 104, Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate

AASHTO T 119, Slump of Hydraulic Cement Concrete

AASHTO T 121, Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

AASHTO T 126, Making and Curing Concrete Test Specimens in the Laboratory

AASHTO T 131, Time of Setting of Hydraulic Cement by Vicat Needle

AASHTO T 141, Sampling Freshly Mixed Concrete

AASHTO T 152, Air Content of Freshly Mixed Concrete by the Pressure Method

AASHTO T 154, Time of Setting of Hydraulic Cement Paste by Gillmore Needles

AASHTO T 158, Bleeding of Concrete

AASHTO T 160, Length Change of Hardened Hydraulic Cement Mortar and Concrete

AASHTO T 161, Resistance of Concrete to Rapid Freezing and Thawing

AASHTO T 177, Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)

AASHTO T 185, Early Stiffening of Portland Cement (Mortar Method)

AASHTO T 186, Early Stiffening of Hydraulic Cement (Paste Method)

AASHTO T 196, Air Content of Freshly Mixed Concrete by the Volumetric Method

AASHTO T 197, Time of Setting of Concrete Mixtures by Penetration Resistance

AASHTO T 198, Splitting Tensile Strength of Cylindrical Concrete Specimen

AASHTO T 231, Capping Cylindrical Concrete Specimens

AASHTO T 277, Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

AASHTO T 299, Rapid Identification of ASR Products in Concrete

AASHTO T 303, Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to ASR

AASHTO T 309-99, Temperature of Freshly Mixed Portland Cement Concrete

AASHTO TP 60-00, Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete

AASHTO TP 64, Standard Method of Test for Predicting Chloride Penetration of Hydraulic Cement Concrete by the Rapid Migration Procedure

AASHTO PP 34, Provisional Standard to Assess Susceptibility to Cracking

ASTM standards may be found in *Annual Book of ASTM Standards*, ASTM International. www.astm.org.

ASTM C 31/C 31M-03a, Standard Practice for Making and Curing Concrete Test Specimens in the Field

ASTM C 39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C 42/C42M-04/AASHTO T24, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete

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ASTM C 215-02, Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens

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ASTM C 231-04/AASHTO T 152, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

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ASTM C 289, Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)

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ASTM C 295, C295-03, Standard Guide for Petrographic Examination of Aggregates for Concrete

ASTM C 359/AASHTO T 185, Test Method for Early Stiffening of Hydraulic Cement (Mortar Method)

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ASTM C 457-98, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

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ASTM C 672/C672M-03, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals

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Chapter 6

Development of Concrete Mixtures

The parameters for almost all concrete properties for a specific concrete mixture are determined or specified during mix design. The terms "mix design" and "mix proportioning" are often incorrectly used interchangeably.

- Mix design is the process of determining required and specifiable properties of a concrete mixture, i.e., concrete properties required for the intended use, geometry, and exposure conditions.
- Mix proportioning is the process of determining the quantities of concrete ingredients for a given set of requirements. The objective of proportioning concrete mixtures is to determine the most economical and practical combination of readily available materials to produce a concrete that will have the required properties.

The following are factors to be considered in concrete mix design:

- Workability.
- Placement conditions.
- Strength.
- Durability.
- Economy.

This chapter covers how the desired properties of concrete, discussed in chapter 5, can be achieved by optimized selection of concrete ingredients, discussed in chapter 3. The first section of this chapter discusses the sequences of activities when designing a mix. The next section provides one method of optimizing the aggregates to obtain a good combined grading. The third section provides a method of calculating mix proportions, followed by possible modifications to achieve selected concrete properties.

Sequence of Development

Key Points

- Mix design specifications must be appropriate for the construction system, loading, and environment that are expected.
- Series of trial batches, made using job-specific materials including those at the likely placement temperatures, are essential.
- Sufficient trial batches should be made so that adjustments of the workability and air content can be made in the field with confidence.
- Field trials using the full-scale batch and handling plant are recommended.
- Workability and air content are the primary concrete properties that can be manipulated during the batching process in the field.

Pre-Construction

Long before construction begins, the mix specification must be set, bids evaluated, and trial batches prepared.

Specifications for Mix Design

The process of designing a concrete mix for a paving project begins with setting out the specification. There are two different approaches to concrete mixture specification:

1. In the prescriptive approach, specifiers define the required materials, proportions, and construction methods based on fundamental principles and practices that exhibit satisfactory performance.
2. In the performance approach, specifiers identify functional requirements, such as strength, durability, and volume changes, and rely on concrete producers and contractors to develop concrete mixtures that meet those requirements.

All specifications should require the use of materials that meet minimum quality requirements as described in chapter 3. Prescriptive specifications should also provide general guidelines for materials proportions, such as minimum cement content, maximum replacement rates for supplementary cementitious materials, water-cementitious materials ratio (w/cm), aggregate grading requirements, and air content.

Traditionally, strength has been the primary acceptance criteria for concrete pavements. Durability, however, is not simply a function of strength (see Concrete Durability is Affected by Many Concrete Properties in chapter 5, page 130.) Many other factors contribute to pavement durability and should be considered in all stages of mix design development. Non-strength-related concrete properties that influence durability include but are not limited to the following:

- Air entrainment (spacing factor and specific surface area).
- Permeability.
- Robust workability properties that enable placement at various temperatures without significant changes to the w/cm ratio.

At a minimum, specifications should require that trial batches (laboratory mixes or field-batched mixes) be prepared with job-specific materials, and that the trial batches be tested for the required durability factors before paving.

Many local departments of transportation (DOTs) may have a listing of materials approved for concrete pavement construction. State DOT certifications together with other documentation can help facilitate the materials approval review process.

Bidding

Economics are introduced as a constraint during the bidding stage. The contractor/concrete supplier is faced with the challenge of optimizing the mix proportions with respect to cost, specifications, and performance requirements.

In most instances, prospective bidders can make reasonable assumptions because they have prior experience with the specifications and materials that will be used for the project. However, when specifications change, when new material sources are introduced, or when material sources change, it may be necessary to batch and test trial laboratory mixes during the bidding process to reduce the risks of uncertainty. When testing before the bid is deemed appropriate, test results should be interpreted carefully with respect to sample size, test precision, and between-batch variability.

Laboratory Mixes

All of the desktop approaches that can be used to proportion a mixture are only the starting point for making trial batches. The risk of severe problems is significant if a new mixture is taken from the calculator to the batch plant. It is essential to prepare trial batches in the laboratory to ensure that the fresh and hardened properties comply with the requirements, and that there are no incompatibilities between the materials, at the temperatures at which the field mixes will be made.

It is more convenient and economical to test concrete mixes in the laboratory than to batch large quantities at a concrete plant. However, project conditions are often significantly different from the controlled environment of a laboratory. Production variability and testing variability need to be considered and understood when laboratory test results are interpreted. Ideally, some laboratory tests should be conducted at the same range of temperatures expected in the field.

Choose a qualified laboratory and design a testing plan that will provide the information desired. Laboratories and technicians should be experienced with concrete mixtures and accredited by an independent source. The testing plan should be specific and include all tests needed to verify the mix properties. A suggested testing plan is shown in table 6-1.

When the potential for changes in materials sources or environment can be anticipated, it is advisable to batch additional laboratory mixes with alternative materials and at different temperatures as a backup.

Anticipating Responses to Field Conditions

Laboratory mixes should be batched so that the w/cm ratio and air content are representative of the mix that will be used during paving. Field adjustments should be anticipated. In other words, different laboratory mixes should be batched that will allow the plant to respond to changes in the materials sources and properties, environment, and demands on the concrete system without deviating from the specification.

When the raw materials are delivered to a concrete plant, it is too late to change the cement chemistry or the physical properties of the aggregates. Therefore, workability and air content are the primary concrete properties that can be manipulated during the batching process in the field. This can be accomplished by adjusting the dosage of the appropriate admixture and, if still within the specified w/cm ratio, the water.

Particular attention should be paid to preparing laboratory mixes that are representative of the materials that will be used on the project. Portland cement and supplementary cementitious materials should be obtained from the suppliers' normal production and not be specially prepared. If necessary, aggregates should be screened into separate sizes and recombined to match as closely as possible the gradation that will be provided on the project.

The suggested laboratory testing plan should be followed for the target w/cm ratio. Additional laboratory mixes should be batched at different w/cm ratios, one higher and one lower.

Figure 6.1 provides an example of a plot showing the strength values for mixes with different water-cement ratios. This graph provides a basis for setting limits for field adjustments that may occur. At the point that concrete production begins, it is assumed that if the "recipe" is followed, an acceptable mix will be delivered to the paver.

Once the mix proportions have been proven in the laboratory, they can be tested in full-scale batches in the equipment that will be used on the project. This may appear expensive at the outset, but the savings in preventing later problems will more than offset this investment.

Field Trials

Just before paving, the mix designs should be verified in the field (unless there is experience with a similar mix). This process is necessary to ensure that the materials and the final mix are substantially the same as those that were used during the laboratory trials.

The following questions should be considered when verifying laboratory mixes in the field:

- Are the fresh properties acceptable for the type of equipment and systems being used?
- Are there signs of incompatibilities?
- Are the strengths from the field mix comparable to those from the laboratory mix (±1.7 MPa [250 lb/in^2])?

Table 6-1. Suggested Laboratory Testing Plan

Concrete property	Test description	Test method	Comments
Workability	Slump at 0, 5,10,15, 20, 25, & 30 minutes	ASTM C 143 / AASHTO T 119	Changes in workability may indicate changes in the w/cm ratio and affects placement in the field
	Concrete temperature when batched	ASTM C 1064	Temperature differences in the field may affect w/cm ratio, workability, and volumetric stability
	Grading and moisture content of aggregates	ASTM C 136 / AASHTO T 27 and ASTM C 566 /AASHTO T 255	Use the moisture content in conjunction with the absorption of the aggregate to calculate w/cm ratio
	Combined grading	Coarseness / workability factors “8-18” analysis 0.45 power chart*	Project variability may affect workability and w/cm ratio
Strength development	Compressive or flexural strength	ASTM C 39 / AASHTO T 22 and/or ASTM C 78 / AASHTO T 97	Cast as many specimens as possible from a single batch– break 3 @ 3 days, 3 @ 7 days, and 12 @ 28 days
	Maturity curve	ASTM C 1074 or Agency special provisions	May also be developed in he field during the field trial stage
Air content	Air content	ASTM C 231 / AASHTO T 152	Target the middle of the specification range – laboratory batches with air contents on the low end of specification tolerances will provide higher strengths
	Air-void analyzer and/or image analysis	AASHTO TP XXXX** or ASTM C 457	Spacing factor and specific surface area are both critical for freeze/thaw durability
Density	Density / unit weight	ASTM C 138 / AASHTO T 121	Indicates (1) volumetric quantity (yield) of concrete produced per batch, (2) air content of concrete mixture, (3) uniformity
Permeability	Rapid chloride penetration ranges that are broadly	ASTM C 1202 / AASHTO T 277	Results are interpreted in related to permeability

* See 0.45 power chart later in this chapter.
** www.aashtotig.org/ (Click on Focus Technologies.AVA)

Field trials are also a preferred practice when portable plants are used. The batching process, including mix time, should be the same as that to be used during paving operations.

Workability of the field trial batches should be tested immediately after batching and at a later time to simulate the transportation time. Field trial batches should be remade until the desired workability is achieved after the estimated time in transport and then tested (table 6-2).

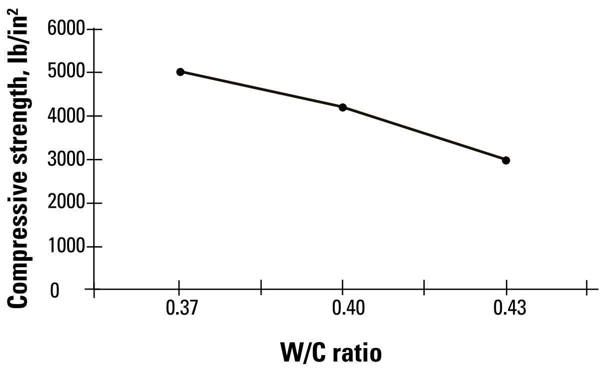

Figure 6.1. Example w/c ratio vs. strength curve (laboratory mix target w/c = 0.40)

Table 6-2. Suggested Field Trial Batch Testing Plan

When or what	Action or test
Before production begins	Test and verify scales and plant operations
	Determine aggregate moisture contents and adjust batch proportions
The primary mix design	Workability
	Air content
	Unit weight
	Three- and seven-day strength
	Yield
	Maturity curves
Mixer uniformity test (front to rear of the batch)	CRD-C-55
	Slump
	Air content
	Unit weight

Aggregate Grading Optimization

Key Points

- Optimized grading of the combined aggregates will enhance the concrete mixture.
- Shilstone's method for optimizing aggregates to obtain a good combined grading uses three tools, each of which provides a different kind of analysis.

Aggregates are generally chemically and dimensionally stable; therefore, it is desirable to maximize aggregate content in concrete mixtures compared to the more chemically reactive cement paste. Well-graded aggregate reduces the space between aggregate particles that has to be filled with cement paste. Well-graded aggregate also contributes to achieving a workable mix with a minimum amount of water.

Shilstone considers that the best means of specifying and selecting mix proportions is through combined grading analysis (Shilstone 1990) (see Combined Grading in chapter 9, page 253). He developed three tools to help in the process of optimizing the combined aggregate grading:

- The Coarseness Factor Chart (CFC): provides overview of the mixture.
- The 0.45 Power Chart: shows trends.
- The Percent of Aggregate Retained on Each Sieve (PARS): shows details.

Some mixtures that appear excellent based on the CFC may be found, by the other two analyses, to have problems that need to be addressed.

Coarseness Factor Chart

To analyze data using the CFC, the combined aggregate grading is mathematically separated into three size groups:

- Coarse particles are those retained on the 9.5-mm (3⁄8-in.) sieve. They provide the primary body of the mixture.
- Intermediate particles pass the 9.5-mm (3⁄8-in.) sieve and are retained on the 1.18-mm (#8) sieve. These particles fill major voids between the coarse particles.
- Fine particles pass the 1.18-mm (#8) sieve.

The mass fractions of the combined aggregate that fall into each of the above size groups are used to calculate the coarseness factor and the workability factor. The coordinates from that data are plotted on the CFC (figure 6-2).

The coarseness factor is the mass of the coarse-sized aggregate divided by the sum of the masses of the coarse and intermediate sizes:

$$\textit{Coarseness Factor} = \frac{\textit{\% Coarse Aggregate}}{\textit{\% Coarseness} + \textit{\% Intermediate Aggregate}}$$

Thus, a coarseness factor of 100 describes a grading with no intermediate aggregate, i.e., no particles passing the 9.5-mm (3⁄8-in.) sieve and retained on the 2.36-mm (# 8) sieve. Such a mixture is gap-graded. A value of 0 describes a mixture with no coarse aggregate, i.e., no particles retained on the 9.5-mm (3⁄8-in.) sieve.

The workability factor is the percent of the combined aggregate that passes the 2.36-mm (# 8) sieve plus an adjustment for the amount of cementitious material in a mixture. The base cementitious materials content for the chart is 335 kg/m^3 (564 lb/yd^3). The workability factor is increased 2.5 points for each 56 kg/m^3 (94 lb/yd^3) variation from the original cementitious materials content. The coarseness factor and the workability factor establish the coordinates for a mixture.

Coarseness Factor Zones

The trend bar (figure 6-2) defines a region where combined rounded or cubical crushed stone and well-graded natural sand are in balance. However, such mixtures have limited application, as the aggregate grading must be well-controlled. They may be used for bucket-placed concrete in large footings. Mixtures represented by plots above the bar identify mixtures with increasing amounts of fine aggregate. Those below the trend bar generally contain an overabundance of coarse particles and are not desirable.

The coarseness factor zones identify regions where plotted mixtures will have generally predictable characteristics:

- Zone I indicates that a mixture is gap-graded and has a high potential for segregation during placement and/or consolidation due to a deficiency in intermediate particles. These mixtures are likely not cohesive; therefore, segregation may occur. Mixtures plotting in this zone may result in local cracking, blistering, spalling, and scaling.
- Zone II indicates an optimum mixture for concretes with nominal maximum aggregate size from 50 mm (2 in.) through 19 mm (¾ in.). Mixtures in this zone generally produce consistent, high-quality concrete. Mixtures that plot close to the trend bar or near the limits for Zones I and IV require close control and adjustments in proportions, as small variations in consecutive batches can result in the aggregate plotting outside of Zone II.
- Zone III indicates an optimum mixture for maximum nominal aggregate sizes smaller than 19 mm (¾ in.).
- Zone IV indicates excessive fines and a high potential for segregation during consolidation and finishing. Such mixtures will likely produce variable strength, high shrinkage, cracking, curling, spalling, and scaling.
- Zone V indicates a mixture that has an excessive amount of coarse and intermediate aggregate and is not plastic.

0.45 Power Chart

The chart provides a means to describe an ideal combined aggregate grading. Sieve sizes, in microns to the 0.45 power, are plotted along the X axis.

The cumulative amount of the total aggregate that passes each sieve can then be plotted and compared to a line on the 0.45 power chart. A well-graded combined aggregate in a concrete mixture will follow a trend from the nominal maximum aggregate size to the 2.36 mm (# 8) sieve and then bend downward, as shown in figure 6-3. Deviations from this line identify deviations from the optimum.

Examining plotted points from right to left, the first point that falls well below the line indicates that too much material was retained on the corresponding sieve. Correspondingly, a point that falls well above the line indicates that not enough material was retained on the corresponding sieve.

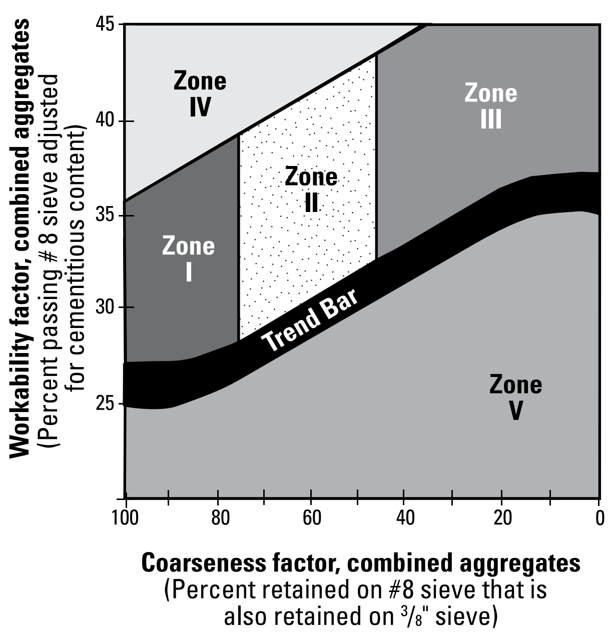

Figure 6-2. Modified coarseness factor chart (Shilstone 1990)

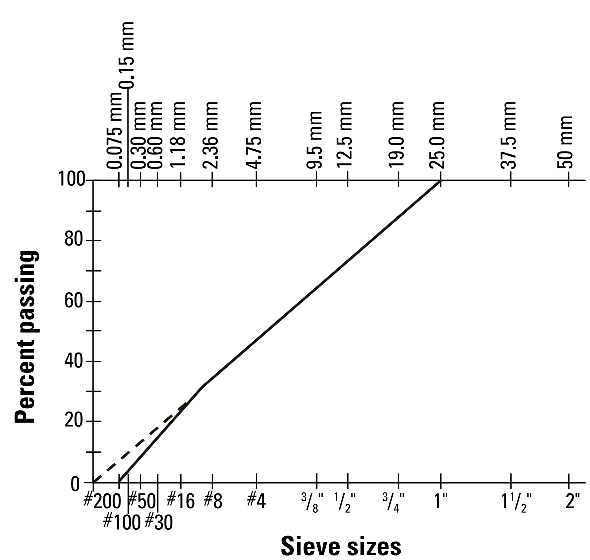

Figure 6-3. 0.45 power chart for 25 mm (1 in.) nominal maximum aggregate (Shilstone personal communication)

The 0.45 power chart should be used only as a guide and should not be incorporated into specifications. Experience shows that good gradations plot roughly parallel to and within a few percent of the line on the 0.45 power chart. Trial batching and the behavior of the mixture will indicate whether the selected combined aggregate is satisfactory.

Percent Aggregate Retained Chart

Figure 6-4 graphically illustrates the aggregate particle distribution as a plot of the percent of aggregate retained on each sieve size (Shilstone 1990). An optimum combined aggregate particle distribution exhibits no gaps in the intermediate particles, as illustrated by the (a) grading on figure 6-4.

Often, the sand available is finer and the coarse aggregate is coarser than desired, thereby creating a wider gap in the grading. Due to the nature of locally available fine aggregate, combined aggregate gradings are often found to have a deficiency in particles retained on the 2.36-, 1.18-, and 600-µm sieves (#8, #16, and #30) and an abundance of particles retained on the 300- and 150-µm sieves (#50 and #100). When there is a deficiency in two adjacent sieve sizes, the sizes on either side tend to balance them. However, three adjacent deficient sizes indicate a problem that should be corrected, as illustrated by the (b) grading in figure 6-4.

Special attention must be given to cases where the sum of the percentage retained on two adjacent sieves is less than 13 percent of the total aggregate.

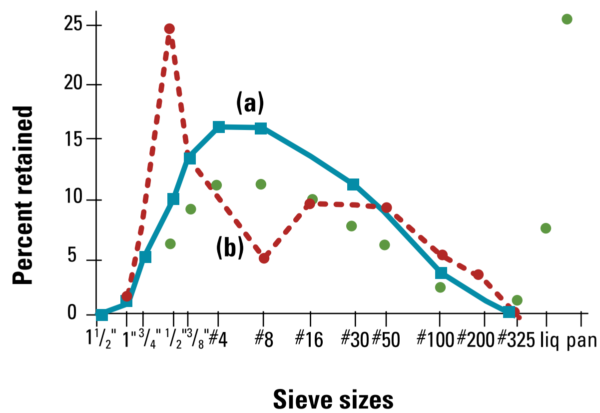

Figure 6-4. Percent retained chart

Calculating Mixture Proportions

Key Points

- Desktop calculations of mix proportions must be followed by trial batches.
- Several methods of calculating proportions are available. One—the Absolute Volume Method—is outlined here.

Calculated mix proportions provide a starting point for trial batches. A concrete mixture can be proportioned by calculation, from field experience (historical data), or from trial mixtures with trial and error. Several calculation methods are available, one of which is described in detail below. The requirements for a given mix are often an act of balancing different (and possibly contradictory) requirements for the fresh and hardened properties.

Concrete mixture proportions are usually expressed on the basis of the mass of ingredients per unit volume. The unit of volume is either a cubic meter or a cubic foot of concrete. The absolute volume method of mix proportioning (ACI 211), explained below, involves using relative density (specific gravity) values for all the ingredients to calculate the absolute volume each will occupy in a unit volume of concrete (see page 184). If the aggregate grading has been calculated using the Shilstone approach described above, then some of the steps in ACI 211 are unnecessary.

Further information on this and other methods can be found in the standard practices developed by ACI 211 (2002) and Kosmatka et al. (2002). Hover (1994 and 1995) provides a graphical process for designing concrete mixtures, and Thomas and Wilson (2002) provide a self-contained training program on compact disk for selecting mix characteristics in accordance with ACI 211.1.

The Absolute Volume Method

The absolute volume method of mixture proportioning may be summarized in 12 steps:

Step 1: Concrete Strength

The specified strength of a concrete mix is selected considering both the structural and durability requirements of the concrete. The strength (flexural or compressive) required to resist the loads applied to the structure is part of the thickness design (see Concrete Strength in chapter 2, page 16). Some durability issues can be addressed with a limit on the w/cm ratio (see Permeability in chapter 5, page 131).

In order to be reasonably sure of meeting the specified strength, the average design strength of a concrete mix, f´cr, must be greater than the specified strength, f´c, to account for variations in materials and variations in the production, curing, and testing of cylinders. See ACI 301, section 4.2.3, for a statistical approach for determining the required average strength.

Step 2: Water-Cementitious Material Ratio

The w/cm ratio is simply the mass of water divided by the mass of cementitious materials (portland cement; blended cement; fly ash; ground, granulated blast-furnace [GGBF] slag; silica fume; and natural pozzolans). The w/cm ratio used in the mix design should be the lowest value required to meet both strength and durability requirements.

ACI 318 (and AASHTO) has requirements for various exposure conditions (see chapter 5, table 5-4, page 140, for requirements for concrete exposed

W/C or W/CM Ratio?

The w/cm ratio is often used synonymously with water-to-cement (w/c) ratio; however, some specifications differentiate between the two ratios. Traditionally, w/c refers to the mass ratio of water to portland cement or to blended cement, while w/cm refers to the mass ratio of water to cement plus any supplementary cementitious materials in the concrete.

to sulfates). When durability does not control, the w/cm ratio should be selected on the basis of concrete strength (figure 6-5). In such cases, the w/cm ratio and mixture proportions for the required strength should be based on adequate field data or trial mixtures made with actual job materials to determine the relationship between the ratio and strength. The type of supplementary cementitious materials should be known and allowed for when selecting the w/cm ratio.

Step 3: Aggregates

Grading (particle size and distribution), shape, porosity, and surface texture of the aggregate have an important influence on proportioning concrete mixtures because these characteristics affect the workability—and therefore the water demand—of the concrete (see Aggregate Gradation in chapter 3, page 44).

The most desirable fine-aggregate grading will depend on the type of work, the paste content of the mixture, and the size of the coarse aggregate. For leaner mixtures, a fine grading (lower fineness modulus) is desirable for workability. For richer mixtures, a coarse grading (higher fineness modulus) is used for greater economy.

The quantity (bulk volume) of coarse aggregate can be estimated using figure 6-6. The values in the tables are based on aggregates in a dry-rodded condition (ASTM C 29). They are suitable for producing concrete with a moderate workability suitable for general concrete construction. For less workable concrete (slipform paving), the bulk volume may be increased by about 10 percent.

Following is a list of key considerations when evaluating local aggregates:

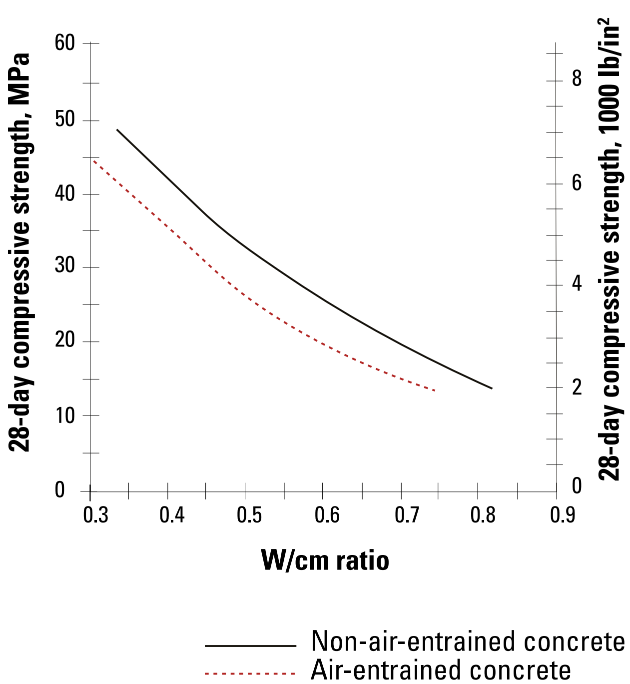

Figure 6-5. Approximate relationship between compressive strength and w/cm ratio for concrete using 19-mm to 25-mm (3/4 in. to 1 in.) nominal maximum size coarse aggregate. Strength is based on cylinders moist-cured 28 days per ASTM C 31 / AASHTO T 23. (Adapted from ACI 211.1, ACI 211.3, and Hover 1995)

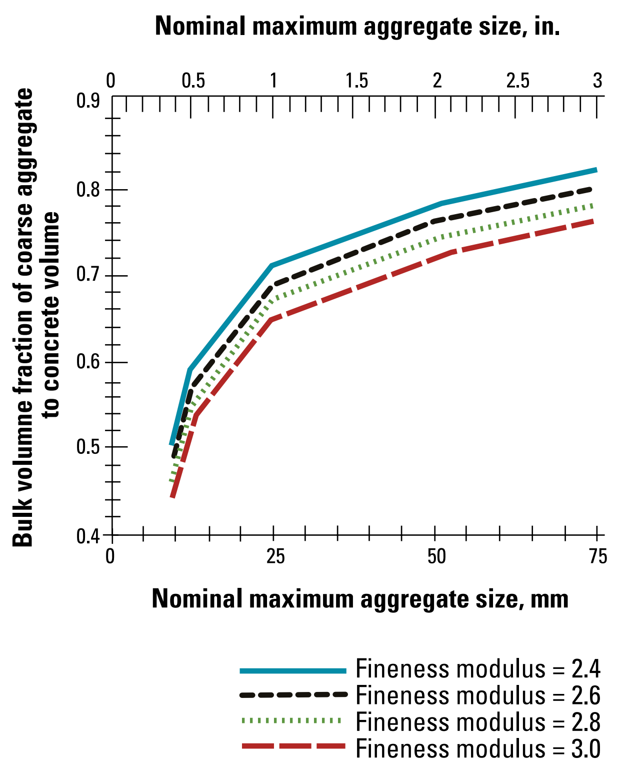

Figure 6-6. Bulk volume of coarse aggregate per unit volume of concrete. Bulk volumes are based on aggregates in a dry-rodded condition (ASTM C 29 / AASHTO T 19). For less workable concrete (slipform paving), the bulk volume may be increased by about 10 percent. (Adapted from ACI 211.1 and Hover 1995)

1. The largest maximum size consistent with the requirements for placing the concrete will produce the most economical concrete with the least tendency to crack due to thermal effects or autogenous, plastic, or drying shrinkage.
2. The maximum size should generally not exceed one-fourth the thickness of the pavement or 64 mm (2.5 in.), whichever is less.
3. In areas where D-cracking in pavements is known to be a problem, a smaller maximum size may help mitigate the problem. Testing at the reduced maximum size is advisable.
4. Aggregates should contain no more than the specified percentages of deleterious materials listed in ASTM C 33/AASHTO M 6/M 43 or in the contract specifications.

Step 4: Air Content

Concrete that will be exposed to cycles of freezing and thawing should be adequately air-entrained. The amount of air required (figure 6-7) is a function of the severity of exposure and the maximum size of aggregate used in the concrete. Testing for spacing factors by ASTM C 457 or use of the air-void analyzer will give better assurance of freeze-thaw durability.

Step 5: Workability/Slump

Concrete must always be made with a workability, consistency, and plasticity suitable for job placement conditions. The slump test is used to measure concrete consistency.

However, slump is only indicative of workability when assessing similar mixes and should not be used to compare mixes of significantly different proportions. Also, the slump test is not a true indicator of concrete for slipform paving. Typical slump requirement for side-form concrete is 25 to 75 mm (1 to 3 in.) and for slipform concrete is 12.5 to 50 mm (0.5 to 2 in.). Workability must be assured for the given mixture characteristics, the project paving equipment, and expected ambient conditions at time of paving.

Step 6: Water Content

The amount of water required in a concrete mix depends on several factors:

1. Slump requirements of the job.
2. Aggregate size, texture and shape.
3. Air content.
4. Amount of cementitious material.
5. Temperature of the concrete.

Water content can be reduced by incorporating water-reducing admixtures (see Water Reducers in chapter 3, page 58).

For batch adjustments, the slump can be increased by about 10 mm by adding 2 kg of water per cubic meter of concrete (by about 1 in. by adding 10 lb of

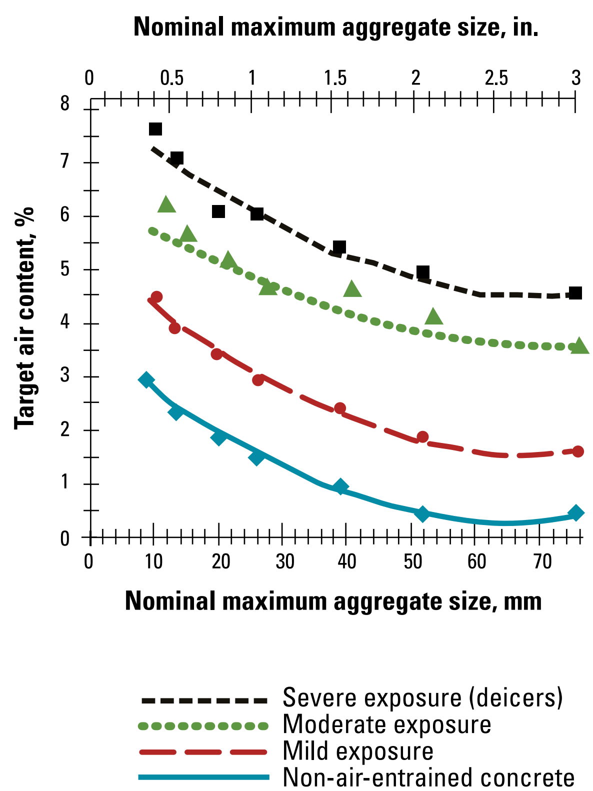

Figure 6-7. Target total air content requirements for concretes using different sizes of aggregate. The air content in job specifications should be specified to be delivered within –1 to +2 percentage points of the target value for moderate and severe exposures. (Adapted from ACI 211.1 and Hover 1995)

water per cubic yard). The water content required for air-entrained concrete can be determined from figure 6-8. For some concretes and aggregates, the water estimates can be reduced by approximately 10 kg (20 lb) for subangular aggregate, 20 kg (35 lb) for gravel with some crushed particles, and 25 kg (45 lb) for a rounded gravel to produce the slumps shown. This illustrates the need for trial batch testing of local materials, as each aggregate source is different and can influence concrete properties differently.

See ACI 211.1 for the requirement for non-air-entrained concrete. Air-entrained concrete has a lower water demand than non-air-entrained concrete, and this allows the quantity of mix water required for a given level of durability to be reduced. (Rule of thumb: Decrease water by 3 kg/m³ [5 lb/yd³] for each 1 percent air).

(For requirements regarding water quality, including the use of recycled water, see Water in chapter 3, page 52.)

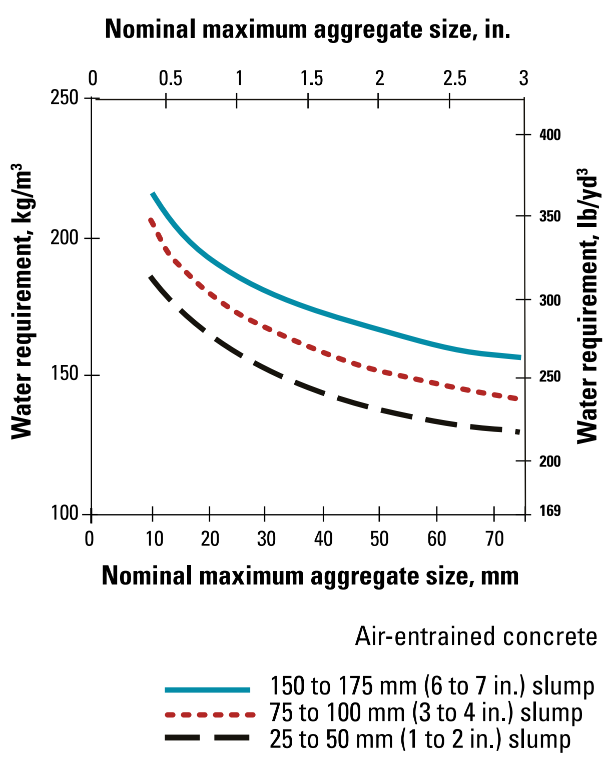

Figure 6-8. Approximate water requirement for various slumps and crushed aggregate sizes for air-entrained concrete (Adapted from ACI 211.1 and Hover [1995])

Step 7: Cementitious Materials Content

The cement content is calculated by dividing the water content by the water-cementitious materials (w/cm) ratio.

$$\textit{Cementitious Materials Content} = \frac{\textit{Required Water Content}}{\textit{w/cm Ratio}}$$

However, it is not unusual for a minimum cement content to be specified for a particular job for the purpose of durability, finishability, or improved abrasion resistance. For severe freeze-thaw, deicer, and sulfate exposures, it is desirable to specify the following:

1. A minimum cementitious materials content of 335 kg/m³ (564 lb/yd³) of concrete.
2. Only enough mixing water to achieve the desired consistency.

See ACI 302 for minimum cementitious material contents for concrete flatwork.

Step 8: Cementitious Materials Type

Note: Mix designers may do this step first, because the type of cementitious materials selected can affect the previous seven steps.

The cement type is selected to meet any special requirements, like sulfate resistance, alkali-silica reactivity, or low-heat requirements. Fly ash reduces water demand, silica fume (and to a lesser effect metakaolin) increases it, and GGBF slag has a minimal effect on water demand.

Changes in the volume of cementitious material components due to different specific gravities (portland cement = 3.15; fly ash = 1.9 to 2.8; silica fume = 2.25; GGBF slag = 2.85 to 2.95; metakaolin = 2.5) should be considered. Supplementary cementitious materials (SCMs) also change the relationship between the w/cm ratio and strength. The ACI 318 Building Code places limits on the maximum amount of SCM allowed in concrete exposed to deicing salts (table 6-3) (see Sulfate Resistance in chapter 5, page 139).

Step 9: Admixtures

The quantities of admixtures are calculated to provide the required air and water-reducing effect. Consideration must also be given to ensuring that the chloride limits for reinforced concrete are not exceeded when using calcium chloride as an a accelerator or other chloride-containing admixtures.

Incorporating certain chemical admixtures will result in changes to the water requirement or the air content of concrete (see Set-Modifying Admixtures in chapter 3, page 59):

1. Water reducers typically decrease water requirements by 5 to 10 percent and may increase air content by up to 1 percent.
2. Calcium chloride-based admixtures reduce water requirements by about 3 percent and increase air by up to 0.5 percent.
3. Retarding admixtures may increase air content.

Table 6-3. Cementitious Materials Requirements for Concrete Exposed to Deicing Chemicals

Cementitious materials*	Maximum percent of total cementitious materials by mass**
Fly ash and natural pozzolans	25
GGBF slag	50
Silica fume	10
Total of fly ash, GGBF slag, silica fume and natural pozzolans	50***
Total of natural pozzolans and silica fume	35***

Source: Adapted from ACI 318

* Includes portion of supplementary cementitious materials in blended cements.

** Total cementitious materials include the summation of portland cements, blended cements, fly ash, slag, silica fume, and other pozzolans.

*** Silica fume should not constitute more than 10% of total cementitious materials and fly ash or other pozzolans shall not constitute more than 25% of cementitious materials.

Step 10: Fine Aggregate

Fine aggregate amount is determined after the quantities of coarse aggregate, air, water, and cementitious materials are known.

In the absolute volume method, these quantities are converted to volumetric proportions using the appropriate specific gravity (relative density) of the material. These volumes are then subtracted from a unit volume (1 m^3 or 1 ft^3/1 yd^3) to give the required volume of sand.

The volume of sand is then converted to a mass proportion using its specific gravity. If the combined aggregate grading has been optimized (see page 176), then the sand quantity calculated here must be checked against the amount indicated by the optimization calculation.

Step 11: Moisture/Absorption Correction

Corrections are needed to compensate for moisture in and on the aggregates. In practice, aggregates will contain some measurable amount of moisture. The dry-batch weights of aggregates, therefore, have to be increased to compensate for the moisture that is absorbed in and contained on the surface of each particle and between particles. The mixing water added to the batch must be reduced by the amount of free moisture contributed by the aggregates. The magnitude of the water correction should be equal to the correction made to the aggregate; the overall mass of material in the unit volume must remain unchanged.

Consider the following example of aggregate moisture correction: A particular mix design calls for 1,800 lb/yd^3 of fine aggregate. The measured absorption of the aggregate is 1.8 percent by mass of sample, and the in-storage aggregate moisture content is 2.8 percent. Therefore, the aggregate contains 1 percent of water above the amount the aggregate absorbed. To determine the amount of water that must be withheld from the batch, multiply 1 percent by 1,800 lb: 18 lb.

Step 12: Trial Batches

At this stage, the estimated batch weights should be checked through trial laboratory batches and full-size field batches. Enough concrete must be mixed for appropriate air and slump tests and for casting the cylinders required for compressive-strength tests, plus beams for flexural tests if necessary. The batch proportions are multiplied by the volume of the batch required to produce the actual quantities required for mixing (see Laboratory Mixtures in this chapter., page 173).

Computing Absolute Volume

The absolute volume of a granular material (such as cement and aggregates) is the volume of the solid matter in the particles; it does not include the volume of air spaces between particles. The volume (yield) of freshly mixed concrete is equal to the sum of the absolute volumes of the concrete ingredients—cementitious materials, water (exclusive of that absorbed in the aggregate), aggregates, admixtures when applicable, and air. The absolute volume is computed from a material's mass and relative density (specific gravity) as follows:

$$\text{Absolute Volume} = \frac{\text{Mass of Loose Material}}{\text{Relative Density of a Material} \times \text{Density of Water}}$$

A value of 3.15 can be used for the relative density (specific gravity) of portland cement.

Blended cements have relative densities ranging from 2.90 to 3.15.

The relative density of fly ash varies from 1.9 to 2.8, GGBF slag from 2.85 to 2.95, and silica fume from 2.20 to 2.25.

The relative density of water is 1.0, and the density of water is 1,000 kg/m^3 (62.4 lb/ft^3) at 4°C (39°F) (accurate enough for mix calculations at room temperature).

The relative density of normal aggregate usually ranges between 2.4 and 2.9. The relative density of aggregate as used in mix design calculations is the relative density of either saturated surface-dry (SSD) material or oven-dry material.

Relative densities of admixtures, such as water reducers, can also be considered if needed.

Absolute volume is usually expressed in cubic meters (cubic feet).

The absolute volume of air in concrete, expressed as cubic meters per cubic meter (cubic feet per cubic feet), is equal to the total air content in percent divided by 100 (for example, 7% ÷ 100) and then multiplied by the volume of the concrete batch.

The volume of concrete in a batch can be determined by either of two methods:

1. If the relative densities of the aggregates and cementitious materials are known, these can be used to calculate concrete volume.
2. If the relative densities are unknown or if they vary, the volume can be computed by dividing the total mass of materials in the mixer by the density of concrete. In some cases, both determinations are made, one serving as a check on the other.

Adjusting Properties

Key Points

- Achieving the required properties in the concrete may require making adjustments to the materials selected, to materials proportions, or even to other factors such as temperature.
- Refer to corresponding sections of chapter 5 for descriptions of various concrete properties and related tests and specifications.

Chapter 5 describes the properties (and related tests) that are required to achieve a constructable concrete mix and a durable concrete pavement. This section outlines some adjustments that can be made to a mix to achieve these properties. Adjustments may include changes in the materials selected or in their proportions.

Sometimes, the required properties may impose mutually exclusive demands on the mix design. Mix proportioning is, therefore, a series of decisions to find the best compromise among competing needs.

Workability

Fresh concrete mixtures must possess the workability—including mobility, compactability, stability, and freedom from segregation—required for the job conditions (Kosmatka et al. 2002; Mindess et al. 2003). The following can be adjusted to achieve the desired workability (Scanlon 1994; Mindess et al. 2003):

- Water content: Increasing the water content of concrete will generally increase the ease with which the concrete flows. However, increased water content will reduce the strength and increase the permeability of the hardened concrete and may result in increased segregation. Shrinkage also increases with increased water content.
- Proportion of aggregate and cement: In general, an increase in the aggregate-to-cement ratio will reduce workability. As the aggregate grading becomes finer (particle sizes are reduced), more cement is required to maintain the same consistency. Further, mixtures containing little cement are often harsh, whereas mixtures rich in cement are generally more workable but may become sticky and difficult to finish if too much cement is used. Mixtures deficient in fine aggregate will be harsh, prone to segregation, and difficult to finish, whereas mixtures made with an excess of fine aggregate are typically more permeable and less economical, although readily workable. The use of finer sand will also reduce workability unless water content is increased, whereas concrete made with coarse sand is often difficult to finish.
- Aggregate properties: In general, the more spherical the aggregate, the more workable the concrete, due to a reduction in mechanical interlock that occurs with angular particles. A high degree of flat and/or elongated coarse aggregate particles will reduce workability, as will the use of rough-textured aggregate versus smooth aggregate.
- Cement characteristics: Although less important than aggregate properties, finer cement (e.g., Type III) reduces workability at a given water-to-cement ratio.
- Admixtures: The use of air-entraining admixtures will increase workability by creating small, spherical bubbles that act as ball bearings in the fresh concrete. As the name implies, water-reducing admixtures will also increase workability if other mixture design parameters are not changed. Pozzolans and finely divided materials, including inert, cementitious materials, generally improve workability when used to replace part of the sand instead of the cement.
- Time and temperature: As ambient temperature increases, workability decreases. Yet over short periods of time, temperature appears to have little effect. Workability decreases with time as hydration proceeds. Also, increases in workability achieved through the use of water-reducing admixtures are often relatively short-lived.

The slump test (ASTM C 143 / AASHTO T 119) is most often used to measure the workability of fresh concrete. Although this test does not measure all factors contributing to workability, it is convenient as a control test, providing an indication of consistency from batch to batch (Scanlon 1994). In general, concrete used for paving is relatively stiff, with slipform paving mixtures having slump values specified between 12.5 and 50 mm (0.5 and 2 in.).

Stiffening and Setting

The rates of stiffening and setting of a concrete mixture are critically important for the contractor because they will directly influence its ability to be placed, finished, and sawed without surface blemishes and cracking.

Both stiffening and setting can be affected by the following in the concrete mixture:

- Cementitious materials: The rate of stiffening and setting of a concrete mixture will be primarily controlled by the cement content, chemistry, and fineness. Generally, setting is delayed with increasing dosages of ground, granulated blast-furnace slag and fly ash, although the presence of tricalcium aluminate (C_3A) in some fly ashes may result in false set, particularly at elevated temperatures. It is important to make trial mixes using the materials available at the plant to check for incompatibility (see Potential Materials Incompatibilities in chapter 4, page 97.)
- Chemical admixtures: Chemical retarders and accelerators are available to assist with controlling set time, but they generally do not influence the rate of slump loss. Some chemical admixtures may react with some cements or supplementary cementitious materials to cause early stiffening.
- Aggregate moisture: If aggregates are dry when the mixture is batched, it is likely that water absorbed into the aggregate will cause excessive slump loss. The amount of water added during batching must be adjusted for the moisture conditions of the aggregates in order to meet the water requirement of the mix design and keep a constant water-cementitious materials ratio (see Step 11, page 183). Ideally, aggregates should be at or near an SSD state.
- Temperature: The higher the temperature, the shorter the setting time and the higher the risk of incompatibility issues. Use chilled water or ice to reduce the mix temperature to 16 to 21°C (60 to 70°F) where possible.
- Water-cementitious materials (w/cm) ratio: A lower w/cm ratio reduces set time.

Bleeding

Bleeding, as described in chapter 5, is the development of a layer of water on the surface of freshly placed concrete. Bleeding is caused by the settlement of cement and aggregate particles in the mixture and the simultaneous upward migration of water (Kosmatka et al. 2002).

A number of techniques can be used to prevent or minimize bleeding in the mix design stage, including the following (Kosmatka 1994):

- Reducing the water content, water-cementitious materials ratio, and slump.
- Increasing the amount of cement or supplementary cementitious materials in the mix (resulting in a reduced w/cm ratio).
- Increasing the fineness of the cementitious materials.
- Using properly graded aggregate.
- Using certain chemical admixtures such as air-entraining agents may be effective in reducing bleeding.

Air-Void System

The air-void system of concrete is fundamentally important to the durability of concrete in environments subject to freezing and thawing. It includes total air content, spacing factors, and the specific surface.

The air-void system in a concrete mix can be controlled with the following adjustments (Whiting and Nagi 1998):

- Cement: Increasing alkali content and decreasing fineness in a cement is likely to result in increased entrained air.

- Supplementary cementitious materials: Increasing the carbon (LOI) content of fly ash will rapidly reduce the amount of air entrained for a given air-entraining admixture (AEA) dosage. Small variations in a fly ash composition may result in large swings in the air content, making production of uniform concrete difficult. The use of GGBF slag or silica fume may require the use of an additional air-entraining admixture to achieve the desired air content.
- Aggregates: Increasing the amount of material retained on the 600- to 300-μm sieves (#30 to #50) will result in increased air entrainment.
- Workability: Increasing workability will result in increased air content for a given concrete mix.

Trial batching prior to the start of the job will indicate the air contents expected with the job-specific materials, batching sequence, and mixing time and speed. However, the air-void system in the field will be affected by the following factors:

- Changes in the grading of the aggregates: The air content requirement decreases with an increase in large-size aggregate, and air content increases with an increased fine aggregate content, especially with an increase in the 600- to 300-μm (#30 to #50) sizes.
- Water: Air content increases with extra water.
- Admixture dosage: Air content increases with an increase in water-reducing and retarding admixtures based on lignin.
- Delays. Some air loss is expected during delivery and with time.
- Temperature. An increase in temperature will require an increase in the amount of air-entraining admixture to maintain the target air content (Whiting and Nagi 1998).

Density (Unit Weight)

Conventional concrete, normally used in pavements, has a density (unit weight) in the range of 2,200 to 2,400 kg/m^3 (137 to 150 lb/ft^3). The density of concrete varies, depending on the amount and density of the aggregate, the amount of air entrapped or purposely entrained, and the water and cement contents, which in turn are influenced by the maximum size of the aggregate. Density is a useful indicator of batching uniformity and consolidation. Density is affected by the following factors:

- Density of the material in the mixture, with the most influence from the coarse aggregate.
- Moisture content of the aggregates.
- Air content of the mixture.
- Relative proportions of the materials, particularly water.

The density (unit weight) and yield of freshly mixed concrete are determined in accordance with ASTM C 138 (AASHTO T 121) (see chapter 9, page 258). The results should be sufficiently accurate to determine the volumetric quantity (yield) of concrete produced per batch. The test can also indicate air content, provided the relative densities of the ingredients are known.

Strength

The pavement designer establishes the concrete strength requirement that meets the intent of the design. Strength and rate of strength gain are influenced by the following factors:

- Water-cementitious materials ratio: Reducing the w/cm ratio will increase strength.
- Cement chemistry: Cements with high alkali and tricalcium silicate, or alite (C_3S), contents and high fineness will tend to gain strength more quickly, although long-term strengths may be slightly reduced.
- SCMs: GGBF slag and Type F fly ash may reduce early strength gain, but will normally result in higher long-term strengths.
- Chemical admixtures: Water reducers that effectively decrease the w/cm ratio will result in increased strengths. Retarders may reduce early strengths but increase long-term strengths.
- Aggregates: Optimizing aggregate grading will help reduce the water requirement of the system with a consequent strength increase. Using crushed coarse aggregates and increasing coarse aggregate size will increase flexural strengths.
- Temperature: Increasing temperature will increase early strengths and suppress later strengths.

During construction, changes in the environmental conditions and variations in materials, consolidation, and curing affect the strength at a specified age and affect strength development with age. Increased temperatures will increase early strength but may suppress long-term strength gain.

Quality control measures will indicate whether the strength gain is as expected. Generally, the strength gain of the specimens sampled and cured in a standard manner are determined, which indicates the potential of the mixture. However, the strength gain of the in-place concrete is also very important, and test procedures are available to estimate that.

Volume Stability

Concrete experiences volume changes (i.e., shrinkage/contraction or expansion) as a result of temperature and moisture variations.

To minimize the risk of cracking, it is importance to minimize the tendency to change in volume by considering the following:

- Paste content: The most important controllable factor affecting drying shrinkage is the amount of water per unit volume of concrete. Shrinkage can be minimized by keeping the water content of concrete as low as possible. Water content is normally controlled by controlling the maximum w/cm ratio This is achieved by keeping the total coarse aggregate content of the concrete as high as possible (minimizing paste content).
- Aggregates: Avoid aggregates that have high drying shrinkage properties and aggregates that contain excessive amounts of clay. Quartz, granite, feldspar, limestone, and dolomite aggregates generally produce concretes with low drying shrinkages (ACI Committee 224). Aggregate selection will also have the greatest influence on thermal expansion.
- Curing: The longer and more effective the curing practices, the lower the shrinkage will be. Good curing will also allow the concrete to gain more strength and thus be better able to resist the shrinkage stresses and reduce the risk of cracking.

Permeability and Frost Resistance

Permeability is a direct measure of the potential durability of a concrete mixture.

Lower permeability can be achieved by making the following adjustments:

- Increasing the cementitious materials content.
- Reducing the water-cementitious materials ratio.
- Using supplementary cementitious materials at dosages appropriate to the expected likelihood of freezing weather.
- Using good curing practices.
- Using materials resistant to the expected form of chemical attack (e.g., GGBF slag is preferred for chloride penetration, while Class F fly ash can improve sulfate resistance).
- Using aggregates that have a proven history of resistance to D-cracking. Reducing maximum coarse aggregate size will reduce the risk of damage if aggregates prone to damage are unavoidable.
- Ensuring that a satisfactory air-void system is provided in the concrete.

Abrasion Resistance

Abrasion resistance is required to maintain skid resistance in a pavement. This can be improved with the following adjustments:

- Choosing hard, dense, siliceous aggregates.
- Increasing compressive strength.
- Increasing the curing time.

Sulfate Resistance

Sulfate attack is a problem when concrete is exposed to substrates that have high sulfate contents. Resistance to such attacks can be improved by making the following adjustments:

- Reducing the w/cm ratio to reduce permeability.
- Using a sulfate-resisting cement (ASTM C 150 Type II, or for more resistance Type V; ASTM C 595 Types IP[MS], IS[MS], I[PM][MS], I[SM][MS], or P[MS]; or ASTM 1157 Types MS or HS).
- Using Class F fly ash (15 to 25 percent).
- Using 20 to 50 percent GGBF slag for moderate sulfate resistance.

- Using a higher percent of supplementary cementitious materials through ternary mixes.

Alkali-Silica Reaction

Deleterious expansion of pavements due to alkali-silica reaction can be a serious problem. Reduction of this reaction can be achieved by making the following adjustments:

- Using aggregates that have a history of satisfactory performance.
- Using low-alkali cement. (Using low-alkali cements may not mitigate all situations.)
- Using supplementary cementitious materials, which has been shown to reduce the expansion of a given system.
- Perhaps using lithium admixtures. (The effectiveness of lithium has not been proven, and no accepted testing protocols exist.)
- Perhaps blending reactive aggregate with non-reactive aggregate.

The PCA's *Guide Specification for Concrete Subject to Alkali-Silica Reactions* (PCA 1998) provides guidance on evaluating and selecting systems that can be used to prevent deleterious expansion when potentially reactive aggregates are used.

References

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AASHTO T 23, Test Method for Making and Curing Concrete Test Specimens in the Field

AASHTO T 119, Test Method for Slump of Hydraulic Cement Concrete

AASHTO T 121, Test Method for Density, Yield, and Air Content of Concrete

AASHTO M6, Specification for Fine Aggregate for Portland Cement Concrete

AASHTO M 43, Specification for Sizes of Aggregate for Road and Bridge Construction

ASTM standards may be found in *Annual Book of ASTM Standards*, ASTM International. www.astm.org.

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ASTM C31, Standard Practice for Making and Curing Concrete Test Specimens in the Field

ASTM C 33, Standard Specification for Concrete Aggregates

ASTM C 138, Standard Test Method for Density, Yield, and Air Content of Concrete

ASTM C 143, Test Method for Slump of Hydraulic Cement Concrete

ASTM C 150, Standard Specification for Portland Cement

ASTM C 457, Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

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Chapter 7

Preparation for Concrete Placement

Other than early-age cracking, the most common cause of distress in a pavement is failure of the subgrade or base below the pavement. It is important that a concrete pavement or slab be provided suitable support that is uniform, level, and able to carry the loads imposed.

Before the concrete pavement is placed, the existing subgrade must be properly prepared and compacted. On top of this, a base is usually constructed. It is also essential to pay attention to the levelness or grade of the base. Concrete on a base with irregular grades will have variable thickness, potential thin spots, and a tendency to roughness.

This chapter provides a brief outline of subgrade and base preparation issues that are critical to the life of the concrete pavement. The information is limited to that which is relevant to the pavement system; it is not a full discussion of construction practice. More detailed information can be found through the American Concrete Pavement Association, www.pavement.com.

Subgrades

Key Points

- The subgrade is the natural ground, graded and compacted, on which the pavement is built.
- A uniform and stable subgrade is required for long-term durability of the pavement. (In general, subgrade uniformity and stability are more important than subgrade strength for pavement performance.)
- Three major causes of subgrade nonuniformity—expansive soils, frost action, and pumping—must be controlled.
- Pavement subgrades may need to be improved temporarily (soil modification) or permanently (soil stabilization) through the use of additives or binders.

The subgrade is the natural ground, graded and compacted, on which the pavement is built. Subgrade uniformity and stability affect both the long-term performance of the pavement and the construction process. Requirements for subgrade preparation may vary considerably, depending on soil type, environmental conditions, and amount of heavy traffic. In any case, the objective is to obtain uniform support for the pavement that will prevail throughout its service life.

Preparation of the subgrade includes the following activities:

1. Compacting soils at moisture contents and densities that will ensure uniform and stable pavement support.
2. Whenever possible, setting grade lines high enough and making side ditches deep enough to increase the distance between the water table and the pavement.
3. Cross-hauling and mixing soils to achieve uniform conditions in areas where there are abrupt horizontal changes in soil types.
4. Using selective grading in cut and fill areas to place the better soils nearer to the top of the final subgrade elevation.
5. Improving extremely poor soils by treating them with lime, cement, cement kiln dust, or fly ash, or by importing better soils, whichever is more economical.

Uniform Support

Due to its rigid nature, a concrete pavement distributes the pressure from applied loads over a larger area of the supporting material. As a result, deflections are small and pressures on the subgrade are low (ACPA 1995). Concrete pavements, therefore, do not require especially strong foundation support.

More important than a strong foundation is a uniform foundation. The subgrade should have a uniform condition, with no abrupt changes in the degree of support (figure 7-1). That is, there should be no hard or soft spots. Nonuniform support increases localized deflections and causes stress concentrations in the pavement. Localized deflections and concentrated stresses can lead to premature failures, fatigue cracking, faulting, pumping, rutting, and other types of pavement distress.

Providing reasonably uniform support conditions beneath the concrete slab requires controlling three major causes of subgrade nonuniformity:

1. Expansive soils.
2. Frost action.
3. Pumping.

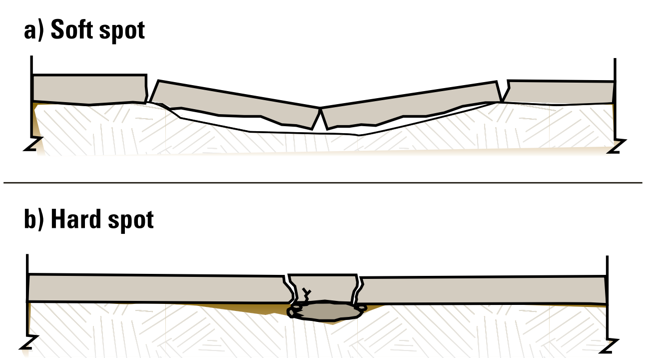

Figure 7-1. Effects of two examples of nonuniform support on concrete slabs on the ground (Farny 2001)

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Expansive Soils

Excessive differential shrinkage and swelling of expansive soils can cause nonuniform subgrade support. As a result, concrete pavements may become distorted enough to impair riding quality. Several conditions can lead to expansive soils becoming a problem under concrete pavements:

1. The expansive soils were compacted too dry or allowed to dry out before paving.
2. The expansive soils have widely varying moisture contents, leading to subsequent shrinkage and swelling.
3. There are abrupt changes in soil types and associated volume-change capacities along the project.

The key to minimizing the effects of potentially expansive soils is to identify and treat them early in the process. Table 7-1 lists simple index tests that can be performed to determine the potential for expansion in soils.

Procedures such as ASTM D 1883, ASTM D 3152, ASTM D 4546, ASTM D 4829, and CALTRANS Test 354 are especially suitable for evaluating the volume change of subgrade soils. Some factors determined by these tests that are not indicated by the simple index tests are the following:

- The effect of compaction moisture and density on soil swell characteristics.
- The effect of surcharge loads.
- Expansion for the total sample grading rather than for only a finer grading fraction of the soil.

Frost Action

Frost action includes the effects of both frost heave and subgrade softening. However, only frost heave is a consideration for concrete pavements. (Field experience has shown that subgrade softening, which occurs in the spring in many areas of the United States, is not a design factor because strong subgrade support is not required under concrete pavements. Concrete pavement reduces pressure on the subgrade layers by distributing applied traffic loads over large areas. Concrete pavements designed for typical subgrade conditions will have ample reserve capacity for the two to three weeks of the spring softening of the subgrade.)

Frost heave occurs when ice lenses form in the soil, which continue to attract water and expand further. The heaving itself is not a problem for concrete pavements; rather, it is the subsequent thawing and differential settling of the concrete slabs that can lead to roughness and/or cracking.

For frost heave to occur, all three of the following conditions must be present:

1. A frost-susceptible soil.
2. Freezing temperatures that penetrate the subgrade.
3. A supply of water.

Controlling any one of the three conditions will dramatically reduce the potential for frost heave.

The degree of frost susceptibility of a particular soil is related to its capillarity, or suction, and its permeability (figure 7-2).

Table 7-1. Soil Index Properties and Their Relationship to Potential for Expansion (Bureau of Reclamation 1998)

Degree of expansion	Data from index tests*			Estimation of probable expansion,** percent total volume change (dry to saturated condition)
	Plasticity index, percent (ASTM D 4318)	Shrinkage limit, percent (ASTM D 427)	Colloid content, percent minus 0.001mm (ASTM D 422)	
Very high	>35	<11	>28	>30
High	25 to 41	7 to 12	20 to 31	20 to 30
Medium	15 to 28	10 to 16	13 to 23	10 to 20
Low	<18	>15	<15	<10

* All three index tests should be considered in estimating expansive properties.
** Based on a vertical loading of 7 kPa (1.0 lb/in^2). For higher loadings the amount of expansion is reduced, depending on the load and the clay characteristics.

Low-plasticity, fine-grained soils with a high percentage of silt particles (0.005 to 0.05 mm [0.0002 to 0.002 in.]) are particularly sensitive to frost heave. These soils have pore sizes small enough to develop capillary potential and large enough to permit water to travel to the frozen zone. Coarser soils accommodate higher rates of flow, but lack the capillary potential to lift moisture from the water table. More cohesive soils, although they have high capillarity, have low permeability, which prevents water from moving quickly enough to form ice lenses in the soil.

Pumping

Pumping is the forceful displacement of a mixture of soil and water (i.e., mud) from underneath a concrete pavement during heavy applied loads. Continued, uncontrolled pumping eventually leads to the displacement of enough soil so that uniformity of the subgrade is destroyed, which can result in cracking, faulting, and settling of the concrete pavement.

Three factors are necessary for pumping to occur:

1. Pump-susceptible material beneath the slab.
2. Free water between the pavement and subgrade or base.
3. Rapid and large deflections of the pavement slabs.

Controlling any one of these three factors by providing good load transfer between panels and well-drained support using appropriate materials will dramatically reduce the potential for pumping.

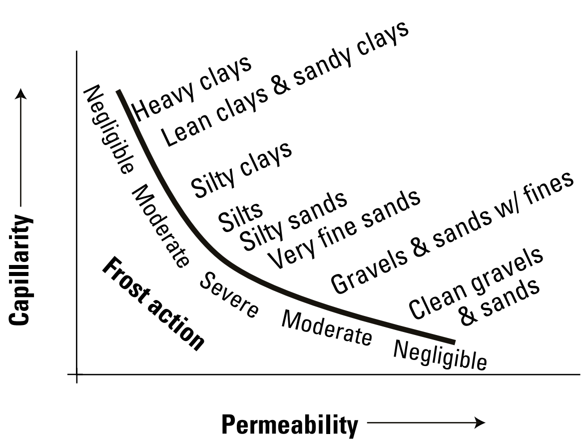

Figure 7-2. Relationship between frost action and hydraulic properties of soils (ACPA 1995)

Grading and Compaction

Grade preparation lays the foundation for the entire pavement structure. The uniformity and stability of the subgrade affect both the long-term performance of the pavement and the rest of the construction process. The important elements of subgrade preparation include evaluating subgrade stability and uniformity, modifying the subgrade to improve stability, and evaluating surface tolerances.

Pre-Grading

The first step in preparing the subgrade is to determine areas for cross-hauling and mixing of soil types to establish uniformity. Silt pockets can be removed, and expansive soils can be placed in lower parts of embankments to reduce swell potential. Mass grading is accomplished in this phase, which involves cutting high points and filling low spots to roughly achieve the desired alignment.

Moisture-Density Control

Subgrade volume changes are reduced by adequate moisture and density control during compaction. Expansive and frost-susceptible soils should be compacted at one to three percent above optimum moisture using ASTM D 698 / AASHTO T 99.

Improving Soil Characteristics

Pavement subgrades may need to be improved for a number of reasons:

1. To improve low strength soil.
2. To reduce swelling potential.
3. To improve construction conditions.

Subgrades may be improved through the use of additives or binders. Commonly used materials for soil improvement include cement, cement kiln dust, lime, lime kiln dust, and fly ash. Which material is used and at what addition rate depends on the type of soil, amount of stability desired, and the length of time necessary. If the subgrade support is needed only during the construction phase to support construction vehicles, the process is termed “soil modification” or “cement-modified soil.” If the support is intended to be permanent and function as a supportive layer to the pavement, the process is termed “soil stabilization” or “soil-cement base.” Certain techniques, additives, or addition rates lend themselves to temporary soil modification, while others are often used for the more permanent soil stabilization.

For more information on soil characteristics, refer to www.cement.org/pavements/pv_sc.asp.

Trimming

Once the subgrade has been compacted to the desired density at the proper moisture level and/or treated to reduce expansion potential, it is trimmed to the proper grades, elevations, and cross-slopes. Typically, a string line is set up to guide an automatic trimmer at the correct grade. For fixed-form construction, an automatic trimmer can ride on the forms after they are fastened into place (figure 7-3). For smaller projects or pavements without a smoothness specification, the grade is not typically trimmed according to a string line, but is graded with a motor grader or small loader and then spot-checked from survey hubs set approximately 15 m (50 ft) apart (ACPA 2003).

Proof-Rolling

Proof-rolling can locate isolated soft areas that are not detected in the grade inspection process. It involves driving a heavy, pneumatic-tired vehicle over the prepared grade while observing for rutting or deformation. A fully-loaded tandem axle truck or rubber-tired loader may be used as the proof-roller. Steel drum rollers are not recommended because they may potentially distribute the load across soft areas without any observed movement. Proof-rolling is recommended if an unstabilized base is to be used between the concrete pavement and subgrade.

Figure 7-3. Autograder that references the string line and trims the subgrade material (ACPA)

Bases

Key Points

- A base is defined as the layer of material that lies immediately below the concrete pavement.
- Bases may be constructed of granular materials, cement-treated materials, lean concrete, or open-graded, highly permeable materials, which may be stabilized or unstabilized.
- As with subgrades, the most important characteristics of a base are uniformity and adequate support.
- Balance must be achieved between the degree of drainage and the stability of the base layer. Stability should not be sacrificed for the sake of drainage.

Under certain conditions, such as expected heavy traffic or poor-quality subgrades, a base layer is needed on top of the prepared subgrade and immediately below the concrete pavement. The material quality requirements for a base under concrete pavement are not as strict as those for a base under asphalt pavement because the pressures imposed on a base under concrete are much lower than those under asphalt.

For light traffic pavements, such as residential streets, secondary roads, parking lots, and light-duty airports, the use of a base layer is not required, and the desired results can be obtained with proper subgrade preparation techniques.

Types of Bases

Bases may be constructed of granular materials, cement-treated materials, lean concrete, hot-mixed asphalt, or open-graded, highly-permeable materials, which may be stabilized or unstabilized.

When the use of a base is considered appropriate, the best results are obtained by following these guidelines:

- Selecting base materials that meet minimum requirements for preventing pumping of subgrade soils.
- Specifying grading controls that will ensure a reasonably constant base grading for individual projects.
- Specifying a minimum base depth of 100 mm (4 in.).
- Specifying a minimum density for untreated bases of 105 percent of ASTM D 698 / AASHTO T 99 for heavily traveled projects.
- Specifying a cement-treated or lean concrete base that provides a strong and uniform support for the pavement and joints, provides an all-weather working platform, and contributes to smoother pavements by giving firm support to the forms or paver during construction.
- Specifying a permeable base for pavements carrying high volumes of heavy trucks for which past experience indicates the potential for pavement faulting and pumping.

Unstabilized (Granular) Bases

A wide variety of materials and gradings has been used successfully by different agencies for untreated bases. These materials include crushed stone, crushed concrete, bank-run sand-gravels, sands, soil-stabilized gravels, and local materials such as crushed wine waste, sand-shell mixtures, and slag.

The principal criterion is to limit the amount of fines passing a 75-µm (#200) sieve. Soft aggregates should be avoided because fines may be created due to the abrasion or crushing action of compaction equipment and construction traffic. Generally, aggregates having less than 50 percent loss in the Los Angeles abrasion test (ASTM C 131 / AASHTO T 96) are satisfactory (see Abrasion Resistance in chapter 5, page 146).

Stabilized (Treated) Bases

Stabilized or treated bases can be accomplished using hydraulic cement or asphalt. Types of stabilized bases include cement-treated, asphalt-treated, econocrete, lean concrete, asphalt-treated open-graded, and cement-treated open-graded. Such stabilized bases provide the following benefits:

1. A stable working platform to expedite all construction operations and permit large daily production of concrete pavement with minimum downtime for inclement weather.
2. Firm support for slipform paver or side forms.
3. Construction of smooth pavements due to stable trackline for slipform pavers.
4. Prevention of base consolidation under traffic.
5. Reduction in pavement deflections from vehicle loadings.
6. Improved load transfer at pavement joints.
7. Minimized intrusion of hard granular particles into the bottom of pavement joints.
8. A more erosion-resistant base surface.

Grading Control

The base for an individual project should have a reasonably constant grading to allow compaction equipment to produce uniform and stable support, which is essential for good pavement performance. Abrupt changes in base grading can be nearly as harmful as abrupt changes in subgrade soils.

Compaction Requirements

To prevent the consolidation of granular materials from the action of heavy traffic once the pavements are in service, bases must be compacted to very high densities. Unstabilized bases under concrete pavements should have a minimum of 100 percent of ASTM D 698 / AASHTO T 99 density. For projects that will carry large volumes of heavy traffic, the specified density should not be less than 105 percent of standard density or 98 to 100 percent of ASTM D 1557 / AASHTO T 180 density.

Materials

Granular materials in AASHTO Soil Classification Groups A-1m, A-2-4, A-2-5, and A-3 are used for cement-treated bases. They contain not more than 35 percent passing the 75-µm (#200) sieve, have a PI of 10 or less, and may be either pit-run or manufactured. Cement-treated bases have been built with A-4 and A-5 soils in some non-frost areas and are performing satisfactorily. Generally, however, such soils are not recommended for bases in frost areas or where large volumes of heavy truck traffic are expected. Use of A-6 and A-7 soils is not recommended. To permit accurate grading of the base, the maximum size of material is usually limited to 25 mm (1 in.) and preferably to 19 mm (¾ in.).

Econocrete or lean concrete bases are typically designed for a specific application and environment. In general, they use aggregates that do not necessarily meet quality standards for conventional concrete. A single aggregate, rather than coarse and fine aggregates stockpiled separately, is often used in the mixture. Cement content is less than that for normal concrete and is selected based on the target strength.

A common source of aggregate for any base type is crushed, recycled concrete. Existing concrete pavements can be taken up, crushed, and reused in base courses, either as unstabilized aggregate bases or stabilized bases. The fractured concrete and fine material contain cement that will begin to hydrate and thereby provide some of the benefit of a stabilized base. There is evidence, however, that in some States leaching from recycled aggregates used as a base can cause problems (Mulligan 2002).

Construction

Cement-treated bases can be placed using either road-mixed or pre-mixed methods. In road mixing, the material is processed on the grade. The proper amount of cement is placed with a cement spreader, and the mixing is usually accomplished with a pulverizer or reclaimer. It is then compacted with rollers. For pre-mixed bases, the material can be mixed in either a pugmill or a central-mixed concrete plant. The material is batched into dump trucks and typically placed using an asphalt paving machine. In some cases, the machine will achieve the proper density, but additional compaction may be required.

Econocrete or lean concrete bases are constructed in essentially the same manner and with the same equipment as normal concrete pavements. They are mixed using a central-mixed concrete plant and placed using a slipform paver. The only differences are the jointing practice and the treatment of the surface of the lean concrete base. Construction of joints in the lean concrete base is not considered necessary as long as a debonding treatment is applied to the surface of the base. A few States and some European countries, however, notch the base at the planned locations of the joints in the concrete pavement above.

Because there is a high potential for bonding of the concrete pavement to a stabilized base, it is important that a bond-breaking medium be applied to the base surface. Current practice in the United States includes applying two heavy coats of wax-based curing compound on the base surface (Okamoto 1994). Table 7-2 provides some alternative materials that may be used to reduce friction and prevent bonding of pavement concrete to base layers.

Table 7-2. Alternatives for Reducing Friction or Bond between Concrete Pavement and Stabilized Base Materials (ACPA 2002)

Material	Comments
Curing compound	Two coats of white-pigmented, wax-based compound (ASTM C 309 / AASHTO M 148) works well.
Sand	Broadcasting or dusting about 5.5 kg/m^2 (12 lb/yd^2) works well.
Bladed fines	Recycled job site material works well as thin layer.
Asphalt emulsion	Works well on smoother base surfaces. Must be an even coating.
Polyethylene sheets*	Works well but difficult to use when windy. Could pose traffic hazard in urban areas. May cause problems with moisture in slab or base.
Tar paper	Works as debonding medium directly over shrinkage cracks in the base. Not recommended for application on the entire base area.
Choker stone	For stabilized open-graded materials only. Chip-size material to fill near-surface voids and minimize penetration of concrete into base.

* Polyethylene (i.e., plastic) sheets are recommended for small areas only. Large sheets can be difficult to work with and have been known to contribute to (1) tearing (a form of cracking) along the edges of pavement during slipform construction, (2) slowing production to refasten dislodged sheets, and (3) vehicle accidents if sheets are blown onto adjacent lanes with active traffic.

Bonding of the concrete pavement to a hot-mixed asphalt base is less detrimental, because the asphalt has sufficient flexibility to prevent reflective cracking from occurring.

Drainage in the Base Layer

Pavement drainage is an important factor in pavement performance. In the past, many poorly designed pavements with little drainage failed because of water trapped within the pavement structure, leading to subgrade pumping, reduced subgrade and base strengths, and resulting pavement distresses.

A method of providing drainage in a pavement section is to specify a drainable or permeable base layer, utilizing an open-graded aggregate grading. This layer can be daylighted to the side ditches, or it can direct water to flow into edge drains.

The number of voids in the base has a direct relationship to the material's stability. Dense-graded granular materials and materials stabilized with cement or asphalt provide firm support for construction equipment and the concrete pavement. Unstabilized permeable bases or stabilized but highly permeable bases, which became popular in the 1990s, have caused some construction as well as performance problems, often related to initial quality or maintenance issues.

An important balance must be achieved between the degree of drainage and the stability of the base layer. Base stability should not be sacrificed for the sake of drainage. A target permeability of 60 to 90 m/day (200 to 300 ft/day) produces a stable draining layer that will support the paving equipment and construction vehicles. Layers with higher permeability do not have the in-place stability necessary for construction and pavement performance.

Trackline

One of the most significant design considerations for obtaining a consistently smooth concrete pavement is provision of a stable, smooth trackline or pad-line (ACPA 2003).

Tracklines are the paths along which a slipform paving machine's tracks will follow. They are usually 1 m (3 ft) outside either edge of the concrete slab (figure 7-4). Agencies that specify and pay for this extra three feet of base width on either side of the slab get the benefit of smoother pavements, as well as the additional support provided to the slab edges, shoulders, and curb-and-gutter sections.

Trimming to Grade

Like subgrades, unstabilized bases can be trimmed to grade. Econocrete (lean concrete) and asphalt bases are typically not trimmed after being placed, but are instead constructed to the planned grade referenced from a string line or the trimmed subgrade surface. Care must be exercised, however, when trimming cement-treated bases. Trimming these types of bases prior to paving can disturb the base surface.

After trimming, the base may be rough in certain locations, increasing the surface for bonding. One of the following methods will minimize bonding in trimmed areas:

- Reapply the cutback asphalt curing agent and spread a thin layer of sand before paving.
- Apply two coats of wax-based curing compound before paving.

Figure 7-4. Trackline of slipform paving machine (ACPA)

Preparation for Overlays

Key Points

- Concrete overlays are used to extend the service life of an existing pavement.
- The surface of the existing layer must be appropriately prepared, either for bonded or unbonded overlays.

Concrete overlays are used to extend the service life of an existing pavement (see Concrete Overlays in chapter 2, page 23). They can be grouped into two main types:

- Overlays of existing concrete pavements (either bonded concrete overlays or separated concrete overlays).
- Overlays of existing asphalt pavements (conventional whitetopping, thin whitetopping [TWT], or ultra-thin whitetopping [UTW]).

In addition, concrete may also be overlaid on composite (asphalt on concrete) pavements (Grove 2005).

Preparing for Bonded Treatments

Three treatments—bonded concrete overlays, TWT, and UTW—are designed and constructed so that a bond forms between the existing pavement and the new concrete overlay. This bond creates in effect one monolithic structure that supports traffic loadings. In TWT and UTW projects, the bonding reduces stresses in the concrete overlay. This allows a relatively thin layer of concrete to carry heavier traffic loadings.

These three treatments, therefore, require that the existing pavement surface be prepared to maximize bonding with the new layer.

TWT and UTW Treatments

To prepare an existing asphalt pavement for a TWT or UTW treatment (thin layer of concrete over asphalt), the existing asphalt should be cleaned thoroughly by milling or shot-blasting the surface. This procedure removes a thin layer of the existing asphalt pavement surface; removes oil, loose stones, and other materials that could prevent bonding; increases the surface area for bonding; fractures aggregate particles and exposes the aggregates, which aids in bonding; and levels the surface to remove deformations.

In TWT and UTW projects, the age of the existing asphalt surface influences its ability to develop a strong bond with the thin concrete overlay. For example, milling new asphalt will simply smear the fresh, oily asphalt binder across the milled surface and will not expose fractured aggregate faces. It is difficult to develop a good bond in these cases.

Bonded Concrete Overlays

To prepare a concrete pavement for a bonded concrete overlay, the existing surface should be milled. Milling may be followed by shot-blasting or sand-blasting to remove any fractured concrete not dislodged by the milling process. The combination of milling and shot-blasting usually results in the highest bonding strengths.

For bonded concrete overlays, however, bonding grouts are generally *not* recommended between the existing concrete and the concrete overlay for several reasons:

1. The bonding grout may dry out before the concrete is placed, thereby becoming a debonding layer.
2. Bonding grout is a low-strength material compared to the existing concrete and the bonded concrete overlay.
3. Studies have shown equal or better bond strengths from in-place bonded overlays without grout (FHWA 2002; ACPA 1990a).

Preparing for Separated Overlays

The goal of separated concrete overlays is to allow the two concrete pavement layers to remain independent and distinct. This ensures independent movement of the slabs and minimizes the potential for reflection cracking.

Separated concrete overlays do not require extensive surface preparation of the existing concrete pavement. Separation is accomplished by constructing a thin separation layer (usually asphalt) between the two pavements, which acts as a stress relief course. A minimum 25-mm (1-in.) interlayer of asphalt pavement typically works best.

The asphalt interlayer does bond to both concrete layers but is flexible enough to provide the required stress relief, ensuring that joints and cracks in the existing concrete do not reflect into the overlay (ACPA 1990b).

Preparing for Conventional Whitetopping

Conventional whitetopping overlays require the least amount of surface preparation of all the concrete overlay types. In most cases, all that is required is a power brooming of the existing asphalt pavement to remove loose stones, road dust, and debris. The concrete is then directly applied to the asphalt surface.

If there is extensive rutting (greater than 50 mm [2 in.]) in the asphalt, a leveling course or profile milling may be employed to remove or minimize the ruts.

In conventional whitetopping projects, bonding between the existing asphalt and the concrete overlay is not required or relied upon. However, any such bonding that may occur is generally desirable.

References

AASHTO standards may be found in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 24th Edition, and *AASHTO Provisional Standards*, 2004 Edition, HM-24-M. https://www.transportation.org/publications/bookstore.nsf.

AASHTO T 96, Resistance to Degrading of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

AASHTO T 99, Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and 305-mm (12-in.) Drop

AASHTO T 180, Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and 457-mm (18-in.) Drop

ASTM standards may be found in *Annual Book of ASTM Standards*, ASTM International. www.astm.org.

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ASTM D 698-00a, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lb/ft3 (600 kN-m/m^3))

ASTM D 1557-02e1, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lb/ft^3 (2,700 kN-m/m^3))

ASTM D 1883-99, Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils

ASTM D 3152-72(2000), Standard Test Method for Capillary-Moisture Relationships for Fine-Textured Soils by Pressure-Membrane Apparatus

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Chapter 8

Construction

The starting point for constructing good-quality concrete pavement is to design and use good-quality concrete during construction. The plastic properties of concrete affect many construction operations, including mixing, transporting, placing, paving, curing, and jointing. Concrete's hardened properties affect long-term pavement performance.

The other significant requirement is to use appropriate, high-quality equipment and good practices. Failures in construction are often due to a combination of marginal materials used in marginal equipment operated by insufficiently trained operators.

This chapter discusses various concrete pavement construction operations and addresses how decisions made about the concrete or its constituent materials may affect constructability or pavement performance. The information is generally limited to that which is relevant to the pavement system; it is not a full discussion of construction practices. More detailed information can be found through the American Concrete Pavement Association, www.pavement.com.

Field Verification

Key Points

- Properties of the concrete must be verified both before and during construction to confirm that it is suitable for the intended use.
- Field verification of mixtures should use the production equipment anticipated for the job.

The mixture properties that are required depend, in large part, on the intended use of the concrete. Concrete suitable for slipform paving is different from concrete required for hand placing flatwork. Similarly, fast-track concrete differs significantly from normal-setting concrete. Regardless of the mixture, its properties must be verified both before and during construction to confirm that it is suitable for the intended use. Field verification of mixtures should use the production equipment anticipated for the job and should also include the construction of a test strip, if possible. Table 8-1 provides available tests and analysis tools for field analysis and mixture verification. A preconstruction meeting between the contractor, agency, construction manager, and/or testing laboratory is recommended to establish working criteria, goals, and practices for the project. The meeting provides an opportunity for the project team to resolve issues before they occur during construction. It also gives the team an opportunity to establish a system for responding to problems that may occur during construction. The contractor typically furnishes a quality control plan for production and paving.

Table 8-1. Tests/Tools for Field Verification

Property	Available tests / analysis tools
Air content	ASTM C 231 (pressure meter) Unit weight AVA (air-void analyzer)
Grading	See chapter 9 page 253
Shrinkage	Temperature sensors to feed data for HIPERPAV analysis
Strength - early	ASTM C 1074 (maturity)
Strength	ASTM C 31 / AASHTO T 23 (test specimens) ASTM C 39 / AASHTO T 22 (comp. strength) ASTM C 78 (flexural strength)
Water/cement ratio	Microwave oven AASHTO T 318
Loss of consistency	Slump loss

Concrete Production

Key Points

- Variability of the production process must be minimized to produce concrete of consistent quality and uniformity.
- Material variations must be recognized and accounted for with planned and permitted field adjustments.
- The plant must have the capacity to meet production requirements for the project.
- A quality control plan outlining the process for material verification may be required.
- Critical aspects of aggregate stockpile management include maintaining uniform grading and moisture content and preventing aggregate contamination.
- Dry ingredients in concrete should be batched by weight.
- The order in which materials are introduced into the mixer must be consistent.
- Sufficient mixing time must be allowed to ensure a homogeneous mixture and to entrain the required air-void system.
- Concrete delivery must be consistent and on time.

Concrete production is a manufacturing process. However, concrete is manufactured from raw or commodity materials such as aggregates, fly ash, and cement, which have inherent variability. Because of variability in the constituent materials and in measuring them, a concrete mixture's properties will vary. To produce concrete of consistent quality and uniformity, the variability of the production process must be minimized while recognizing and accounting for material variations.

It is important to consider the mix design, as well as a realistic production schedule, in the plant selection process. Production capacity and limits on haul time require forethought. Projects in congested areas, which do not allow for on-site production, may require a mix design that allows for extended hauling and placement times.

Setting Up the Plant

Concrete plants are either permanent, stationary facilities, or they may consist of portable equipment that is erected adjacent to the paving site (figure 8-1). Plant location and setup depend primarily on site factors like zoning, access to utilities, availability of materials, and public traffic (urban or rural). The plant must have the capacity necessary to meet the production requirements for the project.

Optimizing traffic flow at the plant is important. Items to consider include the following:

- Delivery of raw materials.
- Delivery of concrete.
- Quality control-related traffic operations and testing personnel safety.
- Operation of equipment for managing the aggregate stockpiles.
- Plant safety.
- Environmental impact.

The concrete plant needs to be in good condition, operate reliably, and produce acceptable concrete

Figure 8-1. Portable concrete plant (ACPA)

uniformly from batch to batch. Plants should be inspected prior to the start (or restart) of each paving project and when uniformity or strength problems are encountered during production. Table 8-2 provides a checklist for inspection.

Handling Materials

Material management requirements are similar for either transit mix or central mix operations. The contractor and/or material suppliers should handle all of the materials in such a way as to maintain quality and uniformity. The contractor should use only certified materials on the project and follow the manufacturer's recommendations, as appropriate.

The contractor and the concrete producer should ensure that all materials meet the project specifications. Many projects require a quality control (QC) plan outlining the process for material verification. The agency typically reviews the QC plan and assumes an integral role in the process.

At the plant, different cementitious materials (cement, fly ash, or ground, granulated blast-furnace slag) must be kept in separate silos or storage units. Systems must be implemented to ensure that the cementitious materials are loaded into the correct silos when they are delivered. Unloading of the cementitious materials takes time. Therefore, it is vital to maintain an adequate area for cement, fly ash, and other supplementary material deliveries.

Table 8-2. Concrete Plant Checklist

No.	Inspection item
1	Check foundations of stockpiles for proper separation and adequate drainage.
2	Check bins for adequate partitions to prevent intermingling of aggregates.
3	Check scales with test weights throughout range to be used.
4	Check scales for seals by approved agency.
5	Check water meter for accuracy.
6	Check for leakage of lines.
7	Check capacity of boilers and chillers if their use is anticipated.
8	Check admixture dispensers for accuracy.
9	Check mixers for hardened concrete around blades.
10	Inspect concrete hauling units for cleanliness.
11	Check to ensure that all concrete-making materials have been certified and approved for use.
12	Observe stockpiling operations. Verify that segregation and contamination will not occur.
13	Observe charging of the bins. Verify that segregation and contamination will not occur.
14	Review aggregate moisture tests.
15	Observe batching operations at start and periodically during production.
16	Check scales for zeroing.
17	Check to ensure proper batch weights are set on the scales.

Stockpile Management

Stockpile management is the coordination of the aggregate delivery, storage, and loading into the mixing plant, which is a vital aspect of consistent, quality concrete production (ACPA 2004a). Locating the stockpiles is an important first consideration. A relatively flat area is preferred to facilitate unloading and stockpiling the aggregates. Also, place a pad or aggregate separation layer in the stockpile area. This will minimize contamination of the aggregate from the soil below as well as prevent material loss.

The goal with aggregate stockpiles is to maintain uniform gradation and moisture content and prevent aggregate contamination throughout the project. Consistent aggregate will contribute to consistent concrete. A few basic stockpiling concepts include the following:

- Pile the material in lifts.
- Complete each lift before beginning the next.
- Do not dump material over the edges of a stockpile.
- Minimize free-fall heights of aggregates to avoid segregation.
- Only stockpile as much material as practical.
- Minimize crushing of the aggregate by the loader.
- Manage the stockpile carefully to obtain close to saturated surface dry (SSD) condition. For example, thoroughly wet the aggregate, then let it stand an hour before batching.
- Monitor the moisture content of the aggregate using probes in the stockpile.

In some cases, the aggregates may be contaminated with clay or soil before arriving on the plant site. Dirty aggregates require washing or cleaning or should be rejected. In addition to causing clay ball problems in the concrete, dirty aggregates can lead to problems such as low strength. The loader operator has a key role in preventing clay or mud from being deposited into the plant's feed hoppers (figure 8-2). The operator must control the elevation of the loader blade to prevent picking up contamination from below the aggregate stockpile.

Portable central-mix plants are usually more susceptible to producing concrete contaminated with clay balls, simply because they are temporarily placed near the project site and may have clay or loose soil underneath the stockpiles. The batch plant or concrete foreman must keep a close eye on stockpile management at portable plant sites. Stationary ready-mix plants often have a paved surface or bunkers on which the stockpiles are placed or stored and where the loader operates. This reduces the likelihood of clay being introduced into the ready-mixed concrete.

The aggregate loader operator is an important person in the production of consistent quality concrete. The primary functions of the loader operator include the following:

- Working the stockpile to provide uniform water content and gradation, while avoiding segregation.
- Minimizing contamination.
- Observing and reporting moisture variations.
- Adding material to the feed hopper(s) appropriately.
- Notifying the plant foreman of anticipated aggregate shortages.

Batching

Batching is the process of measuring the mixture ingredients and introducing them into the mixer (for information about batching as it affects concrete uniformity, see Batching Operations in chapter 5, page 106).

Dry ingredients in concrete should be batched by weight, while water and chemical admixtures may be batched by volume. The potential error in volume batching cement and aggregates is large because of bulking of the materials with handling and increasing moisture content.

The order in which materials are introduced into the mixer is important to ensure uniform mixing and maximize concrete consistency. Figure 8-3 shows the typical sequence of adding components into a stationary mix plant. Materials are blended in approximate proportions as they enter the mixer. One batch of concrete is mixed while another is being batched. These operations occur simultaneously.

Specific sequences may vary depending upon the materials. The plant operator may adjust the sequence to accommodate production requirements or if

Figure 8-2. Loader operation is key to stockpile management. (ACPA)

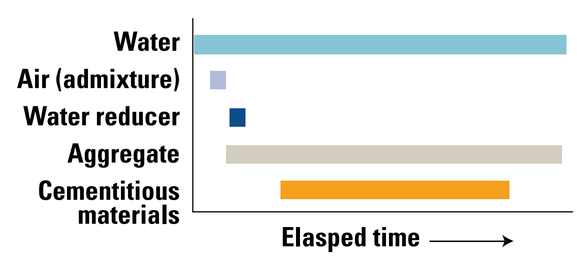


Figure 8-3. Typical sequence of adding material in a stationary mix plant (Ayers et al. 2000)

incompatibility is reported to occur. The requirements for specialty materials, such as fibers and other additives, may also alter the sequence. The sequencing of ingredients will also have an important effect on the uniformity of truck-mixed concrete. Elevating the rear portion of the truck mixer during charging operations minimizes the time required to get all the ingredients into the drum. Figure 8-4 shows the typical sequence of adding components into a truck mixer. Once agreed upon, the sequencing process should remain the same. A sequencing diagram is a useful tool in clearly showing the particular charging process for the concrete mix and plant.

In a dry batch process, the first ingredients into the drum are usually a portion of the water and a portion of the coarse aggregate. The water is shut off and aggregates and cementitious materials are combined until all of the cementitious material is in the drum. The final portion of water goes in with the last of the aggregates to clean and wash any cementitious material clinging to the mixer's hoppers, rear fins, and chutes (Ayers et al. 2000).

Ribbon loading is a method of batching concrete in which the solid ingredients, and sometimes the water, enter the mixer simultaneously. This process will often produce a very consistent product if the plant is configured appropriately.

Aggregate moisture content (monitored using probes in the stockpile) and the potential for segregation greatly affect concrete quality and uniformity.

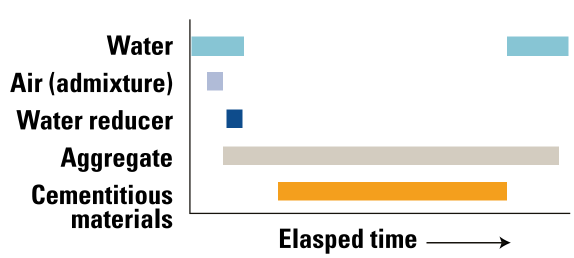


Figure 8-4. Typical sequence of adding material in a truck mixer (Ayers et al. 2000)

If the aggregate moisture content is lower than the saturated surface dry (SSD) moisture, additional water will be required in the mix to prevent stiffening caused by water being absorbed into the aggregate (see Step 11, Moisture/Absorption Correction, in chapter 6, page 183).

The maximum additional amount of water required in the mix is calculated as the difference between the SSD moisture and the current moisture content, multiplied by the mass of the respective aggregate. However, if the aggregate is wetter than the SSD value, the amount of water must be reduced at the batch plant. Otherwise, the water-cementitious materials ratio of the mix will be exceeded, leading to low strength and poor durability.

Aggregate moisture content and the potential for segregation greatly affect concrete quality and uniformity. ASTM C 94 provides four key items to control uniformity:

- For each size of coarse aggregate, use separate aggregate bins that can shut off material with precision.
- Use controls to monitor aggregate quantities during hopper charging.
- Use scales accurate to +0.2 percent tested within each quarter of the total scale capacity. Adequate standard test weights for checking scale accuracy should be available.
- Add water to an accuracy of one percent of the required total mixing water.

The following considerations are important for controlling batch-to-batch consistency (ACPA 2004a):

- The plant foreperson must ensure a consistent and clean operation of the front-end loaders and other heavy equipment that move raw materials at the batch plant.
- Some coarse aggregates for use in concrete are highly absorptive, requiring a significant quantity of water to create the saturated surface dry condition assumed in the mixture design, so that additional water is not absorbed during mixing. Watering the stockpiles may be necessary for these coarse aggregates.
- Periodic moisture tests on the fine and coarse aggregate are necessary (at least twice a day).

- Truck operators must be sure to remove free water or excess release compounds from drums or dump beds after washing or rainfall.

Mixing Concrete

Concrete is normally mixed and delivered using one or a combination of the following operations:

- Central mixing. In a central mix concrete plant, the plant operator adds the batched (weighed or metered) ingredients into a stationary mixer. The mixer then completely mixes the components before discharging the concrete into a delivery vehicle for transporting to the point of discharge. The delivery vehicle can be a truck mixer operating at low mixing speed, a truck agitator, or a nonagitating (e.g., flatbed) truck.
- Shrink mixing. Shrink-mixed concrete is partially mixed in a stationary mixer and then transported while mixing is completed in a truck mixer.
- Truck mixing. Truck-mixed concrete is mixed entirely in the truck mixer.

Changes to the mixture's water and admixtures are possible at the job site if a truck mixer is used to transport the mixture (Ayers et al. 2000).

The required mix time varies depending on the equipment, proportions, and materials used, gradations of aggregates, amount and types of admixtures, temperature, etc. However, if there are any problems regarding a concrete mix, such as segregation, bleeding, finishing, etc., the first and easiest aspect to change or consider is the mix time. For a portable central mix batch plant that is used to produce a concrete paving mixture, mix times will typically range from 60 to 90 seconds. Short mixing periods will reduce the amount of entrained air and will likely lead to a nonuniform mixture (see Type of Plant and Production Procedures in chapter 5, page 134).

Delivering Concrete

Consistent delivery of concrete to the paving project site is an important element in maintaining a uniform, trouble-free paving operation (ACPA 2003b). This is usually less challenging in rural areas than in urban areas because haul roads are wider and haul trucks may travel freely. However, densely populated urban areas require careful evaluation to determine whether traffic delays will hamper concrete delivery. Consideration of the concrete mixture's stiffening properties is also necessary, with normal-setting mixtures allowing longer travel times than fast-setting mixtures allow.

Feeding concrete into the paving machine consistently requires an adequate number of batch delivery trucks. The number of trucks will often dictate the slipform or placement speed. The entire cycle of mixing, discharging, traveling, and depositing concrete must be coordinated for the mixing plant capacity, hauling distance, and spreader and paving machine capabilities. Extra trucks may be needed as the haul time increases.

a) Too much

b) Appropriate amount

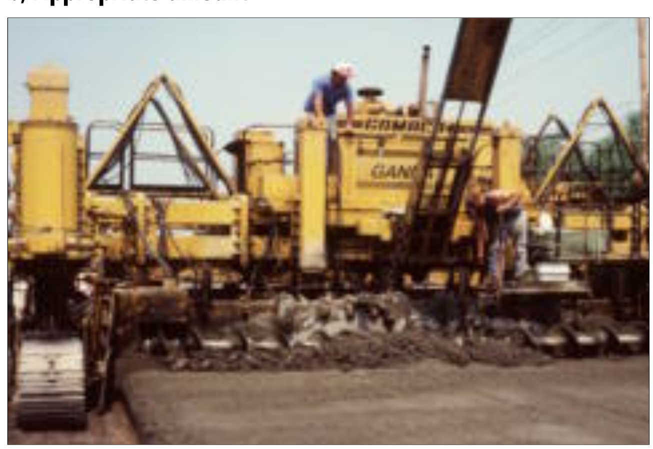


Figure 8-5. Depositing concrete in front of the paving machine (ACPA)

The manner in which the crew deposits concrete in front of the paving operation is an important factor in this cycle and in creating a smooth pavement surface. For slipform paving (see the section later in this chapter on Paving), the amount of concrete being carried in front of the paving machine (the head) must be controlled to ensure that it does not get too high or too low (figure 8-5).

If the head gets too high, it creates a pressure surge under the paving machine. The surge can cause the concrete behind the machine's finish pan to swell, creating an uncorrectable surface bump. The slipform machine may even lose traction and steering. This is more of a problem with small two-track pavers. Larger four-track pavers may be heavy enough to handle concrete buildup in front of the paver. If there is not enough material in front of the paving machine, then the concrete head may run out or the grout box may run empty, creating a low spot and voids or pockets in the pavement surface. Avoid such problems by using a placer/spreader machine (figure 8-6) or by carefully depositing concrete from the haul trucks.

Figure 8-6. A belt placer/spreader ensures a consistent amount of concrete in front of the paver. (ACPA)

Field Adjustments

As discussed above, the materials used to make concrete are inherently variable, as are the conditions in which they are mixed and placed. It is therefore important that the properties of the fresh concrete are closely monitored and proportions adjusted (within the constraints of the specification) to improve the uniformity of the final product from batch to batch and day to day. The following sections discuss some of the variables that have to be considered as paving proceeds.

Ambient Temperatures

Daily and seasonal temperature variations impact the fresh and hardened concrete. Concrete stiffens, sets, and gains strength faster as the temperature rises. Hot weather is therefore a source of problems for the paving process.

Sprinkling aggregate stockpiles and chilling the mix water or using ice are normally the first responses to hot weather; however, the total amount of water and ice in the mixture must not exceed the mixing water in the mix design. If a greater temperature reduction is required, the injection of liquid nitrogen into the mixer may be the best alternative method.

ASTM C 94 / AASHTO M 157 allow water to be added to remix the concrete when the truck arrives on the job site and the slump is less than specified, providing the following conditions are met:

Tips for Managing a Head of Concrete

Allow old concrete being carried in the head in front of the paver to be placed. This material can contain a large amount of lighter aggregate particles that, after the first winter, can cause scaling of the pavement surface. The old concrete can also create honeycombed areas or seams that can lead to cracking.

Do not allow the head to run out. When the head is gone, there may not be enough concrete to completely build the slab. Paving operations must then be stopped and concrete brought to the paver to fill the required head. This is disruptive and costly.

1. Maximum allowable water-cement ratio is not exceeded.
2. Maximum allowable slump is not exceeded.
3. Maximum allowable mixing and agitating time (or drum revolutions) are not exceeded.
4. Concrete is remixed for a minimum of 30 revolutions at mixing speed or until the uniformity of the concrete is within the limits described in ASTM C 94 / AASHTO M 157.

Water should not be added to a partial load.

Adjustments for cool or falling temperatures are less critical with respect to the water-cementitious materials (w/cm) ratio and strength. However, consistent workability must still be maintained. Heated water is a common mix adjustment when cooler temperatures occur. Consistent cool temperatures may also require the addition of an accelerating admixture to minimize the risk of random cracking due to late sawing.

Materials Variability

Three of the four largest constituents in a concrete mix by volume—coarse aggregate, fine aggregate, and cementitious materials—are processed/manufactured from raw materials that are extracted from naturally occurring deposits. The very nature of these materials dictates that they have an inherent variability. The quarrying and manufacturing processes used to produce concrete materials reduce but do not eliminate all of this variability.

Moisture content in the aggregate stockpiles is the most common parameter that requires an adjustment in the plant process. Stockpiles should be sampled and tested at least daily, or, depending on weather conditions, more frequent testing may be required. The plant should be capable of compensating for this free water from the aggregates. Most modern batch plants have moisture sensors in their fine aggregate bins.

Aggregate grading should be monitored at least daily. Frequent density (unit weight) tests can be helpful in detecting changes in aggregate gradation. Modest variations in gradation are normal and will not generally have an adverse impact on performance. Severely segregated stockpiles should be rejected or rebuilt. Batch proportions of the aggregates should be adjusted if the combined gradation of the mix deviates significantly from the mix design and the workability properties are causing placement difficulties.

Variability in cementitious materials also impacts workability. There are currently no standard test methods that provide timely feedback on this variable; therefore adjustments must be made based on feedback from the paver. Changes in cement and supplementary cementitious materials fineness (higher Blaine value) may require additional water and air-entraining admixture to maintain workability and air content.

Material Supply Changes

When an ingredient source is replaced or the amount required changes by more than five percent (excluding admixtures used within recommended dosages), trial batches are needed. Time is usually a critical factor in how material changes are handled. The best and safest alternative is to batch anticipated mix designs in the laboratory well before construction starts. Otherwise, workability, setting time, air entrainment properties, and early-age strength (maturity and/or three-day strength) should be closely compared with the initial mix design; proceed with caution and increase testing frequency during the initial days with the new materials.

Paving

Key Points

- Slipform or fixed-form paving methods can be used.
- Concrete mixtures and practices vary according to placement method.
- Slipform paving is generally for placements requiring higher production rates.
- Fixed-form paving is adaptable to nearly any placement circumstance.
- The paving train is a term referring to the combination of individual machines that place and finish concrete pavement.
- All equipment must be suitable for the application, well-maintained, and operated by suitably trained personnel.

Contractors use either slipform or fixed-form paving methods, depending upon the nature of the placement. The concrete mixtures required by either placement method vary significantly. Slipform paving operations require a low-slump mixture that will not slough after extrusion by the paving machine, while a fixed-form paving operation relies on a higher slump mixture that will flow easily to fill the forms.

Slipform paving is generally for placements requiring higher production rates, such as mainline paving (figure 8-7). Fixed-form paving is adaptable to nearly any placement circumstance, but because it requires setting up side forms to hold the concrete, it is generally not as efficient. Table 8-3 lists common elements of paving machines.

The paving train is a term referring to the combination of individual machines that place and finish concrete pavement. For highway applications, a typical paving train includes the following:

- Spreader with belt placer.
- Slipform paver.
- Texturing machine.
- Curing cart (usually together with the texturing unit).

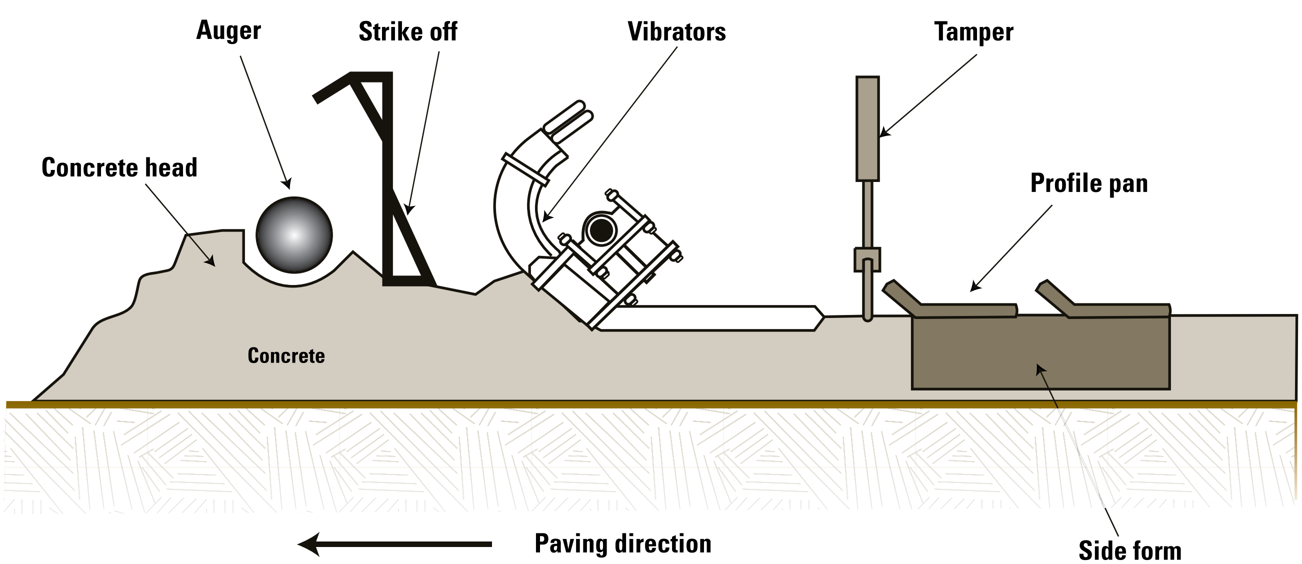


Figure 8-7. Components of a typical slipform paving machine (ACPA)

Placement (Fixed Form)

There are a variety of fixed-form paving machines; the less complex equipment includes hand-operated and self-propelled vibratory screeds, single-tube finishers (figure 8-8), and revolving triple tubes. Larger, form-riding machines can place and consolidate the concrete between forms in one pass. These machines ride on the forms or on pipes laid outside the forms.

To make paving easier, it is important to evenly deposit concrete onto the grade in front of the fixed-form placement machine. Piling too much concrete in front of the machine leads to difficulty with striking off. The concrete should not overly exceed the height of the forms. However, piling too little concrete in front of the machine may produce low spots in the pavement surface. Although it is ideal to distribute the concrete evenly with the chute from the ready-mix or other concrete hauling truck, some distribution of the concrete with hand tools is usually necessary. Concrete should never be moved with a vibrator, which is for consolidation only. Using vibrators to move concrete can segregate the mix, sending the large aggregate

Table 8-3. Common Elements of Paving Machines

Slipform	Fixed form
Self-propelled with either two or four tracks.	Ride on the forms or on self-propelled wheels.
Steering and elevation controlled from reference stringlines.	Steering and elevation controlled by fixed forms.
Paving width: up to 15 m (50 ft), depending upon model and available attachments. (Most are 7.3 to 8.5 m (24 to 28 ft) width.)	Paving width: various.
Weight: about 3,000 kg or more per meter (2,000 lb/ft) of paving lane width.	Weight: about 1,500 kg/m (1,000 lb/ft) of paving width.
Continuous auger or hydraulic plow-pans to distribute concrete in front of the screed (may carry head of concrete in front of paver).	Suspended screw auger to spread concrete in front of screed or roller.
Contain variable speed hydraulically controlled internal vibrators, with optional vibration monitoring capabilities.	Have one or two vibrators that move transversely in front of the screed. May also use fixed vibrators near the form edges.
Provide the consolidation energy required for highway pavements as thick as 375 mm (15 in.).	Provide the consolidation energy required for pavements as thick as 250 mm (10 in.).
Allow for various finishing attachments.	

Source: IPRF (2003)

Equipment Setup

The following critical elements should be in place before production paving starts (IPRF 2003):

- Check all the equipment in the paving train to make sure it is in operational condition.
- Verify that an acceptable length of grade is available for concrete paving.
- Check that approved test reports are available for all materials in storage at the job site and the plant site.
- Verify that backup testing equipment is available; develop extra equipment backup plans.
- Verify that all necessary concrete placement tools are available, such as hand tools, straight edges, hand floats, edgers, and hand vibrators.
- Verify that radio/telephone communication with the plant is operational.
- Verify that equipment is available to water the grade, if necessary.
- Monitor the string line regularly and re-tension as necessary (slipform only).
- Check the forms for proper bracing (fixed-form only).
- Verify that the day's work header is in place (or just saw off the excess).
- Develop an extreme-weather management plan.
- Check the weather forecast for each day of paving.
- Make sure a sufficient length of plastic covering is available in case of sudden and unexpected rain.

to the bottom and paste to the top. This can also compromise the air entrainment and ultimately the concrete durability.

For ease of removal and cleaning, forms require a thin application of oil before paving. Without oil, concrete can adhere to the steel or wooden surfaces of the forms. The paving crew should inspect forms just before paving and carefully reapply oil to any dry areas. If steel reinforcement is in place, care is necessary to avoid getting oil onto the bars.

Consolidation (Fixed Form)

The external (surface) vibration that a vibratory or roller screed produces is adequate to consolidate primarily just the surface of most pavement slabs. Supplementary internal vibration with hand-operated spud vibrators is usually necessary for adequate consolidation of unreinforced concrete slabs thicker than 75 mm (3 in.). A combination of internal and surface vibration is preferable for reinforced slabs at any thickness (Kosmatka, Kerkhoff, and Panarese 2002). Because surface vibration of concrete slabs is least effective near the fixed forms, it is also beneficial to consolidate concrete along the forms with a spud vibrator.

Supplemental vibration with hand-held spud vibrators should precede the placement screed. Standard practice for thicker slabs calls for vertical plunges of the vibrator head. For thin slabs, it is preferable to insert the vibrator head at an angle or horizontally to keep it completely immersed in the concrete. Operators should neither drag spud vibrators through the concrete nor attempt to move the concrete laterally, as either will tend to cause segregation. Leaving the vibrator head inserted for about 5 to 15 seconds will usually provide adequate consolidation. In general, proper consolidation of air-entrained concrete takes less time than non-air-entrained concrete, even when both mixtures are prepared with the same consistency (slump).

Figure 8-8. A roller screed (i.e., single-tube finisher) is one type of equipment that can be used to strike off the concrete in fixed-form placements. Others include vibratory screeds, form riders, and bridge deck finishers. (ACPA)

Placement (Slipform)

Slipform paving machines operate by extruding the concrete into the shape of the slab. A series of tools mounted on the front of a slipform paver fill the forms and create a uniform shape. These tools are the auger spreader (or spreader plow), strike-off, vibrators, tamper bar, profile pan, or any combination of these items (see figure 8-7).

The molding components are the bottom of the profile pan or forming plate and the side forms. All of these elements confine the concrete and form its shape in the same manner that a caulking gun nozzle confines the caulk and defines the shape of the bead.

In paving, the mold is forced through or over a volume of concrete that remains static on the grade. Vibrators mounted to the slipform machine fluidize the concrete and make it easier to mold. The slipform paver thus passes over the fluidized concrete while its mass keeps the pan and side forms steady to confine and shape the concrete. The following factors influence the required extrusion pressure:

- Weight of the machine.
- Taper of side forms relative to the desired pavement edge planes.
- Angle of the profile pane relative to the desired pavement surface plane.
- Vibrator power and frequency.
- Paver speed.
- Concrete workability.

The primary adjustments a slipform paving machine operator can make are the machine's speed and the frequency of its internal vibrators. If the concrete's plastic properties vary widely, requiring frequent adjustments of the placing speed or vibration frequency, the result will be a nonuniform surface. A slipform paving machine must spread and consolidate the concrete as it moves forward, and it cannot produce a smooth riding surface if it must stop often or push a large pile of concrete ahead of it.

Consolidation (Slipform)

Vibration is necessary for consolidating the concrete. On slipform pavers, a series of vibrators fluidize the concrete and remove large air voids (figure 8-9).

The vibrators are typically set at a constant frequency, which can be monitored and adjusted by the paver operator. Some adjustment to vibrator frequency may be helpful, but running the vibrator at a higher frequency should not be used to overcome poor equipment setup, poor alignment, or poor mixtures (see Vibration Monitoring in chapter 9, page 248).

Vibrators may cause undesirable effects, such as loss of air entrainment or vibrator trails, when operating at a very high frequency. For most mixtures, a frequency from 5,000 to 8,000 vibrations per minute, at paver speeds greater than 0.9 m (3 ft) per minute, can adequately fluidize and consolidate the concrete without loss of entrained air or segregation of particles (Tymkowicz and Steffes 1997). Vibrator frequency might need to be lower if the paving speed falls below 0.9 m (3 ft) per minute.

Vibrator sensing systems are available to provide a real-time readout of vibration frequency for all of the vibrators on a slipform paving machine. These units permit alarm settings that alert the operator of high or low frequencies, for all or individual vibrators, or total loss of vibration.

Figure 8-9. An array of vibrators under a slipform paver (ACPA)

Studies have shown that heavy vibration is not detrimental to the frost-resistance of well-proportioned mixtures, provided that the proper air-void system is initially established in the concrete (Tynes 1975; Simon et al. 1992). Mixtures that are gap-graded (oversanded) will tend to segregate more easily than well-graded mixtures at a given vibration frequency. Therefore, the need for reduced vibration frequencies is critical for gap-graded mixtures.

If the operator slows the paver to match the delivery of concrete, reduction of the vibration frequency is also likely to be necessary to maintain consistent extrusion pressure. The adjustment is relative to the normal vibration frequency and paving speed of the operation.

String Lines

The profile pan, the part of a slipform paver that controls the pavement surface, references its position from sensors that follow string lines placed along the grade, usually on both sides of the paver. The string line is the primary guidance system for a slipform paver (ACPA 2003b). The paver's elevation sensing wand rides beneath the string, and the alignment sensing wand rides against the inside of the string. Neither of these wands should deflect the line any measurable amount. A typical setup includes a string line on each side of the machine (figure 8-10). The string line itself may be wire, cable, woven nylon, polyethylene rope, or another similar material.

The string lines are not necessarily parallel to the grade, but are set to form the surface regardless of the grade elevation. A well-positioned string line can help overcome minor surface deviations in a base or track line, but it is not a substitute for a smooth, stable track line built to a tight tolerance. The hydraulic systems that control a slipform paving machine's profile pan cannot adjust quickly enough to significant variations in the machine's vertical position caused by an unstable base or track line. An unstable track line causes the profile pan to continually attempt to adjust its position relative to the machine's frame. These types of mechanical adjustments cause bumps or dips in the resulting pavement surface if too abrupt or too frequent (ACPA 2003b).

Achieving a smooth surface with slipform paving requires close attention to the setup and maintenance of the string line. The string line material, stakes, staking interval, splices, and repositioning frequency all may impact the resulting pavement surface. Stakes that secure the string line should be long enough to be firm when driven into the subgrade. There must be an adequate stake length exposed above the grade to allow adjustment of the string line to the desired height above the subgrade survey hub, typically 450 to 750 mm (1.5 to 2.5 ft). A maximum spacing between stakes of no more than 7.5 m (25 ft) on tangent sections will produce the best results. Decreasing this interval in horizontal and vertical curves is also necessary.

Reducing how often a string line must be set up during the project can lead to better smoothness control. Where possible, it is advantageous to set up one string line on each side of the paving area to serve all operations, including subgrade preparation, subgrade stabilization, base construction, and pavement placement. For multioperational usage, the stakes and strings must be offset farther from the pavement area to keep them clear of the equipment and operations.

In many instances, the haul road is next to the string line. This arrangement necessitates regular inspection of the string line by eye to determine whether any heaving or settling of the grade disturbed the hubs and/or line stakes. It takes considerable experience to properly "eyeball" corrections to a string line due to a deviation in the grade. When noticed, the survey or string line crew should reposition misaligned stakes immediately. It is sometimes advantageous to check a string line at night using light shone from vehicle headlights. This night smoothing technique reduces visibility of background objects and enhances the ability to focus solely on the illuminated string line.

Alternatives to String Lines

Recent improvements in technology have resulted in concrete paver guidance systems that require much less surveying, setup, and maintenance than string lines. These technologies include laser-guided systems and global positioning systems (GPS). Another alter-

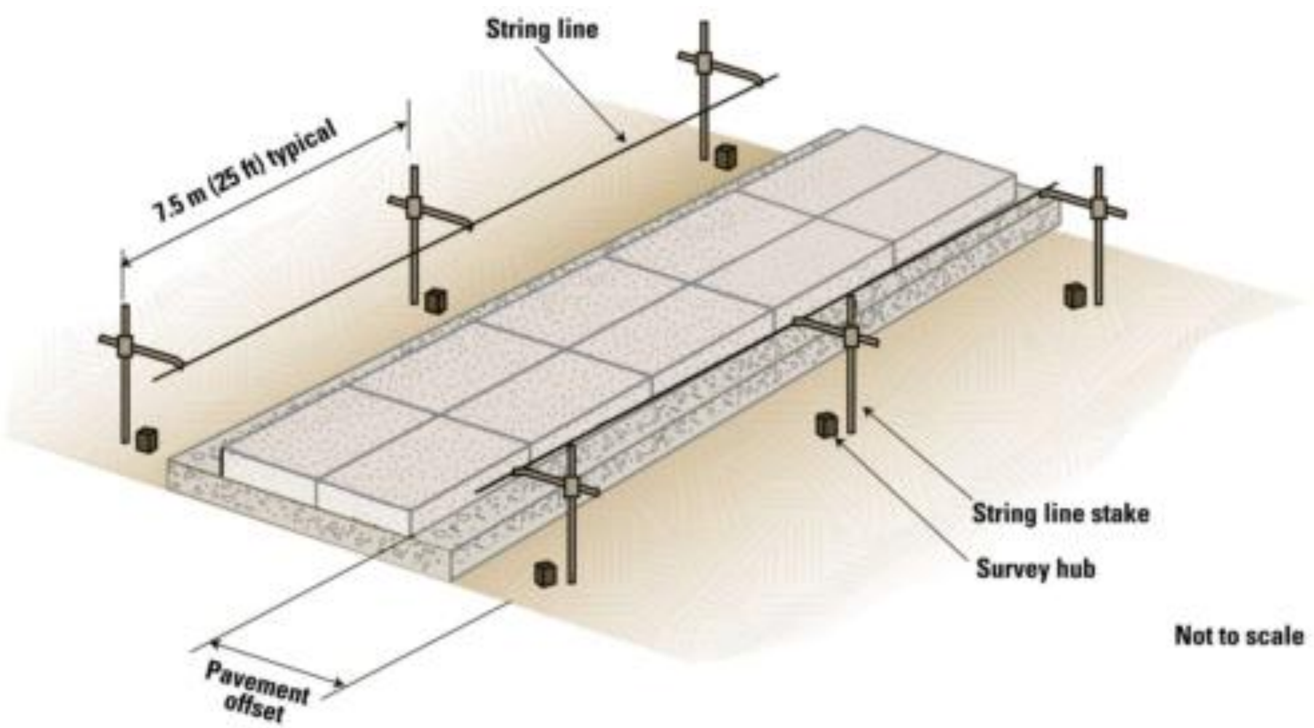


Figure 8-10. Typical string line setup (ACPA 2003b)

native to using string lines is the use of a ski, which rides off of a previously paved surface. This technique is also referred to as being “locked to grade.” The use of these alternatives is dictated by their need in special situations and the demonstration of similar tolerances and accuracies to string line-guided pavers.

Edge Slump

Edge slump occurs when the top edge of a freshly-placed, slipformed concrete pavement sags down after the slab is extruded from behind the paver. A small amount of edge slump is usually acceptable when the longitudinal joint will have some traffic moving across it. When the slab edge forms the absolute extent (free edge) of the pavement, a larger amount of edge slump is acceptable.

Edge slump is generally more common in thicker pavements, which have to stand higher and are therefore more susceptible. The most common form of edge slump is when the top edge slumps down (figure 8-11). The bottom edge slumping out usually indicates a more serious problem with the mix design and is often associated with higher slump mixtures that are not intended for slipform paving. When this type of edge slump occurs, paving should be suspended until the concrete mixture has been modified to work with slipform paving.

The following factors affect edge slump:

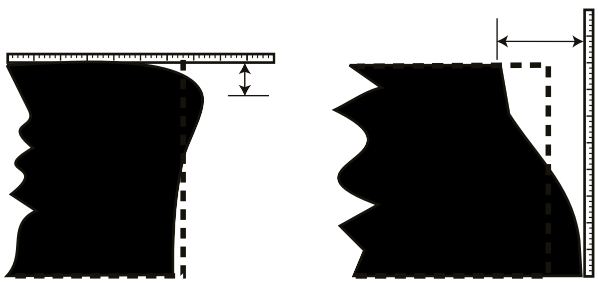
- Concrete consistency.
- Concrete mixture compatibility with placement techniques.
- Paver adjustments and operation.
- Excessive finishing.
- Segregation on the belt placer.

Most specifications limit the area considering edge slump to within 150 to 300 mm (6 to 12 in.) away from the slab edge.In general, most agencies specify an edge slump of 6 mm (¼ in.) as the trigger for corrective action.

Corrective action usually involves the finishers behind the paver reworking the edge to remove the irregularity. However, continual correction of excessive edge slump in fresh concrete can lead to unacceptable levels of joint spalling in the finished concrete. If such a problem develops, paving should be stopped and measures taken to correct excessive edge slump.

In most cases, edge slump can be corrected immediately behind the paver, and the mixture can be calibrated to prevent reoccurrence.

If the edge slump is not detected in time, it may require patching and/or diamond grinding to correct the irregularity.



a) Top edge slumps down Place straightedge on surface. Measure vertical distance between edge of slab at its greatest point of slump and straightedge.

b) Bottom edge slumps out Place straightedge along slab edge at greatest point of slump. Measure horizontal distance between top edge of slab and straightedge.

Figure 8-11. Two types of edge slump

Dowel Bars and Tiebars

Key Points

- Dowel bars and tiebars are used to provide support between adjacent panels in a pavement.
- Dowel assemblies must be placed in the required locations and fixed to prevent movement when concrete is placed over them.
- Using specialized equipment, dowels can be inserted after concrete placement.

Dowel bars and tiebars are used to provide support between adjacent panels in a pavement.

They are either placed in baskets (dowels) or chairs (tiebars) or inserted into the fresh concrete (see Dowel Bars, Tiebars, and Reinforcement in chapter 3, page 61; and Dowel Bar Tolerances in chapter 9, page 248).

Pre-Placed Bars

Dowel assemblies are fastened to the subbase using steel staking pins for granular materials or nailing clips for stabilized materials (figure 8-12).

If not properly fastened, the bars may tip or move under the pressure of paving. It is therefore important that the cages be pinned securely so that they do not move when the paver passes over them.

Care in positioning the baskets is also necessary so that joints can be sawed directly over the basket and perpendicular to the centerline. A permanent mark indicating the location of the dowel baskets, or an indentation in the edge of the slab in the area of the basket, should be made for later reference when sawing the contraction joints.

Dowel baskets and tiebars may disrupt the consolidation pressure during the passage of a slipform paver. The result is a bump and/or dip in the surface of the pavement or an indentation in the edge of the slab in the area of the basket. Some contractors find that placing concrete over dowel assemblies before passage of the paving machine eliminates dowel assembly pressure effects. Others find the use of v-floats or properly adjusted oscillating beam floats to remove spring-back and rippling effects.

In some cases for longitudinal joints, contractors elect to place tiebars into position ahead of paving. Straight deformed bars on supporting chairs fasten to the subbase or subgrade in a manner similar to dowel baskets. In fixed-form construction, standard tiebars or two-piece bars with a threaded coupling insert through holes in side forms for longitudinal construction joints. Care in consolidating the concrete around these bars is necessary.

a) Staking

b) Pinning

Figure 8-12. (a) Staking or (b) pinning dowel cages (ACPA)

Inserted Bars

The alternative to placing dowel bars in basket assemblies is to use automatic dowel insertion equipment (figure 8-13).

The key to controlling the location and positioning of automatically inserted dowel bars is the concrete mixture. Mixtures with well-graded aggregate and appropriate workability produce excellent results with dowel insertion. Mixtures with gap-graded aggregate, on the other hand, tend to allow the dowels to migrate within the concrete mass.

Figure 8-13. Dowel bar insertion equipment (ACPA)

Finishing

Key Points

- It is best to limit the amount of hand and mechanical finishing.
- Hand finishing of the pavement surface using bull floats is necessary only where the surface left from the paving equipment contains voids or imperfections.

Hand finishing of the pavement surface using bull floats is necessary only where the surface left from the paving equipment contains voids or imperfections. Mechanical longitudinal floats are often overused behind the screed or slipform equipment. In general, it is best to limit hand and mechanical finishing. If longitudinal floating is the only method to produce an acceptably closed surface, adjustments are needed in the concrete mixture and/or to the paving equipment. The agency and contractor should review and adjust their design and operations to improve the results achieved by the paving machine alone.

Checking the surface behind the paving equipment with a 3- to 6-m (10- to 20-ft) hand-operated straightedge is a recommended procedure. Successive straightedge checks should overlap by one-half the length of the straightedge to help ensure that the tool detects high and low spots in the surface. Experienced finishers can use the straightedge to remove noticeable bumps by employing a scraping motion. Otherwise, they use a long-handled float to smooth bumps and disturbed places in the surface.

Headers (transverse construction joints) are one of the most consistent contributors to the roughness of concrete pavement. This is because headers occur at the end of a day of work or at an interruption for a bridge, intersection, or leave-out. The paving machine must stop at these locations, and the most common practice is to place a wooden form to create the joint. The forming of a header in this manner increases the chance of a bump in the surface due to the hand work necessary to blend the mechanized paving surface with the hand-placed area.

Hand forming headers can be avoided by using a cutback method to create the joint. The paver operator continues paving until all of the concrete is used. The following morning, a transverse saw cut is made about 1.6 m (5 ft) from the end of the hardened concrete slab. The end material is removed and dowels are grouted into holes drilled into the smooth saw face. This method of header construction is less labor intensive and produces a smoother riding construction joint than is generally achieved using the form and hand finishing technique.

Texturing and Smoothness

Key Points

- The texture of a concrete surface affects skid resistance and noise.
- Texture is usually applied to the pavement surface while it is plastic.
- It is important to apply texture uniformly.
- Pavement condition is often judged by its smoothness. Follow good construction practices.

Concrete pavement surfaces are generally textured to provide adequate friction and skid resistance. The texture also affects tire-pavement noise.

It is generally preferable to conduct texturing sooner rather than later, so that curing can be applied early.

Texturing Options

Most texturing techniques involve dragging a texturing tool across plastic concrete (table 8-4). Work is ongoing to find the optimum means of achieving satisfactory skid resistance while reducing noise effects (Rasmussen et al. 2004) (see Functional Performance in chapter 2, page 13).

Table 8-4. Description of Various Concrete Pavement Texture Options

Texture for fresh concrete	Description
Burlap drag	Produced by dragging moistened coarse burlap from a device that allows control of the time and rate of texturing – usually a construction bridge that spans the pavement. Produces 1.5 to 3 mm ($^1/_{16}$ to $^1/_8$ in.) deep striations.
Artificial turf drag	Produced by dragging an inverted section of artificial turf from a device that allows control of the time and rate of texturing – usually a construction bridge that spans the pavement. Produces 1.5 to 3 mm ($^1/_{16}$ to $^1/_8$ in.) deep striations when using turf with 77,500 blades/m^2 (7,200 blades/ft^2).
Transverse broom	Obtained using either a hand broom or mechanical broom device that lightly drags the stiff bristles across the surface. Produces 1.5 to 3 mm ($^1/_{16}$ to $^1/_8$ in.) deep striations.
Longitudinal broom	Achieved in similar manner as transverse broom, except that broom is pulled in a line parallel to the pavement centerline.
Random transverse tining* (perpendicular or skewed)	Achieved by a mechanical device equipped with a tining head (metal rake) that moves across the width of the paving surface laterally or on a skew. (A hand tool is sufficient on smaller areas.)
Longitudinal tining*	Achieved in similar manner as transverse tining, except the tines are pulled in a line parallel to the pavement centerline.
Exposed aggregate	Occasional European practice of applying a set retarder to the new concrete pavement, covering with plastic sheeting, and then washing or brushing away mortar at a later age to expose durable aggregates. Other techniques involve the uniform application of aggregates to the fresh concrete, and mechanically abrading the mortar at a later age.
Diamond grinding	Longitudinal, corduroy-like texture made by equipment using diamond saw blades gang-mounted on a cutting head. The cutting head produces 164 to167 grooves/m (50 to 60 grooves/ft) and can remove 3 to 20 mm ($^1/_8$ to $^3/_4$ in.) from the pavement surface.

* For best results, most agencies precede with a burlap or artificial drag texture.

Drag Textures

Dragging artificial turf or moistened, coarse burlap across the surface of plastic concrete creates a shallow surface texture.

Longitudinal Tining

Longitudinally tined textures are created by moving a tining device (commonly a metal rake controlled by hand or attached to a mechanical device) across the plastic concrete surface parallel to the centerline.

Transverse Tining

Transversely tined textures are created by moving a tining device across the width of the plastic pavement surface. The tines can be uniformly or randomly spaced, or skewed at an angle.

If transverse tining is used, it is recommended that a spacing of 12.5 mm (0.5 in.) be used.

Diamond Grinding

Diamond grinding is a process of removing a thin layer of hardened concrete pavement using closely spaced diamond saw blades.

Innovative Techniques

Exposed aggregate pavements and pervious pavements are being investigated for their friction and noise levels.

Texture Variability

Whichever technique is used, it is important to apply the texture as uniformly as possible to produce uniform friction and noise levels. The following factors influence variability in textures:

- Consistency of concrete properties (workability).
- Time of texturing related to concrete placement.
- Presence of bleed water on the fresh concrete surface.
- Total pressure and variability of pressure on the texturing tools.
- Evenness of the tools on the surface.
- Angle of tines to the surface.
- Cleanliness of burlap, turf, or tines.

The texture depth primarily depends on both the time at which the texturing tool is applied (relative to when the concrete was placed and finished) and the amount of pressure applied to the texturing tool. Drag textures, such as burlap drag and artificial turf drag, can be weighted down to improve texture depth by piling sand or rock on the material (figure 8-14).

It is important to determine the optimum time to begin texturing and the amount of pressure required to achieve the desired depth, and then to consistently apply the texture at that time and pressure.

Pavement Smoothness

Pavement smoothness is the users' primary measure of a pavement's condition, and it is therefore a very important aspect in terms of quality. Several important specification and construction factors influence the smoothness of a pavement. Tables 8-5 and 8-6 describe these factors (ACPA 2003b).

Figure 8-14. Artificial turf drag texturing rig, weighted with sand (ACPA)

Table 8-5. Specification Factors that Influence Pavement Smoothness

Design / specification factor	Comment
Base/subbase and trackline	Needs to be stable and built to a tolerance; additional subbase width should be in pay item.
Horizontal alignment, cross-slope, and super-elevated curves	Curves and cross-slopes can add to roughness by design.
Grade and staking calculations	Accuracy of surveying and staking is essential.
Embedded reinforcement and fixtures	Manholes, valve access covers, rebar, etc., have potential to affect smoothness.
Concrete mixture	Proper proportioning and gradation is key to having a mix that will slipform easily.
Access to businesses and local residences	Block-outs or leave-outs will add to roughness; minimize or eliminate if at all possible.

Table 8-6. Construction Factors that Influence Pavement Smoothness

Construction factor	Comment
Preparing the grade	Pay attention to the smoothness of each layer of material under the pavement.
Producing consistent concrete	Batch-to-batch consistency is key to producing a smooth pavement.
Delivering concrete	Keeping the paver moving is essential to minimize bumps; hauling is often the critical step in consistent paving.
Setting up fixed forms	Top of form determines surface of the pavement.
Setting and maintaining the stringline	Check often; use night-smoothing techniques; ensure that it is taut.
Operating the paving machine	Keep proper amount of concrete (head) consistently in front of paver; minimize stops; monitor vibrators.
Paving on vertical grades and curves	Adjust the paver's profile pan; adjust staking interval.
Handling dowel bars and reinforcement	Place concrete on dowel assemblies before paver; turn down vibrators.
Finishing the surface and headers	Check surface (cut bumps) behind paver with longest straightedge possible; use cut-back header if formed headers cause bumps.
Educating and motivating the crew	Training is essential; explain factors involved and consequences of actions; implement an employee bonus system for smoothness incentives.

Curing

Key Points

- Curing is the action taken to maintain moisture and temperature conditions in a freshly mixed concrete to allow hydration and pozzolanic reactions to proceed.
- Curing primarily affects the quality of the surface of a pavement, the zone that is impacted most by the environment and loading conditions.
- Curing compounds provide the most efficient means of providing curing for pavement concrete.
- Curing activities include controlling the temperature of the concrete during extreme weather.

Curing is the action taken to maintain moisture and temperature conditions in a freshly mixed concrete to allow hydration and pozzolanic reactions to proceed. Internal temperature and moisture directly influence both early and ultimate concrete properties (Kosmatka, Kerkhoff, and Panarese 2002). Proper curing measures prevent rapid water loss from the mixture and allow more thorough cement hydration. It is essential to apply curing measures as early as possible after placing concrete and to continue them until enough hydration has taken place that the required hardened properties have been achieved.

A variety of curing methods and materials are available for concrete pavement, including the following: water spray or fog, wet burlap sheets, plastic sheets, insulating blankets, and liquid membrane-forming compounds. The most common method of curing is the application of a curing compound.

Curing Compound

Curing compounds are organic materials that form a skin over the surface of the concrete and reduce the rate of moisture loss from the concrete (see Curing Compounds in chapter 3, page 64).

Note: On dry, windy days, or during periods when adverse weather conditions could result in plastic shrinkage cracking, an application of evaporation retarders immediately after final finishing and before all free water on the surface has evaporated will help prevent the formation of cracks. Evaporation retarders should not be confused with curing compounds.

The most common curing method for concrete pavements is the application of a liquid membrane-forming compound to the concrete surface. This material limits water evaporation to about 20 percent of unprotected concrete when properly applied. A liquid membrane-forming compound that meets ASTM C 309 / AASHTO M 148 material requirements is adequate for most situations when applied at the following rates (ACPA 1994):

- 5.0 m^2/L (200 ft^2/gal) for normal paving applications.
- 3.75 m^2/L (150 ft^2/gal) for fast-track concrete.
- 2.5 m^2/L (100 ft^2/gal) for thin overlays.

If the curing regimen is inadequate or applied too late, the concrete will be susceptible to plastic shrinkage cracking, excessive curling, and scaling.

Therefore, for curing compound to be of benefit it should be applied as soon as possible after the water sheen has left the surface and texturing is complete. The concrete surface should be damp when the compound is applied.

Figure 8-15. A curing machine coats both the top surface and sides of a slipform paving slab. (ACPA)

The initial application of curing compound should coat both the top and edges of slipformed concrete (figure 8-15). For fixed-form paving, the curing compound should initially coat the exposed concrete surface. If removing forms early, a second coat is necessary to any exposed vertical edges of the slab in order to provide a complete seal. Timely application is important; curing compound should be applied as the water sheen is disappearing on the surface.

Curing compounds should be applied by hand-operated or power-driven spray equipment immediately after final finishing of the concrete. Hand-operated equipment should be used only for small areas.

Power-driven spray equipment is recommended for uniform application of curing compounds on large paving projects. Spray nozzles and windshields on such equipment should be arranged to prevent wind-blown loss of curing compound.

Complete coverage of the surface must be attained because even small pinholes in the membrane will increase the evaporation of moisture from the concrete. Normally, only one smooth, even coat is applied. If two coats are necessary to ensure complete coverage, the second coat should be applied at right angles to the first as soon as the first coat becomes tacky.

Curing compounds might prevent bonding between hardened concrete and a freshly placed concrete overlay. Consequently, they should either be tested for compatibility or not used when a bonded overlay is used.

White pigmentation in the compound is preferable to a clear compound because the amount of coverage is easy to see. The pigment also reflects solar radiation that may otherwise heat the concrete surface excessively.

Recommendations for curing compound application include the following (IPRF 2003):

- Apply liquid curing compounds using spray equipment mounted on a self-propelled frame that spans the paving lane.
- Limit hand-held sprayers for curing application on small areas.
- Even though a visual check is feasible with white-pigmented curing compound, measure the volume on a given area and compare it to the specified or recommended application rate.
- Apply curing compound to all exposed faces of the concrete after slipforming or after forms are removed.
- When moist curing, maintain the moist condition over the entire concrete surface for the entire curing period (typically seven days) or until a curing compound is applied.

A curing compound is not the same as an evaporation retarder, which is a water-based, spray-on liquid that forms a mono-molecular film over the plastic concrete surface. It is intended to be applied immediately after strike-off and/or between finishing operations to reduce the risk of plastic shrinkage cracking. Evaporation retarders will not retard the setting characteristics of the concrete, but they will minimize the amount of water loss in the concrete due to evaporation. They are useful in very dry or windy conditions, when evaporation rates are high. A curing compound (or other curing method) must still be applied subsequent to final finishing or texturing.

Evaporation retarders should not be used as finishing aids because, as they are worked into the surface of the concrete, they will elevate the water-cement ratio at the surface. This may lead to lower strengths at the surface, poor air content or air-void structure, and nondurable surface mortar.

Other Curing Methods

Plastic sheeting can be used for curing, usually as a supplement to curing compound, to facilitate cold weather placements, or to protect the freshly placed slab from rain (see Weather Considerations on the next page). Plastic sheeting is also useful to sustain the heat of hydration and increase the strength gain because it maintains a layer of air above the surface, which acts as an insulator.

Curing blankets can also be used for curing. Consider carefully before removing curing sheeting or blankets from a recently placed concrete pavement. If the concrete is still warm when the blankets are removed, and the ambient temperature is low, thermal shock can occur, which may cause cracking (Huang et al. 2001).

Weather Considerations

Key Points

- Preparations for hot- or cold-weather paving, as well as for a rain event, should be made well in advance.
- During hot-weather paving conditions, it is critical to reduce the evaporation rate from concrete to minimize plastic shrinkage cracking.
- During cold-weather paving conditions, primary concerns are to keep the concrete temperature above freezing so that hydration continues and to control cracking through joint placement.
- During a rain event, it is important to cover and protect the new concrete surface as well as to prepare for a possible cold front following the rain. A sudden, significant drop in temperature can increase the risk of uncontrolled cracking.

Hot-Weather Concreting

The American Concrete Institute categorizes hot weather as a period when, for more than three consecutive days, the following conditions exist (ACI 1999):

- The average daily air temperature is greater than 25°C (77°F). The average daily temperature is the mean of the highest and the lowest temperatures occurring during the period from midnight to midnight.
- The air temperature for more than one-half of any 24-hour period is not less than 30°C (86°F).

Preparation for hot-weather paving should take place long before paving begins.

Whenever the construction team anticipates building a project in the summer, they should verify the concrete mixture for these conditions. Verification testing is conducted in the laboratory during the mix design phase. The testing laboratory mixes trial batches and casts specimens at temperatures representative of the site conditions to flag whether compatibility problems may arise.

During hot weather, problems that may occur include the following:

- Rapid slump loss.
- Reduced air contents.
- Premature stiffening.
- Plastic shrinkage cracking.
- Thermal cracking.

During hot weather, the construction team should take steps to reduce the evaporation rate from the concrete. The likelihood of plastic shrinkage cracking increases when the evaporation rate increases. Plastic shrinkage cracking results from the loss of moisture from the concrete before initial set. The evaporation rate is a function of the following:

- Air temperature.
- Concrete temperature.
- Relative humidity.
- Wind speed.

If the evaporation rate exceeds 1.0 kg/m^2/hr (0.2 lb/ft^2/hr), it is advisable to provide a more effective curing application, such as fog spraying, or to apply an approved evaporation reducer.

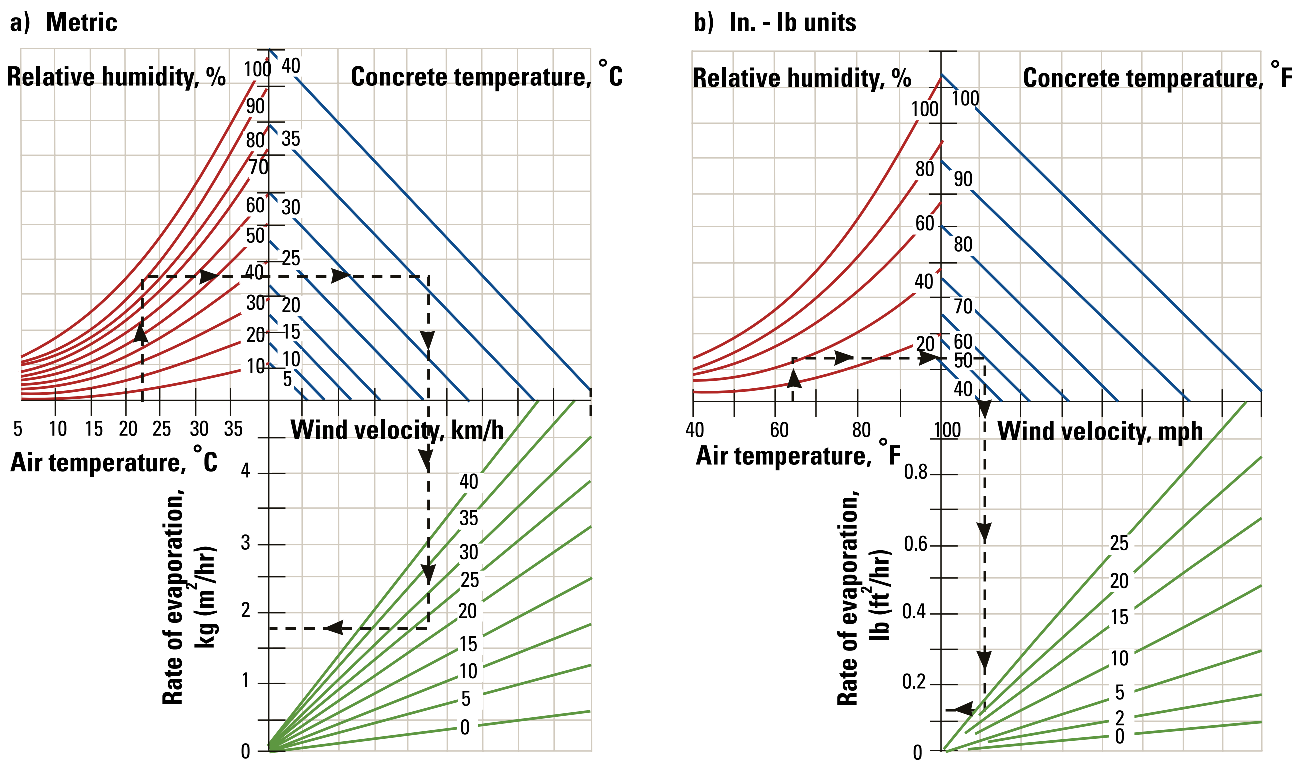
One or more of the following precautions can minimize the occurrence of plastic shrinkage cracking (Menzel 1954, as published in Kosmatka, Kerkhoff, and Panarese 2002). They should be considered while planning for hot-weather concrete construction or while dealing with the problem after construction has started. The precautions are listed in the order in which they should be done during construction:

- Moisten dry, absorptive aggregates.
- Keep the concrete temperature low by cooling aggregates and mixing water.
- Dampen the subgrade and fog forms before placing the concrete.
- Erect temporary windbreaks to reduce wind velocity over the concrete surface.
- Erect temporary sunshades to reduce concrete surface temperatures.

If conditions of temperature, relative humidity, and wind are too severe (figure 8-16) to prevent plastic shrinkage cracking, or if corrective measures are not effective, paving operations should be stopped until weather conditions improve (IPRF 2003).

The following are general recommendations/options/considerations for hot-weather concreting (IPRF 2003):

- Do not exceed the maximum allowable water/cementitious materials ratio or the manufacturer's maximum recommended dosage of any admixture.
- Consider retarding admixtures if their performance has been verified during trial batches.
- Substitute ground, granulated blast-furnace slag or class F fly ash for part of the portland cement. These materials hydrate more slowly and generate lower heats of hydration than cement, reducing tendencies toward slump loss, premature stiffening, and thermal cracking. Certain class C fly ashes, with high calcium and aluminum contents, may cause premature stiffening.
- Low air contents can be corrected by increasing the dosage of air-entraining admixture. Better or longer mixing may allow maintenance of a constant air-void spacing factor without a greater air content. Using additional water reducer may also be helpful.
- Risk of early-age thermal cracking is reduced by ensuring that the temperature of the plastic concrete is as low as practical.
  - Sprinkling with water may cool aggregates; be sure to correct for the aggregate moisture.



To use these charts

1. Enter with air temperature, move up to relative humidity.
2. Move right to concrete temperature.
3. Move down to wind velocity.
4. Move left; read approximate rate of evaporation.

Legend

Relative humidity
Concrete temperature
Wind velocity

Figure 8-16. A monograph to estimate the rate of evaporation (PCA)

  - Aggregates need to be batched in a saturated surface-dry condition to avoid absorbing mixture water.
  - Chilling the mixing water or adding chipped ice in substitution for some of the water lowers the mix temperature. Be sure that all of the ice melts during mixing.
- Consider painting the mixing and transporting equipment white or another light color to minimize the heat absorbed from the sun.
- In extreme conditions, consider scheduling concrete placements for during the evening or night.
- Moisten the base before the concrete is placed to keep the temperature down and to keep it from absorbing water from the concrete.
- Place and finish the concrete as rapidly as possible to apply the curing compound at the earliest possible time. The use of a white curing compound will reflect the sun's heat. If there is any delay in applying the curing compound, use a fog spray or evaporation retardant to keep the surface from drying out.
- Refer to ACI 305, Hot Weather Concreting, for additional information.

Cold-Weather Placement

Cold weather is defined by ACI as a period when, for more than three consecutive days, the following conditions exist (ACI 1988):

- The average daily air temperature is less than 4°C (40°F). The average daily temperature is the mean of the highest and lowest temperatures occurring during the period from midnight to midnight.
- The air temperature is not greater than 10°C (50°F) for more than one-half of any 24-hour period.

Cold-weather paving requires special considerations. The contractor and material supplier should address these considerations well before temperature forecasts predict temperatures to drop close to or below freezing. The primary concern is to keep the temperature of the concrete above freezing so that the hydration reaction continues and to control cracking through joint placement.

Trial batches are needed to verify that the proposed mixtures will achieve the desired strength at the potential temperatures. Mixtures with accelerating admixtures must be treated carefully to ensure that they accelerate the setting and/or early strength gain of concrete but do not lead to workability or constructability challenges.

The following are recommendations/options/considerations for cold-weather concreting (IPRF 2003):

- Consider using a higher portland cement content in concrete mixture designs for placement at cooler temperatures.
- Reduce or eliminate ground, granulated blast-furnace slag, fly ash, and natural pozzolans from the mixture unless they are required for durability.
- The necessary air-entraining admixture dosage will likely be lower for cold-weather concrete than for concrete designed for normal temperatures.
- An accelerating admixture conforming to ASTM C 494 Type C or E may be used, provided its performance has been previously verified by trial batches.
- Do not use admixtures containing added chlorides. Also, do not use calcium chloride.
- Aggregates must be free of ice, snow, and frozen lumps before being placed in the mixer.
- Because the concrete will take longer to set, there is more risk for plastic shrinkage cracking, especially if the concrete is much warmer than the ambient air or the wind speed is significant.
- Consider heating the mix water (if practical for the size of the pour). The temperature of the mixed concrete should not be less than 10°C (50°F).
  - The mixture water and/or aggregates may be heated to 66°C (150°F).
  - The material must be heated evenly.
- Insulating blankets also are necessary for curing concrete pavement in cool weather. The blankets reduce heat loss and lessen the influence of both air temperature and solar radiation on the pavement temperature. The blankets are

not a substitute for curing compound, which is still needed to contain moisture for complete hydration.

- The concrete temperature should be maintained at 10°C (50°F) or above for at least 72 hours after placement and at a temperature above freezing for the remainder of the curing time (when the concrete attains a compressive strength of 20 MPa [3,000 lb/in^2]). Corners and edges are the most vulnerable to freezing.
- Concrete should not be placed when the temperatures of the air at the site or the surfaces on which the concrete is to be placed are less than 4°C (40°F).
- Concrete placed in cold weather gains strength slowly. Concrete containing supplementary cementitious materials gains strength very slowly.
  - Sawing of joints and opening to traffic may be delayed.
  - Verify the in-place strength by a maturity method, temperature-matched curing, nondestructive testing, or tests of cores from the pavement before opening the pavement to traffic.
- Allow the slabs to cool before completely removing insulating blankets to avoid a thermal shock to the pavement that might induce contraction cracking. Insulating blankets may be temporarily rolled aside to saw contraction joints.
- Refer to ACI 306, Cold Weather Concreting, for additional information.

Protection From Rain

Plastic sheeting (figure 8-17) and steel side forms or wooden boards must be available at all times to protect the surface and edges of the newly placed concrete pavement when it rains. If rain is expected on newly placed concrete pavement that has not hardened, cover the surface with the plastic sheeting.

The sheets must be weighted down to prevent them from blowing in the wind. When it starts raining, a "rule of thumb" to determine how much of the pavement to cover is to go back to the point where the rain is not indenting the pavement surface. The covering does not need to be extended to areas where the rain is only washing away the curing membrane (ACPA 2003a).

Climatic conditions during a rain event can actually be conducive to good concrete curing. During rain, the humidity is at or near 100 percent and there is little chance for the evaporation of mix water. Temperatures are generally moderate during rain, which is also beneficial. In these situations, the rain essentially provides a beneficial moist curing environment, which assists with strength development and decreases the chance for uncontrolled cracking. This provides a natural cure.

Sometimes, particularly if the prevailing weather is hot and humid, rain precedes the passage of a cold front, which may drop the air temperature more than 11°C (20°F). Where this occurs, and when the pavement is under construction, the risk of uncontrolled cracking will increase (ACPA 2002). The drop in the dew point that usually occurs with a cold front may also lead to a lower relative humidity above the warm concrete and thus a greater susceptibility for plastic shrinkage cracking.

Some marring of the concrete surface may occur from the plastic sheeting used to protect the slabs from rain. Except for an undesirable appearance, there is nothing wrong with surfaces affected by plastic sheeting. A similar appearance can occur when using plastic sheeting to cure concrete.

Figure 8-17. Plastic sheeting ready for placement to protect the fresh surface from rain (ACPA)

Additional water on the pavement surface will elevate the surface water-cementitious materials (w/cm) ratio, potentially reducing durability. Do not finish rainwater into the concrete surface. This elevates the w/cm ratio, creating a nondurable top surface, susceptible to crazing, scaling, and dusting (figure 8-18).

For slipform paving operations, it is advantageous to install side forms where severe erosion of the fresh concrete edge may occur (figure 8-19) because of heavy rain.

Figure 8-18. Typical scaling of concrete pavement due to rain on nondurable paste surface (ACPA 2003a)

Figure 8-19. Edge erosion of freshly placed slab due to rain (ACPA 2003a)

Crack Prediction with HIPERPAV

Key Points

- A number of variables influence the risk of cracking in concrete:
    - Temperature.
    - Rate of drying.
    - Shrinkage.
    - Restraint.
    - Strength.
    - Modulus of elasticity.
    - Coefficient of thermal expansion (CTE).
- A computer program, HIPERPAV, is available to model the risk of cracking for a given mix under a given environment.

Many variables can influence the propensity of a specific concrete to crack (see Early-Age Cracking in chapter 5, page 148). However, it is possible to numerically model the dominant mechanisms of failure to assess the risk of cracking within a given set of conditions.

Such a model has been developed for pavements by the Federal Highway Administration (FHWA 1999). The resulting software package, known as HIPERPAV, is briefly described below. For more information, see www.fhwa.dot.gov/pavement/pccp/hipemain.cfm.

HIPERPAV is a commercially available computer software package. It is intended to be used by personnel involved in constructing concrete pavements and bonded overlays. Its purpose is to model and predict whether the concrete is likely to crack at an early age due to conditions unrelated to structural slab loading.

The program is also used to estimate the window of opportunity for saw cutting.

The program considers the following factors:

- Concrete pavement temperature.
- Concrete coefficient of thermal expansion (CTE).
- Drying shrinkage.
- Slab-sub-base restraint.
- Modulus of elasticity.
- Strength.

All of these performance parameters are calculated based on complex numerical models that use the following factors as input parameters:

- Pavement design inputs:
    - Subbase type.
    - Slab-base friction (bond).
    - Transverse joint spacing.
    - Tensile strength.
    - Modulus of elasticity.
    - Slab thickness.
    - Mix design inputs.
    - Concrete strength development.
    - Portland cement type.
    - Cement chemistry.
    - Cement content.
    - Silica fume content.
    - Fly ash (type F and C) content.
    - GGBF slag content.
    - Water content.
    - Coarse aggregate type and content.
    - Fine aggregate content.
    - Water reducer content.
    - Super water reducer.
    - Retarder content.
    - Accelerator content.
- Environmental inputs:
    - Air temperature.
    - Relative humidity distribution.
    - Cloud conditions.
    - Moisture conditions.
    - Wind speed.
- Construction inputs:
    - Curing method.
    - Time of curing application.
    - Time of curing removal.
    - Time of construction.
    - Time of saw cutting.
    - Initial portland cement concrete.
    - Mix temperature.
    - Initial subbase temperature.

The output of the HIPERPAV program is a plot of allowable stress (developed strength anticipated) in the concrete and the predicted stress over a period of 72 hours (figure 8-20). If the predicted stress exceeds the allowable stress, cracking is indicated as likely and changes need to be made to the concrete mix or construction practices, and/or protection must be provided from the environment.

The HIPERPAV package has been validated for a range of designs, materials, and climatic conditions at several sites in the United States. Pavements under construction were instrumented and the data were compared with the predictions made by the program. The system was found to predict crack formation with an accuracy of approximately five hours.

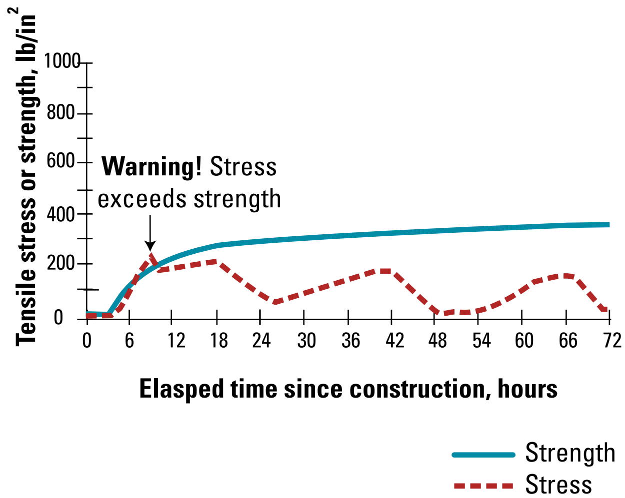


Figure 8-20. An example plot reported by HIPERPAV showing a high risk of cracking at about six hours after paving

Joint Sawing

Key Points

- Joints are required to control cracking in a concrete pavement.
- Joints can be saw cut after the concrete has been placed.
- It is critical to cut the joints at the right time: too early will result in raveling, too late will be after random cracking occurs.
- The timing of saw-cutting is dependant on concrete properties and the environment.

Like all materials, concrete expands and contracts with variations in temperature and moisture content, which can cause cracking if it is restrained. Cutting the pavement into smaller elements helps relieve the restraint and generally ensures that the cracks form where desired rather than at random (see Early-Age Cracking in chapter 5, page 148).

Concrete slabs crack when tensile stresses within the concrete overcome the tensile strength. At early ages, the tensile stresses develop from restraint of the concrete's volume change or restraint of slab bending from temperature and moisture gradients through the concrete (Okamoto et al. 1994). Early volume changes are associated with the concrete's drying shrinkage and temperature contraction. Each transverse and longitudinal saw cut induces a point of weakness where a crack will initiate and then propagate to the bottom of the slab.

In most cases, cracks first appear at large intervals, 10 to 45 m (30 to 150 ft), and then form at closer intervals over time. Intermediate sawed joints, normally required to control cracking from differentials, sometimes do not crack for several weeks to months after opening the pavement to traffic. However, this may not be true on every pavement, and it may be very difficult to determine whether restraint to volume changes or restraint to temperature or moisture gradients cause the first cracks.

A fundamental of jointed concrete pavement design is to introduce a jointing system to control the location of this expected cracking. Of the three joint types, contraction, construction, and isolation, contraction joints are specifically for crack control. For unreinforced concrete pavement, joint spacing or slab length depends upon slab thickness, concrete aggregate, subbase, and climate (ACPA 1991). In most areas, the typical maximum transverse joint spacing for unreinforced (plain) pavement is about 4.5 m (15 ft) (ACPA 2004b). Longitudinal joints are typically about 3.0 to 4.2 m (10 to 13 ft) apart and serve the dual purpose of crack control and lane delineation.

The climate and concrete coarse aggregate common to some geographic regions may allow transverse joints to be further apart or require them to be closer together than the average. For example, concrete made from granite and limestone coarse aggregate is much less sensitive to temperature change than concrete made from siliceous gravel, chert, or slag aggregate. A less temperature-sensitive concrete does not expand or contract much with temperature change, which allows a longer spacing between pavement contraction joints without a greater chance of random cracking.

Various kinds of saws can be used for cutting joints (figure 8-21).

Saw Timing

There is an optimum time to saw contraction joints in new concrete pavements. That time occurs within the sawing window (figure 8-22) (Okamoto et al. 1994). The window is a short period after placement when the concrete pavement can be cut to successfully control crack formation (see the Stages of Hydration charts and Concrete Strength Gain, Tensile Stress, and the Sawing Window in chapter 4, pages 76 and 93, respectively). The window begins when concrete strength is sufficient for sawing without excessive raveling along the cut. The sawing window ends when random cracking starts to occur.

Sawing too early causes the saw blade to break or pull aggregate particles free from the pavement surfaces along the cut. The resulting jagged, rough edges are termed raveling. Some raveling is acceptable where a)

b)

c)

Figure 8-21. Common sawing equipment. (a) For most projects, transverse or longitudinal contraction joints are cut with single-blade, walk-behind saws. (b) For wider paving, contractors may elect to use span-saws that are able to saw transverse joints across the full pavement width in one pass. (c) A newer class of saw, the early-entry dry saw, is a walk-behind saw that allows sawing sooner than with conventional saws. (ACPA)

a second saw cut would be made for a joint sealant. If the raveling is too severe, it will affect the appearance and/or the ability to maintain the joint. Figure 8-23 shows different degrees of raveling.

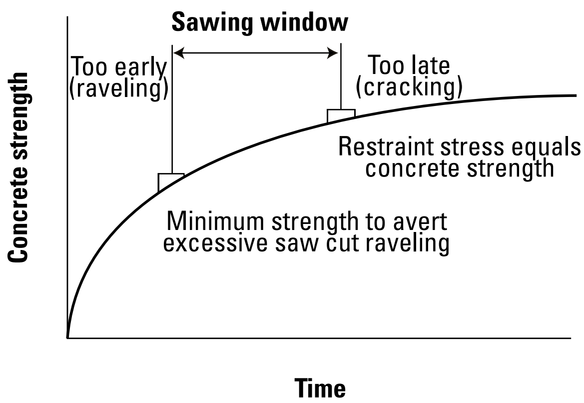
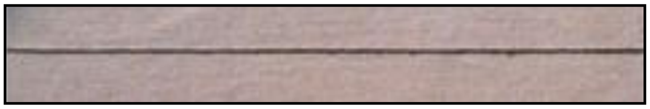
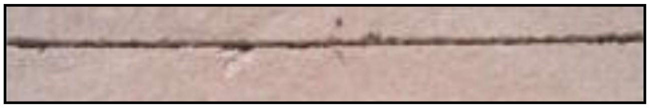


Figure 8-22. Sawing window (ACPA)

a) No raveling—sawed later in the window



b) Moderate raveling—sawed early in the window



c) Unacceptable raveling—sawed too early

Figure 8-23. Close-up of different degrees of raveling caused by joint sawing (ACPA)

When Can You Begin Sawing Joints?

To determine when the concrete is ready to cut, use the Scratch Test (Saraf 1985). Scratch the concrete surface with a nail or knife blade. As the surface hardens, the scratch depth decreases. In general, if the scratch removes the surface texture, it is probably too early to saw.

One study (Okamoto et al. 1994) found that raveling was within acceptable limits when the concrete compressive strengths were from 2.1 to 7.0 MPa (300 to 1,015 lb/in^2), depending upon the type of aggregate used in the mixture. Refinement of a specific strength threshold number to be used on a project would require trial and error testing of the job materials using the concrete maturity principle.

The length of the sawing window depends upon many factors and is likely to be different for each project and each day of construction. Certain design features, materials, or weather conditions can considerably shorten the window (table 8-7). Under most weather conditions and for typical pavement designs, the window will be long enough to complete sawing with excellent results. In extreme conditions, the window can be so short as to be impracticable for crack control. Concrete maturity testing helps indicate the influence of ambient conditions on the concrete strength profile and consequently helps define the sawing window. Other tools include the FHWA's HIPERPAV software, which can help determine saw timing and predict the possibility of uncontrolled cracking (McCullough and Rasmussen 1999).

Table 8-7. Factors that Shorten the Sawing Window

Category	Factor
Concrete mixture	High water demand Rapid early strength Retarded set Fine aggregate (fineness and grading) Coarse aggregate (maximum size and/or percentage)
Weather	Sudden temperature drop or rain shower Sudden temperature rise High winds and low humidity Cool temperatures and cloudy Hot temperatures and sunny
Subbase	High friction between the subbase and concrete slab Bond between the underlying subbase and concrete slab Dry surface Porous aggregate subbase materials
Miscellaneous	Paving against or between existing lanes Saw blade selection Delay in curing protection

Source: ACPA (2002)

Early-entry saws are now frequently used on paving projects. Smaller and lighter than conventional saws, they have the advantage of allowing sawing to begin within an hour or two of paving. The sawing window for early-entry saws begins earlier and ends sooner than for conventional saws; see figure 4-13.

First-generation early-entry saws were designed to cut shallow (25 mm [1 in.)]) joints. At final set (the beginning of the sawing window for early-entry saws), a shallow joint is enough to create a plane of weakness where a crack will form to relieve stresses as the pavement builds strength. Early, shallow cuts work well for transverse joints, regardless of the thickness of the pavement.

Longitudinal joints, on the other hand, are typically cut later (often within the first day). By this time, the concrete has developed more strength, and a deeper cut is required to effectively create a plane of weakness. Therefore, first-generation early-entry saws were not normally used for longitudinal joints. Today, both early-entry and conventional saws can cut longitudinal joints to the required one-third depth of the slab.

Note about joint width: Because transverse joints move, they are typically sealed to prevent the infiltration of water and foreign matter. The saw cuts (whether early-entry or conventional) must therefore be at least 6 mm (1/4-in.) wide to form adequate reservoirs for the sealant. Because longitudinal joints are tied and thus designed not to move, many states do not seal them. The saw cuts can therefore be narrow (3 mm [1/8 in.]). With granular bases and subdrains, any water entering longitudinal joints will effectively drain away.

Mixture Effects

Regardless of other related factors, the concrete mixture itself is a primary factor in defining the potential to control cracking with a jointing system.

The primary influences of the mixture are the following:

- Paste content.
- Water-cementitious materials ratio.

- Type of cementitious materials.
- Aggregate type.

The volume of shrinkage is directly controlled by the total water content, which is a function of cementitious content and w/cm ratio. Increased water content increases shrinkage. On the other hand, the greater the strength, the better able the concrete is to resist shrinkage induced stresses.

Mixtures containing fly ashes or ground, granulated blast-furnace (GGBF) slag or blended cement may experience a delay in early-age strength development, especially in cooler weather. This could delay the concrete set time and the ability to saw without excessive raveling. After setting, the time available for sawing before cracking begins may be shorter than normal. This decrease in available sawing time increases the risk of uncontrolled cracking in cooler weather. Many agencies specify a usage period for such mixtures, prohibiting their use in early spring or late fall.

The coarse aggregate influences the temperature sensitivity of the concrete. Concrete that is more temperature sensitive will expand or contract more with temperature change, increasing cracking potential.

Joint Sealing

Key Points

- Joints are filled with sealant to prevent ingress of deleterious materials.
- Many alternative sealant systems are available.
- Sealant material selection considerations include the environment, cost, performance, joint type, and joint spacing.

The purpose of sealing joints is to minimize infiltration of surface water and incompressible material into the pavement layers (ACPA 1993). Excess water can contribute to subgrade or base softening, erosion, and pumping of subgrade or base fines over time. This degradation results in a loss of structural support, pavement settlement, and/or faulting.

There are many acceptable materials available for sealing joints in concrete pavements. Sealants are either placed in a liquid form or are preformed and inserted into the joint reservoir. Sealants installed in a liquid form depend on long-term adhesion to the joint face for successful sealing. Preformed compression seals depend on lateral rebound for long-term success. For more specific information on joint sealing materials and required shape factors and sizes, consult reference ACPA 1993.

Sealing prevents incompressible objects from entering joint reservoirs. Incompressibles contribute to spalling and, in extreme cases, may induce blow-ups. In either case, excessive pressure along the joint faces results as incompressibles obstruct pavement expansion in hot weather. Years ago, the term joint fillers described liquid asphalt materials placed in joints. Joint fillers aid more in keeping out incompressibles than minimizing water infiltration.

Sealant material selection considerations include the following:

- Environment.
- Cost.
- Performance.
- Joint type and spacing.

The following list includes common factors for which the concrete material or installation technique affects the joint seal performance:

- Silicone sealants are known to have poor adhesion to concrete containing dolomitic limestone. A primer application to the sealant reservoir walls will ensure that the silicone adheres.
- Concrete containing harder coarse aggregates, such as gravel or granite, will expand and contract more with a given temperature change than a concrete containing limestone. The sealant will be stretched farther for a given joint spacing. To keep this under control, use an appropriate shape factor for sealant (figure 8-24).
  - Hot-poured asphalt-based sealants typically need a reservoir shape factor (width/depth ratio) of one.
  - Silicone and two-component cold-poured sealants typically need a reservoir shape factor of two.
  - Compression sealants are selected such that the maximum compression of the seal is 50 percent and the minimum is 20 percent through the anticipated ambient temperature cycles in the area.
- Chemical solvents used to clean the joint reservoir may be detrimental. Solvents can carry contaminants into pores and surface voids on the reservoir faces that will inhibit bonding of the new sealant.
- For cleaning joints, the air stream must be free of oil. Many modern compressors automatically insert oil into the air hoses to lubricate air-powered tools. New hoses or an oil and moisture trap prevents contamination of the joint face from oil in the compressor or air hoses.

Above all, the most critical aspect in sealant performance is reservoir preparation. A considerable investment in joint preparation and cleaning activities is necessary for almost all sealant types. There is little doubt that poorly constructed joints will perform poorly. Proper cleaning requires mechanical action and pure water flushing to remove contaminants. The following outlines the recommended procedures (ACPA 1993):

- Immediately after sawing, a water wash removes the slurry from the sawing operation. Contractors perform this operation in one direction to minimize contamination of surrounding areas.
- After the joint has sufficiently dried, a sandblasting operation removes any remaining residue. Do not allow sandblasting straight into the joint. Holding the sandblast nozzle close to the surface at an angle to clean the top 25 mm (1 in.) of the joint face provides cleaning where needed. One pass along each reservoir face provides excellent results. This not only cleans the joint faces, but provides texture to enhance sealant adhesion.
- An air blowing operation removes sand, dirt, and dust from the joint and pavement surface. Conducting this operation just prior to sealant pumping ensures that the material will enter an extremely clean reservoir. The contractor must provide assurance that the air compressor filters moisture and oil from the air. The compressor should deliver air at a minimum 3.4 m^3/min (120 ft^3/min) and develop at least 0.63 MPa (90 lb/in^2) nozzle pressure. Some contractors also use a vacuum sweeper and hand brooms to keep the surrounding pavement clean.

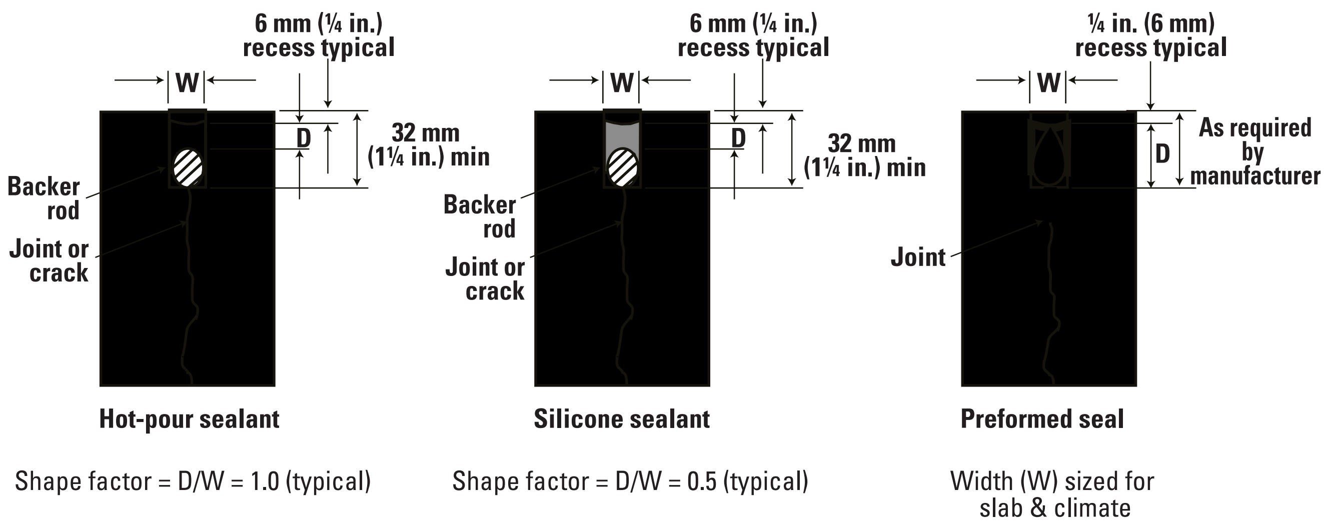


Figure 8-24. Different forms of joint sealant (ACPA)

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Chapter 9

Quality and Testing

This chapter discusses quality assurance and quality control systems as they influence concrete pavement, with special emphasis on materials. The chapter also describes actions that are needed to monitor and adjust for critical parameters, such as the water-cementitious materials (w/cm) ratio, air-void system, and the risk of cracking. Finally, tests commonly used to monitor the materials and concrete quality are described. These descriptions do not represent all quality control tests discussed throughout this manual. Rather, they have been identified as current quality control best practices in the "Materials and Construction Optimization for Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements" project at Iowa State University (TPF-5[066]).

Quality Assurance/Quality Control Records

Key Points

- Quality assurance (QA) is the set of activities conducted by the owner to be sure that the product delivered complies with the specification.
- Quality control (QC) is the set of activities conducted by the contractor to monitor the process of batching, placing, and finishing the concrete to be sure that the pavement will meet or exceed QA test criteria.
- Test laboratories must be appropriately certified by AASHTO (or equivalent) and meet the requirements of ASTM C 1077.
- QA and QC personnel should receive proper training. Most agencies require technicians to be certified (American Concrete Institute, National Institute for Certification in Engineering Technologies, etc.).
- Many tests performed on concrete have varying levels of precision. Open communication and cooperation between QC and QA organizations is important to avoid and resolve conflicts.
- Thorough record keeping allows for interpreting data, making informed decisions, and troubleshooting problems that may arise in the future.

This section defines and distinguishes between quality assurance and quality control.

Quality Assurance

Quality assurance (QA) is the set of activities conducted by the owner/agency or its representatives so that they can confirm that the product delivered complies with the specifications. A more formal definition for quality assurance is "All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality" (AASHTO 1996).

For most contracts QA is associated with acceptance testing by the owner. Emphasis is normally placed on strength, thickness, smoothness, and air content, because it is easy to compare these test results to specified values and determine whether the criteria have been satisfied. Other quality factors that are often overlooked because they are not as easily measured include steel placement for joints, air-void structure, permeability, and curing.

QA testing may also be performed by contractor personnel, but then independent testing is needed for verification. This is especially important when statistical acceptance procedures, such as percent within limits (PWL) specifications, are used.

Most of these specifications are based on the assumption that the property being tested is normally distributed. The average and standard deviation (variability) of test results are then used to estimate the percent of material that is within the specified limits. Since a portion of the overall standard deviation is due to testing variability, the contractor should have the right to maintain control over the acceptance testing.

Acceptance methods that include criteria that are at least partially based upon standard deviation should not penalize contractors if they are not allowed the opportunity to be in control of all factors that contribute to the overall variability. Whether explicitly stated or not, PWL specifications require contractors to reduce variability. This can be accomplished by producing more consistent concrete and attempting to reduce testing variability. Reducing testing variability may be as easy as simply having the same technician perform the same test for all of the samples included in a given lot of pavement.

Quality Control

In contrast to quality assurance, quality control (QC) is always the contractor's responsibility. This work focuses on the process of batching, placing, and finishing the pavement to be sure that the pavement will meet or exceed QA test criteria. AASHTO has defined quality control as "The sum total of activities performed by the seller to make sure that a product meets contract specification requirements" (AASHTO 1996).

Quality control is not an exercise in mirroring QA tests. Materials and processes are monitored at all stages of the batching and paving process to preempt problems or variations rather than simply react to them. A comprehensive QC program encompasses all aspects of the concrete paving process:

- Training of all contractor personnel: Every person on the project contributes to quality.
- Preliminary material testing: Test material before it is batched.
- Equipment and process monitoring: Develop checklists, procedures, and responses to prevent quality deficiencies.
- Testing of concrete and individual materials during trial batching and production: Concentrate on timely and early results. Additional samples may be used as a backup for QA tests.
- Analysis of QC test results and process monitoring: Organize data and identify changes in the process.
- Adjust processes in response to QC analysis: Proactively react to process changes and inputs in a timely manner.

A quality control plan is required to ensure that QC activities are carefully planned, sufficient, and consistent. The plan should provide a detailed description of the type and frequency of inspection, sampling, and testing to measure the various properties described in the specification (AASHTO 1996).

Preliminary information from the "Materials and Construction Optimization for Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements" project at Iowa State University (TPF-5[066]) provides a starting point for alternative and new test methods that can be used for QC purposes. This research project has identified a suite of tests that can be considered to be the current best practices. Summary sheets describing the why and how of each test are provided later in this chapter. These summaries can be used for guidance in determining which tests may be useful in the design of a QC program for constructing durable concrete pavements.

New QC Skills and Tools

Shifting the focus from conventional concrete testing to process control requires a different set of skills and tools. Statistical control charts can be utilized, along with new and/or alternative test methods to improve on traditional QC methods.

Quality of Testing

All personnel involved with QA and QC should receive proper training. Laboratories should be certified by AASHTO (or equivalent) and meet the requirements of ASTM C 1077. Most agencies require certification for QC and QA technicians (American Concrete Institute, National Institute for Certification in Engineering Technologies, etc.).

A thorough understanding of test procedures is necessary. Just as important, however, is the knowledge that many tests performed on concrete have varying levels of precision.

Disputes and disagreements often stem from differing test results between an owner's laboratory and a contractor's laboratory. When two technicians split a sample of concrete and the resulting flexural strength results differ by 90 lb/in^2, which test is correct? Assuming that both tests were performed according to the prescribed test method (ASTM C 78-02), both answers are correct—neither is more right than the other.

The nature of the materials and the tests is such that test results are estimates of actual pavement properties. From the owner's perspective, it is imperative to understand that each test has an inherent level of precision and variability; a single test result may not represent the true condition of the pavement. From a contractor's perspective, this implies that the mix should be designed to accommodate testing variability in order to meet specified tolerances.

At a minimum, marginal test results should be evaluated or examined with the precision and bias associated with that test method (table 9-1).

One way to interpret each of the example test results in table 9-1 is to say that you can be 95 percent confident that the true value of the material being tested is between the lower and upper limits shown. In other words, there is a range of values associated with each test result. The range depends on the precision of each test method.

Open communication and cooperation between QC and QA organizations is important to avoid and resolve conflicts.

Record Keeping

Proper documentation of QC and QA tests is a key factor for interpreting data, making informed decisions, and troubleshooting problems that may arise in the future. Test data can become overwhelming on moderate to large concrete paving projects. Without clear and accurate data, process control adjustments cannot be made with confidence.

Some primary elements of a good record-keeping system include the following:

- Consistent and clear labeling/identification of samples.
- Accurate sample location (centerline survey station) and/or time of sampling.
- Legible handwriting on testing worksheets.
- Organized filing system.

Statistical control charts are useful tools for analyzing changes in materials and the paving process. Practically any variable that is measured in concrete paving can be plotted on a control chart. An example of test data for concrete unit weight is shown in table 9-2. The corresponding control chart for that unit weight data is shown in figure 9-1.

Figure 9-1 is a plot of example concrete unit weight test results. Each point is a test result (Sample ID). The green horizontal line represents the mean of the test results. The dashed horizontal lines are drawn at intervals of one and two times the standard deviation on both sides of the mean. The solid red horizontal lines are the upper and lower control limits and are placed three standard deviations away on each side of the mean.

Standard criteria can be used to determine if an out-of-control condition exists. These criteria are as follows (Seward 2004):

- Any one point is outside of the control limits (more than three standard deviations from the average).
- Nine points in a row are on the same side of the mean.

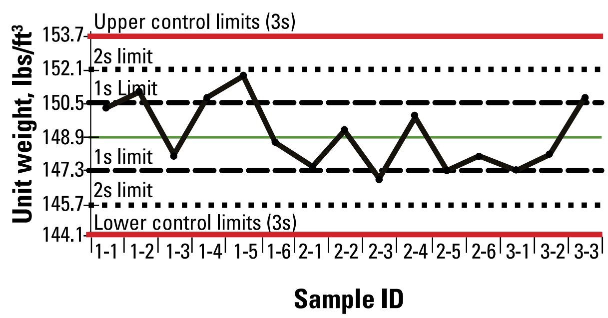

Figure 9-1. Example control chart: concrete unit weight

Table 9-1. Example of Testing Precision

Test	Sample result	95% lower limit	95% upper limit
Grading (% passing 1/2")	28%	24%	32%
Slump	2 1/2 in.	2 in.	3 in.
Air content	5.5%	4.9%	6.1%
Rodded unit weight for aggregate	120 lb/ft^3	114.5 lb/ft^3	125.5 lb/ft^3
Compressive strength	3,600 lb/in^2	3,390 lb/in^2	3,810 lb/in^2
Flexural strength	700 lb/in^2	602 lb/in^2	798 lb/in^2
Smoothness (0.2" blanking band) (data from DOT equipment certification)	4.00 in./mi	2.58 in./mi	5.42 in./mi

- Six points in a row are all increasing or all decreasing.
- Fourteen points in a row are alternating up and down.
- Two out of three points are more than two standard deviations from the mean (and on the same side of the mean).
- Four out of five points are more than one standard deviation from the mean (and on the same side of the mean).
- Fifteen points in a row are all within one standard deviation of the mean.
- Eight points in a row are all more than one standard deviation from the mean (on either side of the mean).

Once an out-of-control condition is identified using these criteria, the process must be analyzed to determine the cause of the variability, and appropriate action must be taken to correct the process.

Table 9-2. Example Concrete Unit Weight Test Results

Sample ID	Unit weight (lb/ft^3)
1-1	150.3
1-2	151.0
1-3	148.0
1-4	150.7
1-5	151.7
1-6	148.6
2-1	147.4
2-2	149.2
2-3	147.1
2-4	149.8
2-5	147.2
2-6	147.9
3-1	147.3
3-2	148.0
3-3	150.7
Average	149.0
Standard deviation	1.6

Batching

Key Points

- The batch plant must be continuously monitored and regularly calibrated.
- Critical issues during batching are aggregate moisture, the water content and water-cementitious materials ratio, and batching by weight, not by volume.

Batching is a critical part of concrete QC. To ensure a uniform mix from batch to batch, the materials must be uniform and the handling systems consistent. The batch plant must be continuously monitored and regularly calibrated (see Stockpile Management and Batching in chapter 8, pages 206 and 207).

Aggregate Moisture

Aggregates' moisture content can influence concrete's workability, strength, and durability. All normal-weight aggregates possess some porosity accessible to water. If the accessible pores are filled, films of water may exist on the aggregate surface. Depending on its moisture condition, aggregate can either take up or add to the mix water. It is therefore important to know the aggregate's moisture condition during batching and to adjust the mix water accordingly.

Most difficulties with surface moisture stem from fine aggregate. Coarse aggregate will commonly have absorption levels of 0.2 to 4 percent and free water content from 0.5 to 2 percent. Fine aggregate will have absorption levels of 0.2 to 2 percent and free water content from 2 to 6 percent (Kosmatka et al. 2003).

Coarse aggregate moisture can be assessed using ASTM C 127-04 / AASHTO T 85; fine aggregate, using ASTM C 70-94 or ASTM C 128-04 / AASHTO T 84. Total moisture content, fine or coarse, can be determined using ASTM C 566-97 / AASHTO T 255. It is common to conduct moisture tests on representative examples of stockpiled aggregates once or twice a day (Kosmatka, Kerkhoff, and Panarese 2003).

Good stockpile management, allowing fine aggregate stockpiles to drain, will help maintain uniform moisture content (Landgren 1994). Because aggregate surface moisture, especially of the fines, is so important to proper mix control, surface moisture is often monitored with moisture meters (electric or microwave absorption) on the batching equipment (Landgren 1994). Properly placed and maintained meters can provide accurate, continuous measurement of aggregate surface moisture, as long as other plant operations are conducted properly.

Water-Cementitious Materials Ratio

The w/cm ratio of a mixture is perhaps the single most important variable and must be carefully controlled to maintain concrete quality. The w/cm ratio is difficult to measure directly, so it is important to carefully monitor and control the batching process.

The microwave test method (AASHTO T 318) has been used to determine the water content of fresh concrete. By coupling the water content (less water absorbed in the aggregates) with batch weights of the dry ingredients, the w/cm ratio is computed.

Batching Tolerances

Aggregates and cementitious materials should be batched by weight. (If batching is done by volume, wide variations can occur in batch quantities due to bulking of moist aggregate, resulting in significant errors.) Liquid constituents, such as mix water and liquid admixtures, can be batched by volume.

ASTM C 94, *Specifications for Ready-Mixed Concrete*, stipulates the recommended tolerances for batching concrete tolerances (table 9-3).

Table 9-3. Recommended Batch Tolerances for Ready-Mixed Concrete* (ASTM C 94)

Constituent	Individual**, %	Cumulative***,%
Cementitious materials	±1	±1
Water	±1	±3
Aggregates	±2	±1
Admixtures	±3	N.R.****

* Batch weights should be greater than 30 percent of scale capacity.
** Individual refers to separate weighing of each constituent.
*** Cumulative refers to cumulative weighing of cement and pozzolan, of fine and coarse aggregate, or water from all sources (including wash water).
**** Not recommended.

Construction Monitoring

Key Points

- During construction, the concrete temperature, air-void system, amount of vibration, and dowel bar locations must be monitored and adjusted as necessary.
- An optimal temperature for freshly placed concrete is from 10 to 15°C (50 to 60°F).
- Routinely achieving the target air content and air-void system is one of the most challenging aspects of controlling concrete mixtures because so many variables affect the air system. Tests should be conducted at the batch plant and, if practical, behind the paver.
- Vibrator monitors help equipment operators ensure that the proper amount of vibration is applied to produce homogeneous, dense concrete without adversely affecting the entrained air.
- Dowel bars must be aligned horizontally and vertically and positioned at about the middle of the slab depth.

Temperature

The temperature of concrete as placed and shortly thereafter can have a large impact on both the fresh and hardened properties (see Temperature Effects in chapter 5, page 127).

Problems associated with high concrete temperatures include the following:

- Increased water demand to maintain workability.
- Decreased setting time.
- Increased danger of plastic and early-age shrinkage cracking.
- Reduction in air-void system effectiveness.
- Lower ultimate strength.

Problems associated with low concrete temperatures include the following:

- Reduced rate of hydration, thus increasing the risk of plastic shrinkage cracking and changing the saw-cutting window.
- Reduced early strength.
- Freezing of the concrete before it sets (with extremely cold temperatures).

An optimal temperature for freshly placed concrete is in the range of 10 to 15°C (50 to 60°F), and it should not exceed 30 to 33°C (85 to 90°F) (Mindess, Young, and Darwin 2003).

For a given concrete mixture, the temperature of fresh concrete can be controlled by adjusting the temperature of the constituent materials or altering the local environment, or through a combination of the two (see Field Adjustments, chapter 8, page 210).

Time of placement will affect the temperature of the concrete at early ages. Heating due to solar energy may coincide with hydration heating to raise the temperature of the concrete more than if the hydration peak occurs overnight.

In hot weather, the concrete mixture can be cooled by adding liquid nitrogen or by cooling one or more of the components. Due to their high volume, cooling the aggregates can be very effective in reducing the concrete temperature. Even though water is a relatively small component, it has a high specific heat capacity and is more practical to cool than aggregates (Kosmatka, Kerkhoff, and Panarese 2003).

In cold weather, the concrete can be sufficiently warmed through the use of hot water. Water near the boiling point can be used if it is mixed with the aggregate prior to the addition of cement (Kosmatka, Kerkhoff, and Panarese 2003). When air temperatures are well below freezing, it may be necessary to heat the fine aggregate as well. In all cases, frozen lumps must be avoided in the aggregate.

ASTM C 1064 / AASHTO T 309 provide the standard for determining the temperature of fresh

Cooling Concrete in Hot Weather

During hot weather, the concrete temperature can often be lowered to an acceptable level simply by doing the following: Cool the aggregates by shading the stockpiles and sprinkling them with water, and chill the mix water or use ice. (Be sure the total of all water and ice does not exceed the mix design.)

concrete. The temperature measuring device used must be accurate to ±0.5°C (±1.0°F) and must remain in the concrete for at least two minutes or until the temperature stabilizes.

Air Content

Routinely achieving the target air content and air-void system is one of the most challenging aspects of controlling concrete mixtures. Project specifications often allow the air content of the concrete to be within -1 to +2 percentage points of the target value.

The factors that affect the air-void system in concrete include the following:

- Ingredients. Any change in source or amount of any of the mix ingredients may change the air-void system.
- Temperature. Increasing concrete temperature tends to reduce air content for a given dosage of air-entraining admixture.
- Mixing time. Air content tends to increase with continuing mixing time up to a limit, at which point it will decrease.
- Batching sequence. Changing the batching sequence may change the air content of a concrete.
- Slump. More air will be entrained in a high-slump mixture than in a similar low-slump mixture. However, water should not be added to the truck in order to raise the air content of a given batch.
- Admixture interactions. Some water-reducing admixtures will affect air.
- Haul time. Increasing haul time may reduce air content.
- Vibration. Excessive vibration may remove air from the concrete.

Tests should be conducted at the batch plant for monitoring purposes and, if practical, behind the paver for payment purposes. Tests should be conducted every hour or every 100 lane-miles (300 lane-feet) of paving, every 50 m^3 (70 yd^3) of concrete, or when samples for strength are made.

Tests are most easily conducted using the pressure air meter (ASTM C 231-04 / AASHTO T 152) (see Air Content [Pressure] in this chapter, page 266) or the air-void analyzer (see Air-Void Analyzer in this chapter, page 265).

Other methods may be considered if necessary: volumetric air meter (ASTM C 173 / AASHTO T 196), or gravimetric (ASTM C 138 / AASHTO T 121) (see Air-Void System in chapter 5, page 133).

Vibration Monitoring

Vibration and consolidation can have a significant impact on the durability of concrete pavement. Proper vibration produces a pavement that is homogeneous and dense without adversely impacting the entrained air in the mix.

Prior to 1996, vibrator monitors were not available commercially (Steffes and Tymkowicz 2002). Today's vibrator monitors give the paver operator a convenient way to preprogram, operate, and monitor vibrator operation. Vibrator monitors also enable the inspection personnel to view in real time the frequency of all vibrators during the paving operation. Data can also be downloaded to a computer for later analysis.

In well-proportioned mixtures, vibrations in excess of 8,000 vibrations per minute (vpm) can be used; however, in oversanded mixtures, reduction in vibrations is needed to prevent the disappearance of beneficial air voids. In such cases, 5,000 to 8,000 vpm are generally used (Steffes and Tymcowics 1997).

Dowel Bar Tolerances

The most critical factors in dowel performance are diameter, alignment, and embedment length. Dowels transfer applied load across joints and must allow freedom of movement between adjacent slabs. Dowel placement tolerances usually reference the three ways that dowel bars can be out of alignment:

- Longitudinal translation. (Is the joint centered on the dowel/is there adequate embedment length?)
- Depth. (Is the dowel near the midpoint of the slab thickness?)
- Horizontal and vertical skew. (Is the dowel parallel to both the centerline and top surface of the pavement?)

Numerous studies have been conducted on the topic of dowel bar alignment, many of them brought about by the advent of dowel bar insertion equipment. In more recent years, the majority of studies have concluded that stricter tolerances are not necessary. Summarized below is the current state of the practice, as well as recommended guidelines for dowel alignment.

Alignment

Alignment of each dowel must be within certain tolerances to allow adequate freedom of movement between slabs. Alignment requirements are typically in both the horizontal and vertical planes, as well as a combination thereof. A survey by the American Concrete Pavement Association in 1999 of State highway agency concrete pavement practices showed that the average tolerance for dowel skew in both the vertical and horizontal dimensions currently allowed by State agencies is 6 mm (0.25 in.) per 300 mm (12 in.) of dowel length, or three percent.

Embedment Length

To provide a construction tolerance, the total length of dowel bars is always somewhat longer than required for embedment depth. The current state of the practice is to provide a minimum dowel embedment length of 150 mm (6 in.) for a joint to be effective under most loading conditions. In highway work, 450-mm long (18-in. long) dowels are specified, providing 150 mm (6 in.) of tolerance (±75 mm [3 in.]). For any given dowel size, the maximum bearing stresses occur near the joint face. Any loss of load transfer that might occur from inadequate dowel embedment relates to the magnitude of the bearing stresses along the dowel.

Dowel Depth

There is usually no problem with placing dowels slightly above or below mid-depth in a concrete slab. The vertical location is not as critical to dowel or joint performance as are many other factors. Increasing the slab thickness by even several centimeters or inches on a concrete pavement, basket assemblies will position the dowels below mid-depth. This is not a significant variation on the design, and there have been no cases of decreased performance of the dowels or the pavement. Many miles of concrete pavement have been placed with the dowels above nominal mid-depth (ACPA 1994).

The current industry-recommended tolerance for dowel skew is 9.5 mm (0.375 in.) per 300 mm (12 in.) of dowel length, or three percent, in the horizontal and vertical planes. Dowels must be lubricated sufficiently to prevent bonding and allow movement.

Test Methods

Key Points

- A suite of tests represents QC best practices but does not include all tests discussed in this manual.
- Readers should refer to the relevant full method statement before attempting to conduct any test.

A suite of tests for use during construction of concrete pavements has been identified in the TPF-5(066) project (table 9-4). The methods should be used during the three phases of a mix's evolution during a project:

1. Material selection and mix design.
2. Preconstruction verification.
3. Quality control.

The tests have been categorized according to five concrete properties:

1. Workability.
2. Strength development.
3. Air content.
4. Permeability.
5. Thermal movement.

Test descriptions on the following pages are not intended to substitute for formal methods described in various specifications and methods published by organizations like AASHTO and ASTM. Sufficient information is given here to help readers understand how and why a test should be conducted. Readers should refer to the relevant full method statement before attempting to conduct any test.

Current Best Practices

The tests listed in table 9-4 and described in the following pages do not represent all QC tests discussed throughout this manual. Rather, they have been identified as current best practices for QC purposes in the "Materials and Construction Optimization for Prevention of Premature Pavement Distress in Portland Cement Concrete Pavements" project at Iowa State University (TPF-5[066]). These tests provide a starting point for alternative and new test methods that may yet be identified as best practices through the TPF-5(066) project.

Table 9-4. Suite of QC Tests from TPF-5(066)

Concrete property	Test name (standard test method)	Laboratory
Workability	Differential scanning calorimetry (DSC)	Central laboratory
	Blaine fineness (ASTM C 204 / AASHTO T 153)	Central laboratory
	Combined grading	Mobile laboratory
	Penetration resistance (false set) (ASTM C 359 / AASHTO T 185)	Mobile laboratory
	Cementitious materials temperature profile - "coffee cup test"	Mobile laboratory
	Water/cementitious materials ratio (microwave) (AASHTO T 318)	Mobile laboratory
	Unit weight (ASTM C 138 / AASHTO T 121M / AASHTO T 121)	Mobile laboratory
	Heat signature	Mobile laboratory
	Concrete temperature, subgrade temperature, project environmental conditions (weather data)	Mobile laboratory
Strength development	Concrete maturity (ASTM C 1074 / AASHTO T 325)	Mobile laboratory
	Flexural strength and compressive strength (ASTM C 78 / ASTM C 39 / ASTM C 39M / AASHTO T 97 / AASHTO T 22)	Mobile laboratory
Air content	Air-void analyzer	Mobile laboratory
	Air content (pressure) (ASTM C 231 / AASHTO T 152)	Mobile laboratory
	Air content (hardened concrete) (ASTM C 457)	Central laboratory
Permeability	Chloride ion penetration (ASTM C 1202 / AASHTO T 277)	Central laboratory
Thermal movement	Coefficient of thermal expansion (ASTM C 531 / AASHTO TP 60)	Central laboratory

Differential Scanning Calorimetry (DSC)

Purpose – *Why Do This Test?*

The form and content of calcium sulfate in portland cement are important factors affecting the workability and durability of concrete mixes. Commonly observed setting problems, such as false set and flash set, are caused by inadequate content and proportions of gypsum and plaster in the cement. Monitoring the level of sulfate forms in cement can help prevent problems during construction and improve the quality of the pavement structure.

Principle – *What is the Theory?*

Gypsum and plaster are two forms of calcium sulfate that greatly affect setting properties, strength development, and volume stability of cement and concrete. Gypsum is added to clinker to control the setting of cement. The addition of gypsum is optimized to produce the highest concrete strength. Gypsum dehydrates to plaster in a cement mill under high temperatures and low humidity conditions.

The amount of gypsum and plaster present in cement can be determined by subjecting the sample to heating and monitoring the change in energy of the sample. The intensity of the endothermic peaks associated with the dehydration process of gypsum and plaster is proportional to the amount of these constituents present in the sample.

Test Procedure – *How is the Test Run?*

The differential scanning calorimetry (DSC) method consists of determining the areas of endothermic peaks associated with the dehydration process of gypsum and plaster. To obtain these endothermic peaks, a cement sample is subjected to heating under specific conditions, such as atmosphere and heating rate.

- Sample crucible: 100-μL aluminum crucible sealed with a pierced lid needed to create the pressure leak necessary to resolve peaks of the two-stage gypsum dehydration.
- Reference crucible: 100-μL aluminum crucible sealed with a lid.
- Measuring cell: Measures the difference between the heat that flows to a sample and a reference crucible. The unit has a high signal resolution and detects changes in the heat flow. The cell obtains measurements, and continuously sends data to the control unit.
- Software: Helps evaluate experimental curves within selected integration limits.

Test Method

- Place a 100-μL aluminum crucible containing a sample and a reference crucible on a sensor plate of the DSC measuring cell.
- Heat the cell at a constant rate of 10°C/min (18°F/min) from 50 to 400°C (122 to 205°F). The experiment is performed under regular atmospheric conditions.
- The cell obtains measurements and continuously sends data to the control unit. An endothermic profile of the tested sample is demonstrated by an obtained experimental curve.
- The area under the peaks, proportional to the heat of the endothermic reaction, is integrated and expressed in joules/gram (J/g). This heat corresponds to specific gypsum and/or plaster content of the submitted sample. The actual amount of gypsum and plaster is determined from a calibration curve (weight percent vs. J/g) established for the DSC used in testing.
- The total amount of sulfate added to the clinker is the calculated sum of sulfate present in gypsum and plaster.

Output – *How Do I Interpret the Results?*

The results of the DSC testing are expressed as weight percent of gypsum and plaster present in the tested samples. The test can also be used to determine other components of the cementitious system.

The effect of various sulfate forms content on the concrete performance greatly depends on the physical and chemical properties of cement, the use of alternate materials such as fly ash and ground, granulated blast-furnace slag in concrete, the type of admixture, and weather conditions.

Data from the test can be used as a monitoring tool, to assess variability of the cement, or to assess the risk of incompatibility.

Construction Issues – *What Should I Look For?*

Changes in workability that may be due to portland cement chemistry variability include the following:

- False set, an initial stiffening that disappears when remixing or vibration occurs.
- Increased slump loss.

Concrete property: workability

Blaine Fineness

Purpose – *Why Do This Test?*

The particle size (fineness) of portland cement affects concrete's rate and heat of hydration, workability, water requirement, rate of strength gain, and permeability. Fine cements can increase early strength gain, but ultimately sacrifice long-term strength gain, which can result in higher concrete permeability. Daily monitoring of the fineness of the cement used on a project will provide a means of tracking variability in the cement.

The smaller a particle is, the greater the relative surface area. Therefore, the finer a given sample of cement is, the greater the surface area per unit mass.

Principle – *What is the Theory?*

The test is based on the theory that the permeability of a powder is related to the fineness of the powder. The test is run under controlled conditions and calibrated against the fineness of a known control sample.

Test Procedure – *How is the Test Run?*

ASTM C 204, *Standard Test Method for Fineness of Hydraulic Cement by Air-Permeability Apparatus (Blaine Fineness)*, consists of determining the time required to draw a standard volume of air through a standard volume of portland cement and comparing that to the time required for the same procedure performed on a reference material (calibration).

- Manometer, half filled with mineral oil.
- Permeability cell: A steel cylinder (1/2-in. diameter) that holds the compacted cement sample.
- Plunger: A steel rod with a 1/8-in. flat slot that fits tightly inside the permeability cell.
- Perforated disk: A steel disk with 1/32-in. holes that fits in the bottom of the permeability cell.
- Paper filters: Circular paper disks cut to fit the cell.

Test Method

- Place the perforated disk inside the permeability cell, and place a paper filter on top of the perforated disk.
- Weigh a cement sample equal to the mass of the calibration sample and place the cement sample in the permeability cell on top of the paper filter.
- Place another paper filter inside the permeability cell on top of the cement sample. (The cement sample is sandwiched between two paper filters on top of the perforated disk.)
- Insert the plunger into the permeability cell to compact the cement sample, then withdraw the plunger.
- Attach the permeability cell to the manometer tube, and draw a given volume of air through the cement sample.
- Record the time required to draw a given volume of air through the cement sample.

Output – *How Do I Interpret the Results?*

Results of the test are expressed in m^2/kg (preferred) or cm^2/g. Typical values for Blaine fineness of portland cement range from 300 to 450 m^2/kg (3,000 to 4,500 cm^2/g). Higher values of Blaine fineness indicate a finer grind of cement.

Construction Issues – *What Should I Look For?*

The risk of incompatibility increases with increasingly finer cement. Changes in fineness that affect the rate of strength gain may have an impact on sawing operations, either delaying or accelerating the timing of initial saw-cutting of contraction joints to avoid random cracking.

Increased water demand due to cement fineness may be compensated for by the use of a water-reducing admixture.

An increase in slump loss after initial mixing may indicate variability in the fineness of the cement, and the use of chilled water may offset this impact during warm weather conditions.

Concrete property: workability

Combined Grading

Purpose – *Why Do This Test?*

Aggregate grading may influence the water requirement, workability, and paste contents. These in turn may impact the risk of segregation, bleeding, and increased shrinkage of concrete paving mixes.

It is desirable to blend different aggregate sizes to obtain a smooth grading curve for the combined aggregates system.

Principle – *What is the Theory?*

The sieve analysis (amount of material retained or passing a series of sieves with different-sized openings) is compared to optimized systems using a number of numerical and graphical models. The closer the batch grading is to the optimum, the lower the risk of grading-related problems in the mixture.

Test Procedure – *How is the Test Run?*

Sieve analyses are conducted in accordance with ASTM C 136 for the coarse and fine fractions, and the data are applied to the following models.

The coarseness/workability chart plots a single point on a graph, with the coarseness factor on the horizontal axis and the workability factor on the vertical axis,

where

Coarseness factor = (percent retained on 3/8-in. sieve) / (percent retained on #8 sieve)

Workability factor = percent passing #8 sieve

The 0.45 power chart plots the combined grading on a chart with sieve size on the horizontal axis (scale = sieve size 0.45 µm) and percent passing on the vertical axis.

The 8-18 chart plots the material retained on each sieve with sieve size on the horizontal axis and percent passing on the vertical axis.

Output – *How Do I Interpret the Results?*

Points on the coarseness/workability chart (figure 9-2) represent the coarseness factor and the workability factor for a mix based on the grading test results of each individual aggregate. For an optimized grading mix, the points should plot above the control line (28<workability factor<44) and inside the zone labeled well-graded (45<coarseness factor<75).

When the sample combined grading plot on the 0.45 power chart (figure 9-3) crosses back and forth across the reference line, it indicates gap grading.

A general rule of thumb for optimized grading is to have between 8 and 18 percent retained on each individual sieve on the 8-18 chart (figure 9-4).

Each of the charts (figures 9-2 through 9-4) provides a different perspective of gradation. When used together, the information in these three charts can provide the contractor and the agency with a basis for evaluating the combined grading of a concrete mix.

Construction Issues – *What Should I Look For?*

Modest variations in grading are to be expected from batch to batch and generally do not have a significant impact on performance. Extreme variations in grading and workability should be addressed as they occur.

Workability concerns attributable to aggregate grading can be identified by observing the following conditions:

- Stockpile segregation and/or inconsistent stockpiling methods.
- Inconsistent slump (mix water is static while grading changes).
- Excessive bleeding.
- Variation in vibrator frequencies.
- Edge slump.
- Poor consolidation observed in cores.
- Segregation observed in cores.

Concrete property: workability

Combined Grading, continued

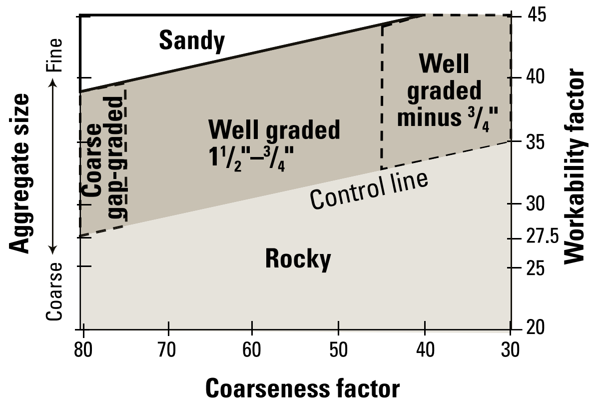

Figure 9-2. Coarseness/workability chart

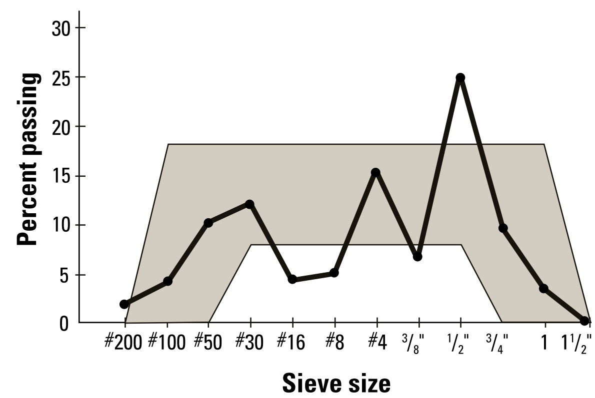

Figure 9-4. Sample combined aggregate gradation 8-18 band

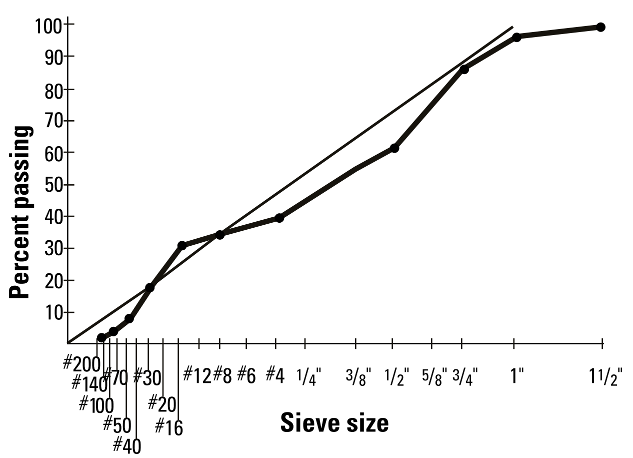

Figure 9-3. Sample combined aggregate gradation 0.45 power curve

Penetration Resistance (False Set)

Purpose – *Why Do This Test?*

Some portland cements and combinations of cement and pozzolans may be prone to false set. False set reduces the workability of the concrete mix. Workability can be restored by remixing without the addition of water.

Since remixing is not normally possible when a central mix plant and dump trucks are used for delivery, the false set condition is usually offset by adding more mixing water, which increases the water-cementitious materials (w/cm) ratio. This is poor practice.

Performing the penetration resistance test on the cementitious materials will indicate whether the mix is prone to false set.

Principle – *What is the Theory?*

As concrete mortar stiffens (sets), the resistance required for a 10-mm diameter rod to penetrate into the mortar will increase. The depth of penetration of the 10-mm rod into a mortar sample is measured and recorded over time. If, after remixing, the 10-mm rod penetrates the mortar sample to a depth greater than was measured before remixing, then a false set condition is occurring.

Test Procedure – *How is the Test Run?*

ASTM C 359, the *Standard Test Method for Early Stiffening of Portland Cement (Mortar Method)* (false set), tests a laboratory-mixed mortar. It may be advisable to test a mortar sample obtained from the actual project-mixed concrete. The test method uses a Vicat apparatus to measure the depth of penetration of a 10-mm diameter plunger 10 seconds after it is released into the mortar at fixed time intervals.

- Vicat: A frame holding the 10-mm rod and an indicator to measure the depth of penetration in mm.
- Mortar Mold: A box 51-mm wide x 51-mm high x 152-mm long (2- x 2- x 6-in.) used for containing the mortar sample.
- Mixer: A laboratory mixer used for remixing the mortar sample.

Test Method

- Obtain a mortar sample from the project-mixed concrete.
- Place the mortar sample in the mold, consolidate it, and strike it off.
- Using the Vicat, hold the 10-mm rod in contact with the top surface of the mortar by a set screw.
- Release the rod from the set screw and allow it to penetrate into the mortar. Record the depth of penetration 10 seconds after the rod is released.
- Take penetration readings 3 minutes, 5 minutes, 8 minutes, and 11 minutes after batching.
- After the 11-minute reading, remix the mortar sample for 1 minute.
- Replace the mortar sample in the mold, consolidate it, and strike it off.
- Measure the penetration 45 seconds after remixing.
- Record the depths of penetration for each of the five repetitions.

Output – *How Do I Interpret the Results?*

The depths of penetration are reported in tabular format, as in this example:

Initial penetration	50 mm
5-minute penetration	40 mm
8-minute penetration	25 mm
11-minute penetration	10 mm
Remix penetration	25 mm

If, as shown in the example, the penetration after remixing is greater than the 11-minute penetration, false set is likely, affecting the workability of the project mix.

Construction Issues – *What Should I Look For?*

Situations that may indicate the occurrence of false set include the following:

- Excessive vibration that essentially remixes the concrete.
- Loss of workability during moderate temperatures.
- Workability changes that occur when pozzolans and/or admixtures are removed or added.

Concrete property: workability (see Testing and Prevention for Incompatibilities in chapter 4, page 100).

Cementitious Materials Temperature Profile ("Coffee Cup Test")

Purpose – *Why Do This Test?*

The chemical reactions that occur during hydration of portland cement generate heat. The coffee cup test is a field procedure that can be performed on a paste mixture to identify potential workability issues. Variability of the cementitious materials and interactions with chemical admixtures may also be tracked by daily monitoring of the coffee cup test results.

Principle – *What is the Theory?*

Measuring the temperature change of a cement paste mixture during hydration may indicate compatibility and workability issues.

Test Procedure – *How is the Test Run?*

Portland cement, supplementary cementitious materials (SCMs), chemical admixtures, and water are mixed and stored in an insulated container. The temperature of the paste is recorded at intervals for up to 24 hours and compared to a sample of sand kept under the same conditions. The first few minutes are the most critical.

- Mixing containers: Insulated containers.
- Scale for measuring the mass of portland cement, SCMs, and water.
- Digital thermometer or data logger with thermocouples.
- Laboratory mixer.

Test Method

There is no standard method for this test at present. The following is one approach:

- Acquire representative material samples from the plant.
- Record the temperature of the materials at the time of sampling.
- Prepare a paste representative of the field concrete.
- Place the paste in an insulated container and a sample of sand in a similar container.
- Record the temperature of the sample and the sand during the first minute and periodically for up to 24 hours.
- Calculate the difference in temperature between the sample and the sand and plot the temperatures, with time on the x-axis and temperature on the y-axis.
- Repeat this procedure with alternative mixtures, changing one parameter (e.g., SCM dosage, admixture dosage, w/cm ratio) at a time.
- Observe the effects of changing the system on the shape of the temperature plot.

Construction Issues – *What Should I Look For?*

Changes in the temperature profile of cementitious materials will indicate potential changes in the following properties:

- Workability.
- Slump loss.
- Setting time.
- Strength gain.

Concrete property: workability

Water-Cementitious Materials Ratio (Microwave)

Purpose – *Why Do This Test?*

The strength of concrete used for pavements is mainly a function of the water-cementitious materials (w/cm) ratio of the concrete mix being used. Acceptance strength tests on hardened concrete are normally performed at least seven days after placement of the concrete. The microwave method can be used to obtain w/cm ratio results within hours, instead of waiting days for strength results. Monitoring the test results may provide an early flag of potentially low-strength concrete, allowing the contractor to adjust operations sooner than conventional strength testing might indicate.

Concrete strength varies inversely with the amount of water in the mix. In simplest terms, less water implies higher strength. Other factors, such as consolidation, curing, aggregate quality, air content, and aggregate shape, affect strength as well. For a given mix with a constant amount of cement, the w/cm ratio has the greatest impact on strength.

Principle – *What is the Theory?*

The total water in a concrete mix comes from the following sources:

- Moisture absorbed in the aggregate.
- Free water on the aggregate.
- Water added in the batching process.

The mass of water removed from a fresh mixture by drying in a microwave can be used to calculate the w/cm ratio of the mixture.

Test Procedure – *How is the Test Run?*

The test is described in AASHTO T 318. A sample of fresh concrete from the project is weighed and then dried in a microwave. It is then reweighed to determine the mass of water that was contained in the mix. The water absorbed in the aggregate is subtracted from this total, and the remainder is used to calculate the w/cm ratio using the batched cementitious materials content.

Test Apparatus

- Microwave oven for drying the concrete sample.
- Glass pan and fiberglass cloth (a container for the concrete sample).
- Scale to obtain the mass of the sample.
- Porcelain pestle for grinding the sample as it is dried.

Test Method

- Weigh the glass pan and fiberglass cloth (tare).
- Place the concrete sample in the glass pan on top of the fiberglass cloth.
- Weigh the glass pan, fiberglass cloth, and concrete sample.
- Heat the concrete sample in the microwave oven for five minutes.
- Remove the sample from the microwave, weigh, and break up the sample using the pestle.
- Reheat the sample for five minutes.
- Repeat the weighing, breaking, and heating cycle at two-minute intervals until the sample loses less than 1 g of mass between reheating cycles.
- Record the mass of the wet concrete sample and the mass of the dry concrete sample and the difference between the two masses (mass of total water content).

Output – *How Do I Interpret the Results?*

The total water content of the concrete sample can be expressed as a percentage:

Total water content % (W_t) = (wet sample mass – dry sample mass) / wet sample mass

This W_t can be monitored and used as a relative indicator of potential variability in pavement strength.

It should be noted that the value of W_t will not provide the true w/cm ratio because the microwave test drives out all of the water in the concrete, including the water that is absorbed in the aggregate. As such, the value of W_t will be greater than the true w/cm ratio of the mix. By compensating for the measured absorption of the aggregate, the result from this test can be used to monitor variability in the concrete from batch to batch.

Construction Issues – *What Should I Look For?*

When variations in W_t are noted, plant operations should be reviewed to ensure that materials are being batched in the proper proportions.

Concrete property: workability

Unit Weight

Purpose – *Why Do This Test?*

The unit weight of fresh concrete is a general indicator that the concrete has been batched in the correct proportions. It is an excellent indicator of uniformity of a mixture from batch to batch.

Principle – *What is the Theory?*

A concrete mix design is composed of several ingredients: portland cement, supplementary cement materials (SCMs), fine aggregate, coarse aggregate, admixtures, air, and water. All of these materials have different specific gravities. A variation in the unit weight of a mixture will indicate a change in proportioning of the mixture, often in the water or air content.

Test Procedure – *How is the Test Run?*

A sample of mixed concrete is consolidated in a container of known volume and weighed to determine the unit weight of the mixed concrete (ASTM C 138).

- Measure: cylindrical container, usually a standard pressure air pot.
- Scale for weighing the sample.
- Tamping rod, vibrator, mallet, and strike-off plate for consolidating the sample in the air pot.

Test Method

- Determine the level-full volume of the air pot.
- Weigh the empty air pot.
- Consolidate a sample of fresh concrete in the air pot using the tamping rod or vibrator and mallet.
- Strike off the concrete so that it is level-full with the top rim of the air pot.
- Clean off all excess concrete from the exterior of the air pot.
- Weigh the air pot full of concrete.
- Record the empty mass, full mass, and volume of the air pot.

Output – *How Do I Interpret the Results?*

The unit weight of the concrete mix is reported in pounds per cubic foot (lb/ft^3):

Unit weight = (full mass – empty mass) / volume

The unit weight of the mix should be compared with the unit weight of the mix design to identify potential problems in the batching process or changes in raw materials.

A variability of more than 5 lb/ft^3 may be considered significant.

Construction Issues – *What Should I Look For?*

When variations in unit weight measurements are observed, the following potential causes should be reviewed:

- Sample consolidation. (Was the sample fully consolidated in the air pot?)
- Air content of the concrete.
- Batch proportions of each material.
- Changes in raw material densities (specific gravities).

Concrete property: workability

Heat Signature (Adiabatic Calorimetry Test)

Purpose – *Why Do This Test?*

Heat signature is a representation of the heat of hydration generated by a specific concrete mix over time. Variations in the chemistry and dosage of portland cement and supplementary cement materials (SCMs), along with interactions between them and chemical admixtures, may be flagged by the heat signature.

Principle – *What is the Theory?*

Chemical reactions that occur as concrete hardens emit heat (heat of hydration). By insulating a standard cylinder of concrete from the influence of outside temperatures and using sensors to record the heat generated by the concrete, it is possible to measure the adiabatic heat signature of a concrete mix. A chart that plots time on the x-axis and temperature on the y-axis is produced from this data.

Test Procedure – *How is the Test Run?*

A concrete cylinder is placed inside an insulated drum that is equipped with temperature sensors that record the temperature inside the drum at 15-minute intervals. The temperature and time data are transmitted by computer to a centralized database, where data are stored and analyzed. For this research, the analysis period will range from 2 days up to 10 days.

- Adiabatic calorimeter: insulated container equipped with temperature sensors.
- Standard concrete cylinder.
- Personal computer to transmit data to a central database.

Test Method

- Cast a standard concrete cylinder (6 in. x 12 in.) from concrete sampled at the project site.
- Place the cylinder inside the adiabatic calorimeter and seal it.
- Temperature sensors record the temperature inside the drum at 15-minute intervals.
- Data from the sensors are uploaded to a central database.
- Centralized database software is utilized for analysis and downloading reports.

Output – *How Do I Interpret the Results?*

The basic analysis of the heat signature consists of a graph of time vs. temperature. Plotting multiple samples on the same chart may reveal differences in the mix's chemistry (figure 9-5).

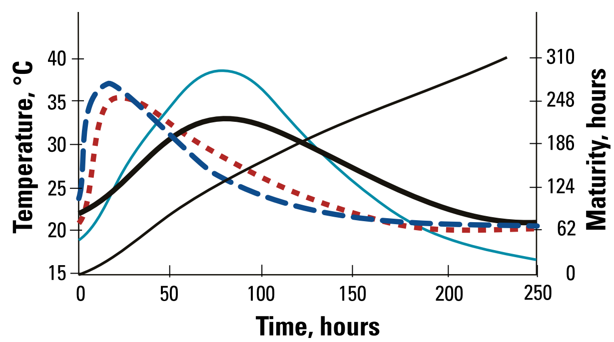

Figure 9-5. Heat signature sample plots

Construction Issues – *What Should I Look For?*

Changes in heat signature may impact the following concrete properties:

- Workability and consolidation.
- Rate of strength gain.
- Ultimate concrete strength.
- Initial window for saw-cutting contraction joints.

Concrete property: workability

Concrete Temperature, Subgrade Temperature, and Project Environmental Conditions

Purpose – *Why Do This Test?*

Interactions between concrete pavements and the environment during construction have the potential to adversely impact the constructability and durability of concrete pavements. Collecting, monitoring, recording, and responding to the temperature of the concrete and the underlying base course, along with weather data from the construction site, will allow the construction team to minimize the risk of problems.

Principle – *What is the Theory?*

Environmental factors, such as temperature, relative humidity, wind velocity, solar radiation, and temperature changes, influence the rate of drying, setting time, and strength gain of a slab, thus changing the saw-cutting window and the risk of cracking or curling.

Test Procedure – *How is the Test Run?*

Concrete (ASTM C 1064) and ambient temperatures are taken with a thermometer when the concrete is sampled.

Subgrade temperature is taken with a pyrometer in front of the paver when the concrete is sampled.

Project environmental conditions are recorded using a portable weather station.

- Thermometer to measure concrete temperature.
- Pyrometer to measure subgrade temperature.
- Weather station to measure project environmental conditions.

Test Method

- Measure and record concrete temperature when the sample is taken.
- Measure and record subgrade temperature in front of the paver, using a handheld infrared pyrometer aimed at the base layer directly beneath the concrete pavement.
- Measure and record environmental conditions using a portable weather station located at the test trailer near the project.

Output – *How Do I Interpret the Results?*

Temperatures and environmental conditions should be reported in a tabular format. Changes in temperature, wind speed, and humidity should be monitored and may require changes in mix proportions or construction practice.

Construction Issues – *What Should I Look For?*

Concrete temperatures should be monitored. Temperatures above 35˚C (95˚F) may affect workability.

Thermal gradients in the slab at an early age may cause premature cracking. This condition may be aggravated by high subgrade temperatures at the time of placement.

Many combinations of weather conditions can adversely affect a concrete pavement. The following are the primary conditions to observe:

- High temperatures may increase the risk of incompatibility between the reactive components of a mix.
- Hot, dry, windy conditions contribute to plastic shrinkage cracking.
- Cold conditions will increase the time of setting.
- Sudden cold fronts can cause premature cracking.
- Rain can damage the surface of fresh concrete unless the surface is protected.

There is an inherent risk in the construction of concrete pavements. Weather conditions are beyond the contractor's control, and forecasts are not entirely reliable. Even with experience and the best judgment, conditions may arise that will result in damage to a concrete pavement.

Concrete property: workability

Concrete Maturity

Purpose – *Why Do This Test?*

Measuring the maturity of concrete pavements is a nondestructive test method for estimating in-place concrete strength. It is quickly becoming standard practice. Maturity may be used as a criterion for opening a pavement to traffic and for quality control purposes.

Principle – *What is the Theory?*

The degree of hydration (leading to strength) of a given mix design is a function of time and temperature. Correlation curves can be developed for a mix design that estimate concrete strength based on its maturity. The in-place strength of a pavement can be estimated by monitoring the temperature of the slab over time and using the correlation curve that was developed for that mixture.

A maturity curve (strength estimate based on maturity) is only applicable to a specific mix design.

Test Procedure – *How is the Test Run?*

The maturity curve is developed by casting, curing, and testing standard strength specimens while measuring and recording the temperature of those specimens over time (ASTM C 1074).

Maturity testing is performed by inserting a temperature sensor in the slab and then downloading the temperature data to a computer that compares the slab temperature data to the maturity curve.

- Beams, cylinders, and hydraulic loading frame for strength testing to develop the maturity curve.
- Sensors to measure the temperature of the test specimens and of the pavement.
- Computer software to analyze strength, temperature, and time data for developing the maturity curve and estimating the pavement strength.

Test Method

- Maturity Curve:
    - Cast 13 strength specimens from materials that are mixed at the project site.
    - Completely embed a temperature sensor in one of the specimens. This specimen is used only for recording the temperature over time and will not be broken.
    - Cure all the strength specimens in the same location (constant temperature).
    - Test the strength of the specimens at one, three, five, and seven days. Break and average three specimens at each age.
    - Download and record the time/temperature factor (TTF) for each set of strength specimens when they are broken.
    - Plot the strength and TTF data for the strength specimens on a graph, with TTF on the x-axis and concrete strength on the y-axis.
    - Fit a smooth curve through the plotted points.
- In-Place Maturity (estimated strength):
    - Completely embed a temperature sensor in the pavement.
    - Download the TTF from the sensor at any time.
    - Estimate the strength of the concrete pavement using computer software and the appropriate maturity curve.

Output – *How Do I Interpret the Results?*

Commercially available maturity systems normally include software that provides the estimated concrete strength based on the maturity of the concrete (TTF). A sample maturity curve is shown in figure 9-6.

Concrete property: strength development (see Maturity Testing, chapter 5, page 121).

Concrete Maturity continued

Construction Issues – *What Should I Look For?*

Maturity testing is a way of nondestructively estimating the strength of a concrete pavement.

It cannot be overemphasized that the maturity vs. strength relationship is mix-specific. Maturity estimates of in-place strength are valid only if the pavement being tested is constructed using the same mix design that was used to develop the maturity curve.

Changes in the water-cementitious materials ratio, air content, grading, aggregate proportions, admixtures, etc., may cause a maturity curve to overestimate the strength of the pavement.

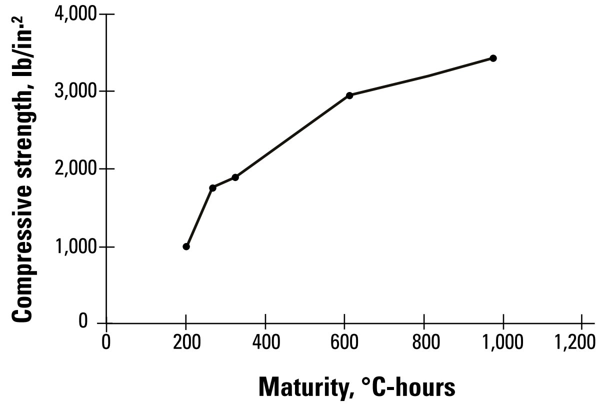

Figure 9-6. Sample maturity curve

Flexural Strength and Compressive Strength (Seven Day)

Purpose – *Why Do this Test?*

Concrete strength is critical because it reflects concrete's ability to carry intended loads. Flexural and compressive strength testing are currently the standard methods of evaluating and assessing pay factors for pavement concrete. The tests are required for calibrating maturity-based monitoring systems.

Principle – *What is the Theory?*

A measured force is applied to concrete samples of consistent cross-sectional area (beams and cylinders) until the samples fail. The force required to break the sample is used to calculate the strength based on the cross-sectional area of the sample.

Test Procedure – *How is the Test Run?*

Samples of fresh concrete from the project are cast in cylinder and/or beam molds. These test specimens are cured in laboratory conditions until they are broken in accordance with ASTM C 39 (compression) or ASTM C 78 (flexure). A consistent and continuously increasing force is applied to the test specimens by a hydraulic testing machine. The maximum force required to break the sample and the actual dimensions of each sample are recorded.

- Cylinder and beam molds for casting strength specimens (6-in. diameter x 12-in. height for cylinders and 6-in. width x 6-in. height x 24-in. length for beams).
- Curing tanks to provide consistent curing conditions for the specimens.
- Hydraulic testing frame for applying the force.
- Cutoff saw, neoprene cap, and miscellaneous tools for preparing the specimens.

Test Method

- Sample and cast cylinder and beam specimens in accordance with standard procedures.
- Cover and protect specimens from evaporation and damage for 24 hours.
- Remove specimens from the molds and transfer to the curing tanks.
- Cure the specimens in a controlled environment until they are broken.
- Remove the specimens from the curing tanks. Trim cylinders to length, taking care to avoid letting the specimens dry out before they are tested.
- Place the specimens in the hydraulic testing frame and apply a force until the specimen breaks.
- Record the maximum force applied and the dimensions of the specimen.

Output – *How Do I Interpret the Results?*

Strength results are reported in a tabular format in units of pounds per square inch (lb/in^2). Other data in the report should include specimen identification, specimen dimensions, span length (beams), and maximum force applied.

Formulas for concrete strength calculations:

Flexural strength = ([force x span] / [width x depth^2])

Compressive strength = force / (π x radius^2)

Concrete property: strength development (see Strength Testing, chapter 5, page 119).

Flexural Strength and Compressive Strength (Seven Day) continued

Construction Issues – *What Should I Look For?*

Laboratory-cured strength tests are a representation of the concrete mix's strength properties. The strength of the pavement will differ from laboratory-molded and laboratory-cured specimens due to differences in consolidation and differences in the curing environment. Core specimens taken from the slab can be used to verify pavement strengths.

Conditions that may prevent the strength tests from being representative of the actual concrete strength include the following:

- The load rate does not conform to standard procedures; faster load leads to higher strength test results.
- Beam specimens are allowed to dry before testing, resulting in higher strength test results.
- Specimen dimensions are not uniform, resulting in lower strength test results.
- Specimens are not adequately consolidated, resulting in lower strength test results.

The strength of the concrete pavement structure is influenced by the following factors:

- Water-cementitious materials ratio.
- Air content.
- Consolidation.
- Curing conditions.
- Aggregate grading, quality, and shape.

Concrete strength has long been an acceptance criterion for concrete pavements. From a long-term performance standpoint, characteristics other than strength have a significant impact on pavement durability. Adequate strength is a good indicator of concrete quality, but it does not guarantee performance. Focusing on strength alone may ignore important properties, such as air entrainment, permeability, and workability.

Air-Void Analyzer (AVA)

Purpose – *Why Do This Test?*

Freeze-thaw resistance of concrete is primarily controlled by the spacing factor of the air-void system. The air-void analyzer provides a method of measuring the spacing factor in fresh concrete, rather than waiting for microscopical analysis of hardened concrete. A sample of mortar is taken from the concrete after it has been through the paver and tested immediately, with a result obtained in about 30 minutes.

Principle – *What is the Theory?*

Gently stirring a sample of fresh concrete mortar releases the air bubbles through a viscous fluid and then through a column of water. The air bubbles are captured under a submerged bowl that is connected to a scale. As the air bubbles collect, the buoyancy (mass) of the bowl is recorded over time. The distribution of different-sized bubbles is a function of Stoke's Law (larger bubbles rise faster than smaller bubbles).

Test Procedure – *How is the Test Run?*

A sample of fresh concrete mortar is taken from the slab behind the paver using a vibrating cage attached to a hand drill. A 20-cc portion of the mortar sample is injected into the instrument, which then gently stirs it to release the air bubbles into the fluid.

The measurement continues for 25 minutes or until the weight of the bowl remains unchanged for 3 minutes.

Software then processes the scale readings that were taken over time and, using an algorithm, calculates the air bubble spacing factor and bubble size.

- Portable drill with vibrating cage for obtaining mortar sample.
- Air-void analyzer (AVA) with all supplies, cables, etc.
- Personal computer with AVA software.

Test Method

- Obtain a sample of fresh mortar behind the paver.
- Using a syringe, extract 20 cc of mortar from the sample.
- Eject the 20-cc sample from the syringe and gently agitate it for 30 seconds.
- The bubbles are released from the mortar sample and, over time, rise through the separation liquid and through a column of water.
- As the bubbles rise, they are collected underneath a submerged bowl.
- The buoyancy (mass) of the submerged bowl is measured over time as the bubbles are collected.
- The test is concluded when the mass of the submerged bowl remains constant for 3 minutes or at the end of 25 minutes, whichever occurs first.
- The computer and software collect and analyze the data from the scale, which is part of the AVA.

Output – *How Do I Interpret the Results?*

Software provided with the AVA produces tabular and graphical reports. Values are reported for the following:

- Spacing factor: Values less than 0.01 in. are desirable.
- Specific surface (bubble size): Values greater than 0.04 mm are desirable.
- Air-void content of paste.
- Air-void content of concrete.

The results may not reflect actual spacing factors, but the output can be calibrated from trial batches in which the data have been collected using both the AVA and linear traverse methods.

Construction issues – *What Should I Look For?*

The AVA permits monitoring of the spacing factor and specific surface (bubble size) in fresh concrete. Changes in the results will indicate changes in the concrete mixture, which should then be investigated.

The instrument may also be used to assess changes in the air-void system due to transporting and handling through the paver.

Concrete property: air content (see Testing / Air-Void System, chapter 5, page 136).

Air Content (Plastic Concrete, Pressure Method)

Purpose – *Why Do This Test?*

Entrained air is essential to the long-term durability of concrete pavements that are subject to freezing and thawing. Air content is a commonly specified parameter in paving specifications. It is usually measured at the truck using a pressure meter (normally a type B meter).

Principle – *What is the Theory?*

The fresh concrete is fully consolidated in an airtight container. Pressure from a fixed-volume cell is applied to the sample in the container. Air in the sample is compressed, and the reduction in pressure in the cell is directly related to the volume of air in the sample. The air content of the sample is thus read directly from the gauge of a properly calibrated meter.

Test Procedure – *How is the Test Run?*

The test is described in ASTM C 231. A sample of fresh concrete is fully consolidated in the air meter and struck off level-full. A known volume of air at a known pressure is applied to the sample in an airtight container. The air content of the concrete is read from the gauge on the pressure meter apparatus.

- Measuring bowl and airtight cover (type B meter) for holding the sample and measuring the air content.
- Tamping rod/vibrator and mallet for consolidating the sample.

Test Method

- Consolidate the concrete in the measuring bowl using a tamping rod or vibrator and mallet.
- Strike off the concrete in the measuring bowl so that it is level-full with the top rim.
- Clean the edge and rim of the measuring bowl and clamp the cover on to form an airtight seal.
- Pump air into the air chamber until the gauge needle is stabilized on the initial pressure line.
- Open the valve between the air chamber and the measuring bowl.
- Tap the measuring bowl with the mallet to ensure that pressure is equalized.
- Tap the gauge lightly if necessary to stabilize the needle indicator.
- Record the percentage of air content indicated on the gauge.

Output – *How Do I Interpret the Results?*

Air content of the fresh concrete mix is read directly from the gauge of a calibrated type B pressure meter.

This is a measure of the percentage of total air content in a concrete mix. Both entrained air and entrapped air are measured.

The results are compared to the specified limits.

Construction Issues – *What Should I Look For?*

Air content should be monitored regularly during paving (minimum one test every two hours).

Generally, air contents greater than 4.5 percent (depending on exposure and aggregate size) provide adequate protection from freeze/thaw conditions. However, the use of an AVA is recommended to be sure that proper bubble spacing and bubble size are present.

High air contents are less worrisome than low air contents, unless the strength is reduced to critical levels due to the high air content.

Air content can be affected by many factors, ranging from cement and admixture chemistry to mixing time and aggregate grading.

Concrete property: air content (see Testing / Air-Void System, chapter 5, page 136).

Air Content (Hardened Concrete)

Purpose – *Why Do This Test?*

Another method of determining the quality of an air-void system in concrete is microscopical analysis of hardened concrete. This method provides information on the total air content, as well as the spacing factor and other parameters.

Principle – *What is the Theory?*

The air-void structure of concrete can be measured and characterized by examining a section of a core with a microscope. The linear traverse method consists of measuring the air voids as a polished concrete sample travels under a microscope in regularly spaced lines. The length of travel across air voids is compared to the length of travel across paste and aggregate, and the data are used to calculate the air content, spacing factor, and specific surface of the air voids in the concrete sample.

Test Procedure – *How is the Test Run?*

The method is described in ASTM C 457. A core from the slab is sectioned and polished. The apparatus is used to move a core sample under a microscope (or vice versa) in straight lines. The total length traversed and the length traversed across air voids are recorded.

Test Apparatus

- Saw for cutting a section of a core.
- Polishing tools for grinding, lapping, and preparing the core section.
- Hardware and software for measuring air voids in the core section.

Test Method

- Obtain a core from the pavement.
- Cut a section of the core.
- Grind, lap, and polish the core section until it is smooth and flat.
- Cover the polished face of the core section with black ink from a stamp pad.
- Heat the core to 54°C (130°F) and coat the ink-covered core section with a zinc paste.
- Allow the core section to cool, and scrape the zinc paste off the surface. The melted zinc paste will remain in the air voids of the surface, providing a white contrast to the black ink surface of the core section.
- Mount the prepared core section in the image analysis apparatus.
- Start the image analysis apparatus.
- The image analysis hardware and software automatically traverse the section and record the data.

Output – *How Do I Interpret the Results?*

The software produces a tabular report showing air content, spacing factor, and specific surface area of the air voids. A digital image of the core section can also be viewed or printed.

The air content is expressed as a percent of volume of the concrete sample.

Spacing factor is the average distance from any point to the nearest air void, or the maximum length measured from the cement paste to the edge of an air void.

Specific surface area is the surface area of the air voids divided by the air voids' volume.

Construction Issues – *What Should I Look For?*

Spacing factors should be less than 0.2 mm (0.008 in.).

Air-void spacing can be impacted by many factors, ranging from cement and admixture chemistry to mixing time to aggregate grading.

Concrete property: air content (see Testing / Air-Void System, chapter 5, page 136).

Chloride Ion Penetration

Purpose – *Why Do This Test?*

The ability of concrete to resist the transportation of chlorides is an important factor in its potential durability. If chlorides can be prevented from reaching any steel in the concrete, then the risk of corrosion is reduced.

The test method also provides an indirect measure of the permeability of the concrete, a critical parameter in all durability-related distress mechanisms. The lower the permeability, the longer the concrete will survive chemical attack.

Principle – *What is the Theory?*

The permeability of concrete can be indirectly assessed by measuring the electrical conductance of a sample of concrete.

Test Procedure – *How is the Test Run?*

The test is described in ASTM C 1202. A 2-in. thick section is obtained from a 4-in. diameter pavement core. The core section is completely saturated with water in a vacuum apparatus. Electrical current is passed from one side of the core section to the other side while it is contained within a cell that has a sodium chloride solution on one side of the core and a sodium hydroxide solution on the other side. The electric current is applied and measured for six hours.

- Vacuum saturation apparatus: Completely saturates the sample.
- Sodium chloride solution.
- Sodium hydroxide solution.
- Sealed cell: Holds the core specimen with each liquid solution on opposite sides of the core section and has electrical leads for connecting a DC electrical source.
- DC power supply: Provides constant DC power to the test specimen.
- Voltmeter: Measures and records volts and amps on both sides of the core specimen.

Test Method

- Completely saturate the core section with water.
- Place the saturated core section in the sealed cell containing the two different sodium solutions on either side of the core section.
- Connect the power supply and voltmeter.
- Apply a 60-volt DC current across the cell for six hours.
- Convert the ampere-seconds curve recorded from the test to coulombs.

Output – *How Do I Interpret the Results?*

The electrical current is conducted through the concrete by chloride ions that migrate from one side of the core section to the other side. Higher permeability will result in a higher current being carried through the core section.

The test results are expressed in coulombs, and the permeability of the concrete is classified according to table 9-5. Note that differences within the range of 1,300 to 1,800 coulombs are not significant.

Table 9-5. Relationship Between Coulombs and Permeability

Coulombs	Permeability
> 4,000	high
2,000 to 4,000	moderate
1,000 to 2,000	low
100 to 1,000	very low

Construction Issues – *What Should I Look For?*

Mix design issues that can influence permeability include the following:

- Lower water-cementitious materials ratio will lead to lower conductivity.
- Use of fly ash; ground, granulated blast-furnace slag; and silica fume will generally reduce conductivity.

Paving process inputs that influence permeability include the following:

- Improved consolidation will reduce conductivity.
- Premature final finishing when excessive bleed water is present will increase surface permeability.
- Proper curing will reduce conductivity.

Concrete property: permeability (see Permeability /Testing, chapter 5, page 131).

Coefficient of Thermal Expansion

Purpose – *Why Do This Test?*

The expansion and contraction of concrete due to temperature changes can impact the durability of joints and the risk of cracking in concrete pavements.

Principle – *What is the Theory?*

Concrete expands and contracts as its temperature changes. When a saturated cylinder of concrete is exposed to changing temperature conditions, its change in length can be measured by a linear variable differential transformer (LVDT).

Test Procedure – *How is the Test Run?*

A saturated concrete cylinder or core is subjected to temperature changes from 10 to 50°C (50 to 120°F). The change in length of the cylinder is measured and recorded at different temperatures. (The procedure has not been standardized.)

- Caliper to measure the initial length of the core specimen.
- Water tank: Maintains saturation of the sample and varies the temperature of the water from 10 to 50°C (50 to 120°F).
- Support frame: Holds the core specimen and the LVDT.
- Thermometer: Measures the water temperature.
- LVDT: Measures the length change of the specimen (resolution = 0.00025 mm [0.00001 in.]).

Test Method

- Soak a 4-in. diameter core in water for a minimum of 48 hours.
- Measure the length of the saturated core using calipers.
- Place the core in the support frame that is submerged in the water tank.
- Adjust the temperature of the water tank to 10°C (50°F).
- Maintain the temperature until three consecutive LVDT readings taken every 10 minutes change by less than 0.00025 mm (0.00001 in.). Record the initial LVDT and temperature values.
- Set the temperature of the water tank to 50°C (120°F).
- Maintain the temperature until three consecutive LVDT readings taken every 10 minutes change by less than 0.00025 mm (0.00001 in.). Record the second LVDT and temperature values.
- Adjust the temperature of the water tank to 10°C (50°F).
- Maintain the temperature until three consecutive LVDT readings taken every 10 minutes change by less than 0.00025 mm (0.00001 in.). Record the final LVDT and temperature values.

Output – *How Do I Interpret the Results?*

The coefficient of thermal expansion (CTE) is a function of length change due to a change in temperature.

CTE = (measured length change / specimen length) / measured temperature change

The CTE reported is the average of both test values.

The CTE is reported in microstrain/°F. Typical values for concrete can range from $4(10^{-6})$ to $7(10^{-6})$°F. CTE is most affected by aggregate type. Concrete produced with siliceous aggregates has a higher CTE than concrete produced with limestone aggregates.

Construction Issues – *What Should I Look For?*

Thermal expansion/contraction is a factor that should be considered in the design phase. During construction, the following items should be monitored for conformity with the plans to avoid the possibly adverse effects of thermal expansion and contraction:

- Joint layout and spacing.
- Joint width.

Concrete property: thermal movement (see Thermal Expansion/Contraction, chapter 5, page 129).

References

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AASHTO T 22, Compressive Strength of Cylindrical Concrete Specimens

AASHTO T 84, Specific Gravity and Absorption of Fine Aggregate

AASHTO T 85, Specific Gravity and Absorption of Coarse Aggregate

AASHTO T 97, Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

AASHTO T 121, Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

AASHTO T 152, Air Content of Freshly Mixed Concrete by the Pressure Method

AASHTO T 153, Fineness of Hydraulic Cement by Air Permeability Apparatus

AASHTO T 185, Early Stiffening of Portland Cement (Mortar Method)

AASHTO T 196, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method

AASHTO T 255, Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying

AASHTO T 277, Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

AASHTO T 309, Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete

AASHTO T 318, Water Content of Freshly Mixed Concrete Using Microwave Oven Drying

AASHTO T 325, Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests

AASHTO TP 60, Coefficient of Thermal Expansion of Hydraulic Cement Concrete

ASTM standards may be found in *Annual Book of ASTM Standards 2004*, ASTM International, 2004. www.astm.org.

ASTM C 39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C 70-94(2001), Standard Test Method for Surface Moisture in Fine Aggregate

ASTM C 78-02, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

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ASTM C 127-04/AASHTO T85, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate

ASTM C 128-04/AASHTO T 84, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate

ASTM C 136, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates

ASTM C 138/C138M-01a/AASHTO 121, Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C 173/C173M-01e1/AASHTO T 196, Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method

ASTM C 204, Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus

ASTM C 231-04/AASHTO T 152, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C 359, Standard Test Method for Early Stiffening of Hydraulic Cement (Mortar Method)

ASTM C 457-98, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete

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ASTM C 566-97(2004)/AASHTO T 255, Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying

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Chapter 10

Troubleshooting and Prevention

Most materials-related problems that occur during paving operations are due to actions taken or conditions met during materials selection or concrete mixing and placing. To prevent and fix problems, all members of the construction team need to understand the materials they are working with and be prepared to address potential scenarios.

Inappropriate repairs may fail to correct the problem and may not last. It is essential, therefore, that before changes are made or remedial action taken, the cause of a problem be understood. This may involve investigative work to uncover the mechanisms and sources of the distress. When doing this type of investigation, it is important to make accurate observations and document them.

Begin any investigation by looking for patterns that may connect cause and effect. In particular, look for changes that may have led to the problem. Possibilities may include weather changes, a change in material source or quality, and staffing changes. Problems are often a combination of factors, including design and detailing, materials selection and proportioning, and construction practices. A project may be proceeding satisfactorily, but a small change in any one of these factors may tip the balance and result in a problem.

Not all problems are observed in the early stages. Some become apparent only later. This chapter contains tables that recommend actions to be taken when problems are observed—before the concrete has set (see plastic shrinkage cracks in figure 10-1), during the first few days after placement (see other early-age cracks in figure 10-1), or some time after the concrete has hardened. The tables refer to sections in the manual where detailed information can be found about the factors that may have contributed to the problem.

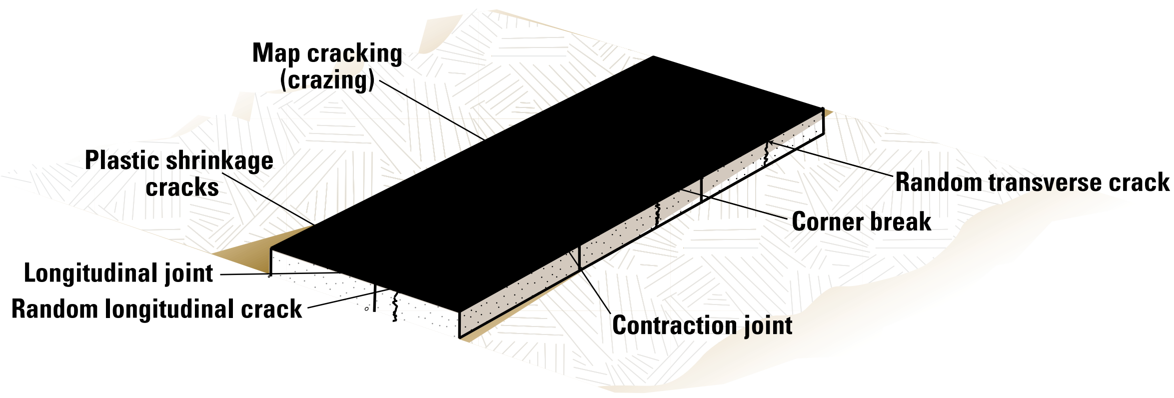

Figure 10-1. Early-age cracking

Key to Troubleshooting Tables

The tables on this page are outlines only of those on pages 275–290.

Before the Concrete Has Set

Some paving problems are generally observed up to the time of final set (table 10-1). Some of these, like insufficient air in the concrete, can be fixed immediately if they are observed early enough. In such cases, admixture dosages might be adjusted if allowed by the specification and good practice. Others, such as rapid stiffening, may be observed only after the concrete has been placed. In such cases, the material may have to be removed, or it may be accepted as long as future deliveries are corrected.

Table 10-1. Problems Observed Before the Concrete Has Set

Mixture and Placement issues

1. Slump is out of specification.
2. Loss of workability/slump loss/early stiffening.
3. Mixture is sticky.
4. Mixture segregates.
5. Excessive fresh concrete temperature.
6. Air content is too low or too high.
7. Variable air content/spacing factor.
8. Mix sets early.
9. Delayed set.
10. Supplier breakdown, demand change, raw material changes.

Edge and Surface Issues

11. Fiber balls appear in mix.
12. Concrete surface does not close behind paving machine.
13. Concrete tears through paving machine.
14. Paving leaves vibrator trails.
15. Slab edge slump.
16. Honeycombed slab surface or edges.
17. Plastic shrinkage cracks.

Some problems, such as early-age cracking, are observed some time between final set and up to a few days after placing (table 10-2). Some remedial work may be possible (and required), and steps should be taken to prevent their recurrence. Finally, some problems are observed only after the pavement has been in place for some time (table 10-3). In these cases, some repair may be possible or replacement may be required. Table 10-3 provides guidelines on how to prevent such problems in future construction.

Table 10-2. Problems Observed in the First Days after Placing

Strength

18. Strength gain is slow.
19. Strength is too low.

Cracking

20. Early-age cracking.

Joint Issues

21. Raveling along joints.
22. Spalling along joints.
23. Dowels are out of alignment.

Table 10-3. Preventing Problems That Are Observed Some Time after Construction

Edge and Surface Issues

24. Clay balls appear at pavement surface.
25. Popouts.
26. Scaled surface.
27. Dusting along surface.
28. Concrete blisters.
29. Surface bumps and rough riding pavement.
30. Surface is marred or mortar is worn away.
31. Cracking.

Table 10-4 is a listing of some of the nondestructive testing (NDT) techniques available to assess the extent of damage in hardened concrete.

Table 10-4. Assessing the Extent of Damage in Hardened Concrete

1. Dowel bar alignment.
2. Pavement thickness.
3. Pavement subgrade support and voiding.
4. Concrete quality in pavement.
5. Overlay debonding and separation.
6. Concrete strength.

Table 10-1. Problems Observed Before the Concrete Has Set

Mixture and Placement Issues

1. Slump is Out of Specification

Potential Cause(s)	Actions to Consider/Avoid	See Page
Change in water content or aggregate grading	Check aggregate moisture contents and absorptions.	44, 47, 183, 206, 207, 211
	Check for segregation in the stockpile.	
	Make sure the batch water is adjusted for aggregate moisture content.	
	Conduct batch plant uniformity tests.	
	Check whether water was added at the site.	
Mix proportions	Check batch equipment for calibration.	207
Admixture dosage	Check delivery ticket for correct admixture dosage.	207
Concrete temperature too high or too low	Adjust the concrete placement temperature.	127
Haul time	Check the batch time on the concrete delivery ticket. Haul times should not be excessive.	209

2. Loss of Workability/Slump Loss/Early Stiffening

Potential Cause(s)	Actions to Consider/Avoid	See Page
Dry coarse aggregates	Make sure the aggregate stockpile is kept consistently at saturated surface-dry (SSD) (use soaker hoses if necessary).	206
Ambient temperature increases	Do not add water.	179, 182, 183, 206, 210, 226
	Chill the mix water or add ice.	
	Sprinkle the aggregate stockpiles.	
	Use a water reducer or retarder.	
	Do not increase the water/cement ratio to a value greater than the maximum approved mix design.	
	Use a mix design that includes slag or fly ash.	
Transport time too long	Reject the load if greater than specified.	183, 209
	Use retarder in the mixture.	
	Use an agitator rather than dump trucks.	
Mix proportions have changed	Check/monitor the moisture contents of the aggregate stockpiles.	206, 207, 246
	Check the batch weigh scales.	
	Verify that aggregate gradations are correct.	
False setting (temporary)	Check for changes in cementitious materials.	58, 209, 211
	Reduce Class C fly ash replacement.	
	Change the type of water reducer.	
	Try restoring plasticity with additional mixing.	
	Contact the cement supplier.	
Incompatibility	Check for changes in the cementitious materials.	97, 246, 247
	Reduce Class C fly ash replacement.	
	Change chemical admixtures.	
	Change the batching sequence.	
	Cool the mixture.	
Variation in air content	Check the air content/air entrainer dosage.	56

Mixture and Placement Issues, continued

3. Mixture is Sticky

Potential Cause(s)	Actions to Consider/Avoid	See Page
Sand too fine	Change the sand grading.	44, 109
Mix too sandy	Check the sand and combined aggregate grading.	180
Cementitious materials	Check the cementitious materials contents. (Mixtures containing GGBF slag and fly ash appear sticky but finish well and respond well to vibration energy.)	31, 109, 179, 214
	Lower the vibration energy to avoid segregation.	
	Adjust the mix proportioning.	
Using wood float on air-entrained concrete	Use magnesium or aluminum floats.	

4. Mixture Segregates

Potential Cause(s)	Actions to Consider/Avoid	See Page
Inconsistent concrete material—batching, mixing, placing	Check aggregate gradation; poorly graded mixtures may tend to segregate.	176, 206, 207, 208, 213, 215, 246
	Verify batching/mixing procedures so that the mixture is adequately mixed.	
	Check aggregate stockpile, storage, and loading procedures to prevent aggregate segregation.	
	Place concrete as close to final position as possible to minimize secondary handling.	
	Perform uniformity testing on batch plant, if necessary, use agitator trucks for transport.	
	Reduce the vibration energy if consolidation efforts cause segregation. (Vibration at 5,000–8,000 vpm is sufficient for most well-graded mixtures.)	

5. Excessive Fresh Concrete Temperature

Potential Cause(s)	Actions to Consider/Avoid	See Page
Hot ingredients	Do not add water.	128, 226, 247
	Follow hot-weather concreting practice as appropriate.	
	Chill the mix water or use ice.	
	Shade and sprinkle the aggregate stockpiles.	
Long haul times	Adjust the hauling operation to minimize haul times.	209
	Adjust paving time to off-peak traffic time if hauling through public traffic.	
Hot weather	Follow hot-weather concreting practice as appropriate.	129, 226, 247
	Chill the mix water; sprinkle the aggregate stockpiles.	
	Pave at night or start paving in afternoon.	

Mixture and Placement Issues, continued

6. Air Content is Too Low or Too High

Potential Cause(s)	Actions to Consider/Avoid	See Page
Temperature changes	The air-entraining admixture dosage may need to be adjusted during hot/cold weather.	186
Materials have changed	Check for uniformity of materials.	
Mix proportions have changed	Altering other admixture dosages may impact the effectiveness of the air-entraining admixture.	176, 180, 246
	Check slump; it is easier to entrain air with increasing concrete workability.	
	Check/monitor the moisture contents of the aggregate stockpiles.	
	Check the batch weigh scales.	
	Verify that aggregate gradations are correct.	
	Verify sand quantity.	
Short or inadequate mixing	Check the charging sequence.	209
	Increase mixing time.	
	Check if the blades of the mixer are missing or dirty.	

7. Variable Air Content/Spacing Factor

Potential Cause(s)	Actions to Consider/Avoid	See Page
Incorrect or incompatible admixture types	Change types or brands of admixtures.	186, 248
	Try to work within one manufacturer's family of admixtures if air-entraining agent is being combined with other admixtures.	
Admixture dosage	Check the batching equipment for calibration and settings.	207, 248
	Change the sequence of batching.	
Mix proportions have varied or changed	Check/monitor the moisture contents of the aggregate stockpiles.	176, 183, 206, 248
	Check the batch weigh scales.	
	Verify that aggregate gradations are correct.	
Cementitious materials	Check for changes in cementitious materials, particularly the loss-on-ignition (LOI) content of fly ash.	34
Poor plant configuration	Introduce aggregates together on the plant's belt feed (requires a multiple weigh hopper).	207
Poor aggregate grading	Use a more well-graded coarse and fine aggregate mixture.	176
	Check variation in the amount of materials retained on the #30 through #100 sieves.	
Temperature changes	Air-entraining admixture dosage may need to be adjusted during hot/cold weather.	56, 133, 247
	Altering other admixture dosages may impact the effectiveness of the air-entraining admixture; air-entraining admixtures work more efficiently with increasing workability.	
Variable mixing	Ensure that each batch is handled consistently in the plant.	207

Mixture and Placement Issues, continued

8. Mix Sets Early

Potential Cause(s)	Actions to Consider/Avoid	See Page
Cementitious materials	Check for changes in the cementitious materials; differing sources or changes in properties of a given material may result in incompatibility; changes in proportions may also affect setting times.	99
Admixture dosage	Check the dosage of chemical admixtures, particularly accelerators.	56, 99, 183, 207, 246
	Check the batching equipment.	
Hot weather	Adjust the mix proportions.	31, 99, 185, 186, 226, 246
	Use mix designs that include GGBF slag or fly ash.	
	Use a retarder.	
	Reduce haul time if possible.	
	Reduce the placement temperature of the concrete.	
	In hot weather, use a hot weather mix design.	
	Cool the concrete ingredients.	

9. Delayed Set

Potential Cause(s)	Actions to Consider/Avoid	See Page
Excessive retarder dosage	Verify the proper batch proportions.	56, 183, 207, 246
	Check the batching equipment.	
	Reduce the dosage of the retarder.	
Excessive water reducer dosage	Verify the proper batch proportions.	56, 183, 207
	Reduce the dosage of the water reducer.	
Retarder not dispersed well	Improve mixing to disperse the retarder.	209
Supplementary cementitious materials interference	Reduce GGBF slag content; GGBF slag in excess of 25 percent can cause a dramatic increase in set time.	31
	Eliminate/reduce fly ash content in the mix.	
Cold placement temperature	Follow cold-weather concreting practices if appropriate.	228
Organic contamination	Verify the proper batch proportions.	39, 52, 207
	Check for contamination of water and aggregates.	

Mixture and Placement Issues, continued

10. Supplier Breakdown, Demand Change, Raw Material Changes

Potential Cause(s)	Actions to Consider/Avoid	See Page
Cement	Refer to backup lab mixes if conditions were anticipated.	28, 171, 211
	Switch sources, batch new mix designs, and develop new laboratory strength gain and maturity information. (This action may require a project delay. To avoid unacceptable delays, a contractual agreement should be arranged prior to paving, which allows for unforeseen material supply changes, burden of delay costs, and risk of paving during batch revision testing. If paving activity is continued during testing, compare early-age strengths (1- and 3-day) and maturity data to confirm that the new mix will perform adequately.)	
Supplementary cementitious materials	See cement supply change.	31
	Switch sources and compare early-age strengths (1- and 3-day) and maturity data to confirm that the mix will perform adequately.	
Aggregates	See cement supply change.	39
	Switch sources and compare early-age strengths (1- and 3-day) and maturity data to confirm that the mix will perform adequately.	
Chemical admixtures	See cement supply change.	55
	Switch admixture sources and compare early-age strengths (1- and 3-day) and maturity data to confirm that the mix will perform adequately.	

Edge and Surface Issues

11. Fiber Balls Appear in Mixture

Potential Cause(s)	Actions to Consider/Avoid	See Page
Fibers not thoroughly dispersed in mix	If added in bags, check the timing of addition and subsequent mixing.	62
	Some mixes do not break down bags as easily as others (i.e., smaller sized rounded coarse aggregate mixes); check compatibility.	
	Use a blower for synthetic fibers or a belt placer for steel fibers instead of bags.	

Edge and Surface Issues, continued

12. Concrete Surface Does Not Close Behind Paving Machine

Potential Cause(s)	Actions to Consider/Avoid	See Page
Insufficient volume contained in the grout box	Place more material in front of the paver; consider using a spreader.	209
The concrete is stiffening in the grout box	Check for premature concrete stiffening (admixture compatibility). (See no. 2: Loss of workability/slump loss/early stiffening.)	97
The fine/coarse aggregate volume or paste volume is too low	Check mixture proportions, particularly aggregate gradations.	171, 176
	Check the uniformity of aggregate materials/supplies.	
The finishing pan angle needs adjustment	Adjust the pan angle.	
The paver speed is too high or vibrators need to be adjusted	Slow the paver.	215, 248
	Lower the vibrator frequencies or use vibrators with greater force.	
	Adjust the location of the vibrators; raise them closer to the surface.	
	Place more material in front of the paver; consider using a spreader.	
	Change the vibrator angle.	

13. Concrete Tears Through Paving Machine

Potential Cause(s)	Actions to Consider/Avoid	See Page
Excessive concrete slump loss	Check for slump loss and mixture or weather changes.	109
	See no. 2: Loss of workability/slump loss/early stiffening.	
Insufficient concrete slump	Check the mixture proportions.	171
Angular fine aggregate (manufactured sand)	Replace a portion of the manufactured sand with natural sand.	39
Paver speed too high	Slow the paver.	
Coarse aggregate is segregated	Check the stockpile.	109, 206
Coarse aggregate is gap-graded	Check the combined aggregate grading.	109, 176
	Blend the aggregate with intermediate aggregates to achieve a uniform combined grading.	

14. Paving Leaves Vibrator Trails

Potential Cause(s)	Actions to Consider/Avoid	See Page
Vibrator frequency too low	Check if the seals on the vibrators are leaking.	248
Vibrator frequency too high	Lower the vibrator frequency.	248
Paver speed too slow	Increase the paver speed.	212
Non-workable concrete mix	Review concrete workability field test data.	109
	See no. 2: Loss of workability/slump loss/early stiffening.	
Over-sanded mixes	Increase the coarse aggregate.	176, 180
Poor combined aggregate grading	Check the combined aggregate grading.	176

Edge and Surface Issues, continued

15. Slab Edge Slump

Potential Cause(s)	Actions to Consider/Avoid	See Page
Poor and/or nonuniform concrete—gap-graded aggregate, high water/cement ratio, etc.	Verify the mix design and batching procedures.	176, 246
	Check the aggregate grading—use a well-graded combined aggregate gradation.	
Inadequate operation of equipment	Check the construction procedures.	212
	Adjust the outside vibrator frequency.	
	Adjust the side form batter.	
Improper equipment setup	Adjust the overbuild.	212
	Check the track speed (same on both sides).	
	Check the pan profile.	

16. Honeycombed Slab Surface or Edges

Potential Cause(s)	Actions to Consider/Avoid	See Page
Hot weather may induce premature stiffening	Follow hot-weather concreting practices if appropriate.	226
	See no. 2: Loss of workability/slump loss/early stiffening.	
Inadequate vibration	Check that all vibrators are working properly, at the right frequency and amplitude; the paver speed should not be too high.	248
	Add an additional vibrator near the slipformed edge.	
Poor workability	Check for changes in the aggregate grading.	176

17. Plastic Shrinkage Cracks (figures 5-30, 5-31, 10-1)

Potential Cause(s)	Actions to Consider/Avoid	See Page
High evaporation rate (excessive loss of moisture from surface of fresh concrete; i.e., evaporation rate > bleed rate)	Apply the curing compound as soon as possible to protect the concrete from loss of moisture.	158, 176, 191, 206, 224, 226
	Use additional curing measures: fogging, evaporation retarder, windbreaks, shading, plastic sheets, or wet coverings.	
	Make sure the absorptive aggregates are kept moist; a dry concrete mixture from concrete aggregates that are not saturated tends to surface dry at mixing. This is problematic if not accounted for.	
	Use a well-graded combined aggregate (gap gradation requires more paste and causes more shrinkage).	
	Refer to hot-weather concreting practices if appropriate.	
	Pave at night.	
	Chill the mixing water.	
	Dampen the subgrade.	
	Avoid paving on hot, windy days.	
	Consider adding fibers to the mix.	
Delayed setting time	Check the time of set.	114

Table 10-2. Problems Observed in the First Days After Placing

Strength

18. Strength Gain is Slow

Potential Cause(s)	Actions to Consider/Avoid	See Page
Cold temperature during/after placement	Heat the mix water.	31, 59, 121, 182, 224, 228, 233
	Use burlap/insulating blankets for protection from freezing.	
	Use an accelerating admixture.	
	Eliminate/reduce GGBF slag and fly ash content in the mix.	
	Increase the cement content.	
	Use a Type III cement.	
	Utilize early-entry sawing to reduce the potential for random cracking.	
	Monitor the slab temperature with maturity sensors.	
Mix proportions or materials have changed	Check/monitor the moisture contents of the aggregate stockpiles.	176, 206, 207, 211
	Check for uniformity of the cementitious materials.	
	Check the batch weigh scales.	
	Verify that aggregate gradations are correct.	
	Verify that batch weights are consistent with the mix design.	

19. Strength is Too Low

Potential Cause(s)	Actions to Consider/Avoid	See Page
Cementitious materials	Check for changes in the cementitious materials.	211
	Check that the correct materials have been loaded into the cement/fly ash/slag silos.	
Water	Check the water content.	181, 206, 207
	Verify the aggregate moisture contents and batch weights.	
Change in sand grading	Check the sand stockpile to see whether the grading has changed.	176
Contamination with organics	Contamination of one of the ingredients with organics can also effect a sudden change in the required dosage of air-entraining admixture; try to isolate the source.	
Inadequate or variable mixing	Examine the mixer and mixing procedures.	207, 208
	Check for worn mixer blades.	
	Check for mixer overloading.	
	Batch smaller loads.	
	Check the sequencing of batching.	
	Check for mixing time consistency.	
	Conduct batch plant uniformity testing.	
Plant operations	Verify the acceptability of the batching and mixing process.	207, 208
	Check for adequate mixing times.	
	Check if water was added to the truck.	
Testing procedures	Verify proper making, curing, handling, and testing of strength specimens. (Flexural strength specimens are particularly vulnerable to poor handling and testing procedures.)	263
	Verify the machine acceptability testing.	
	Test the cores sampled from the pavement to verify acceptance.	
Air-void clustering	Use a vinsol resin-based air-entraining admixture.	100, 209
	Avoid retempering.	
	Increase the mixing time.	

Cracking

20. Early-Age Cracking (figures 5-32, 5-33, 5-34, 5-35, and 10-1)

Potential Cause(s)	Actions to Consider/Avoid	See Page
Concrete mixture	Check the combined aggregate grading.	31, 39, 55, 88, 97, 148, 176, 228, 235
	Examine the fine aggregates; fine aggregates may be too fine and angularity may cause harsh finishing (i.e., manufactured sands).	
	Reduce the paste content (minimize shrinkage potential).	
	Materials incompatibility may lead to delayed set and/or higher concrete shrinkage; consider mixture component adjustments.	
	Eliminate or reduce the content of fly ash or GGBF slag in cool-weather conditions.	
	Consider using an accelerator in cold weather.	
Sawing	Saw as early as possible but avoid excessive raveling.	231, 233
	Saw in the direction of the wind.	
	Check that the diamond saw blade is appropriate for concrete aggregate hardness, fines, etc.	
	Use early-entry dry sawing.	
	Use HIPERPAV to model stress versus strength gain for conditions to determine the optimum sawing time.	
Curing	Improve/extend curing.	224
	Apply the curing compound at a higher rate.	
	Apply the curing compound sooner.	
	Use blankets between placing and saw-cutting.	
Insufficient joint depth	Check the saws for depth setting.	231, 233
	Check the saw blade for wear (carbide blades).	
	Check that saw operators are not pushing saws too fast, causing them to ride up.	
	Look for base bonding or mortar penetration into the open-graded base-altered effective section; increase the saw depth to create an effective weakened plane.	
	Check the slab thickness.	
Excessive joint spacing	Reduce spacing between the joints.	
	Slabs are too wide in relation to thickness and length; add intermediate joints.	
	Maintain a reasonable length-width ratio.	
Warping (slab curvature due to moisture gradient; the term "curling," however, is commonly used in the industry to cover both moisture- and temperature-related slab distortion)	Check the moisture state of base.	150, 224
	Improve or extend curing.	
	Minimize the shrinkage potential of the concrete mixture.	
	Cover the slab, particularly when night/day temperatures vary widely.	

(continued on the following page)

Cracking, continued

20. Early-Age Cracking, continued

Potential Cause(s)	Actions to Consider/Avoid	See Page
High temperature	Cool the raw materials before mixing the concrete: shade, spray, ice, liquid nitrogen	64, 156, 224, 226
	Cool the equipment.	
	Work at night.	
	Watch for shaded areas where drying and strength gain may vary within a single day's work.	
	Delay paving if conditions are too hot (>38°C [100°F]).	
	Apply an evaporative retardant prior to texturing.	
	Apply the curing compound at an additional dosage rate and consider a non-water-based compound with better membrane-forming solids.	
Too many lanes tied together (generally only a consideration for longitudinal direction)	Do not exceed 15 m (50 ft) of pavement tied together.	
	Add an untied construction or isolation joint.	
	To prevent additional cracking, consider sawing through a longitudinal joint to sever bars.	
Edge restraint (paving against an existing or previously placed lane)	Cracks occur due to restraint to movement (sometimes referred to as sympathy cracks).	
	Tool the joint or use an early-entry dry saw to form the joints as early as possible.	
	Match the joint location and type.	
	Eliminate tiebars in a longitudinal construction joint that is within 24 inches on either side of transverse joint locations. Match all locations of the joints in the existing pavement (cracks, too).	
Slab/base bonding or high frictional restraint	Moisten the base course prior to paving (reduce the base temperature by evaporative cooling).	191
	Use a bond-breaking medium (see reflective cracks).	
	If the base is open graded, use a choker stone to prevent the penetration of concrete into the base's surface voids.	
Misaligned dowel bars	Investigate whether the joints surrounding the crack have activated and are functioning; misaligned or bonded dowels may prevent joint functioning, causing cracks.	218
Cold front with or without rain shower	Use early-entry sawing to create a weakened plane prior to temperature contraction.	231, 233
	Skip-saw (saw every other joint or every third joint) until normal sawing can be resumed.	
	Use HIPERPAV to model stress versus strength-gain conditions that may warrant a suspension or change of paving activities.	

Joint Issues

21. Raveling Along Joints

Potential Cause(s)	Actions to Consider/Avoid	See Page
Sawing too soon	Wait longer to saw.	233
	Use formed joints.	
	Blank out transverse tining at transverse contraction joints.	
Saw equipment problem	Blade selection for the concrete (coarse aggregate type) may be inadequate.	233
	A bent arbor on the saw causes the blade to wobble.	
	The second saw cut can go back and forth; consider a single-cut design.	
Sawing too fast	Slow down.	233

22. Spalling Along Joints

Potential Cause(s)	Actions to Consider/Avoid	See Page
Excessive hand finishing	Check for mixture problems that would necessitate overfinishing.	220
	Improve construction practice.	
Trying to fix edge slump of low spots by hand manipulating concrete	Check for mixture problems that would cause edge slump.	217
	Improve construction practice.	
Mortar penetration into transverse joints (after hardening mortar prevents joint closure)	Mortar penetration occurs when paving against an existing previously placed lane; apply duct tape or other means to block the penetration of mortar into the transverse joints of the existing lane.	
Collateral damage from equipment, slipform paver tracks, screeds, etc.	Protect the edges of the slab from damage using gravel or dirt ramps.	
	Delay placement of the next phase of construction until the concrete gains sufficient strength.	

23. Dowels Are Out of Alignment

Potential Cause(s)	Actions to Consider/Avoid	See Page
Movement in dowel basket assemblies	Cover the dowel baskets with concrete ahead of the paver.	218, 248
	Use stakes to secure the baskets to the granular base.	
	Increase the length and number of stakes.	
	Use nailing clips on both sides of basket to secure the basket to the stabilized base.	
Dumping directly on dowel baskets	Deposit the concrete a few feet from the dowel basket to allow the concrete to flow around the dowel bars.	212
Poor aggregate gradation	Dowel insertion into mixtures with gap-graded aggregates does not work well; improve the aggregate grading.	176

Table 10-3. Preventing Problems That Are Observed at Some Time after Construction

Edge and Surface Issues

24. Clay Balls Appear at Pavement Surface

Potential Cause(s)	Actions to Consider/Avoid	See Page
Aggregate stockpile contamination generally caused by the following: • Haul trucks tracking clay and mud to stockpiles • Loader operator digging into dirt • Dirt coming from the quarry	Educate the loader operator on proper stockpile management techniques.	206
	Keep end-loader buckets a minimum of 2 ft off the ground.	
	Do not stockpile aggregates on soft foundations.	
	Stabilize the haul road at the plant site to avoid tracking contaminants.	
	Use belt placers at stockpiles rather than end loaders.	
	Check the aggregate producer's stockpiles.	
	Check for contamination in the hauling equipment.	
	Do not drive over a bridge to unload the aggregate.	
Mud being thrown into concrete trucks from muddy haul roads	Cover the trucks.	

25. Popouts

Potential Cause(s)	Actions to Consider/Avoid	See Page
Unsound aggregates	Use only aggregates that have been tested for chert, shale, and/or other undesirable fine particles.	45, 48
	Reduce vibration to minimize the flotation of particles.	
Alkali-silica reactions	Use non-alkali silica reactive aggregates.	31, 48, 141
	Use blended cements or SCMs proven to control ASR.	

26. Scaled Surface

Potential Cause(s)	Actions to Consider/Avoid	See Page
Premature finishing	Improve the finishing technique.	220
Improper finishing	Do not add water to the surface during finishing.	220
Over-finishing	Improve the finishing technique.	220
Frost related	Protect the concrete from freezing until a sufficient strength is achieved.	186, 228
	Concrete damaged by freezing must be removed and replaced.	
	Check the air content and spacing factor in the hardened concrete.	
	Premature salting; salts should not be applied to immature concrete.	
	Check the de-icing salts being used.	

27. Dusting Along Surface

Potential Cause(s)	Actions to Consider/Avoid	See Page
Adding water during finishing or finishing in bleed water	Prevent the addition of water during finishing.	220
	Delay finishing until after the dissipation of the bleed water.	

Edge and Surface Issues, continued

28. Concrete Blisters

Potential Cause(s)	Actions to Consider/Avoid	See Page
Premature closing of surface	Check for bleed water trapping.	220, 221
	Consider using a double burlap drag to open the surface.	
Extremely high/variable air content	Check for the consistency of the air content.	186
Vibrators too low	Check the vibrator depth.	215
Vibrator frequency too high	Reduce the vibrator frequency.	215
Over-sanded mixes	Increase the coarse aggregate.	176
Poor combined aggregate grading (gap grading)	Check the combined aggregate grading.	176

29. Surface Bumps and Rough Riding Pavement

Potential Cause(s)	Actions to Consider/Avoid	See Page
Placement operations	Construct and maintain a smooth and stable paver track line.	212, 215
	Check the string line tension and profile.	
	Maintain a consistent quantity of concrete in front of the paver.	
	Maintain a consistent forward motion; avoid a stop-and-go operation.	
	Check the paver tracks.	
	Check that the machine is level.	
	Check the sensors on the paver.	
	Verify that the paver electronics/hydraulics are functioning properly.	
Nonuniform concrete	Check the batching, mixing, and transport procedures for consistency.	176, 206, 207
	Check the aggregate grading and moisture contents for variations that might lead to wet and dry batches.	
Damming or rebound from dowel baskets	Lack of consolidation to achieve a uniform concrete density within the dowel basket area may create a rough surface because the concrete may settle or slough over the dowels.	215, 218, 248
	Check that the dowel baskets are secured.	
	The basket assembly deflects and rebounds after the slipform paver profile pan passes overhead and the extrusion pressure is released. The result is a slight hump in the concrete surface just ahead of the basket. Spring-back is more apt to occur on steeper grades and when there is too much draft in the pan; do not cut the basket spacer wires to prevent the basket from springing under the paver's extrusion pressure.	
	Do not overvibrate the concrete at the baskets in an effort to prevent basket movement.	

(continued on the following page)

Edge and Surface Issues, continued

29. Surface Bumps and Rough Riding Pavement, continued

Potential Cause(s)	Actions to Consider/Avoid	See Page
Reinforcement ripple	Address reinforcement ripple issues with well-graded aggregates and uniform concrete; consolidation is achieved at lower vibration energy and extrusion pressure.	106, 176
	Reinforcement ripple occurs when plastic concrete is restrained by the reinforcing bars, resulting in a ripple in the surface, with the surface slightly lower near each bar than in the area between the bars.	
	Longitudinal depressions are caused when longitudinal bars limit the restitution of the surface level behind the profile pan by restraining the rebound of the concrete beneath the bars.	
	Transverse ripple is caused by the transverse bars in the same way as longitudinal depressions, except that transverse ripple is found to be less noticeable than the prominent ridge caused by the damming effect of the transverse bars upon the upsurge flow of concrete behind the profile pan.	
	The prominence of surface rippling depends on the finishing techniques and depth of cover to the reinforcement, with less cover producing more prominent rippling.	
Vertical grades (exceeding 3 percent)	Lower the slump of the concrete; the need to make an adjustment depends upon whether it is difficult to maintain a uniform head of concrete in front of the paver.	212, 215
	Adjust the profile pan attitude, draft, or angle of attack. (When paving up a steeper grade, the pan elevation may be adjusted to about 25 mm [1.0 in.] below the surface grade. When paving down a steeper slope, the pan may be adjusted to about 25 mm [1.0 in.] above the surface grade. This adjustment must be made carefully to avoid reinforcement ripple, particularly a spring-back of the embedded dowel baskets.)	
	Adjust the staking interval; closely follow the grade and staking calculations for these circumstances to reduce the semi-chord effect enough to produce a smooth surface.	

30. Surface is Marred or Mortar is Worn Away

Potential Cause(s)	Actions to Consider/Avoid	See Page
Rained-on surface	Cover the slab to protect from rain.	229
	Remove the damaged surface by grinding.	
	Restore the surface texture (if required) by grinding.	
Improper curing type or application	Place a curing blanket or plastic sheets after the bleed water sheen disappears.	224
	Consider using a membrane-forming curing compound instead of sheets/blankets.	
Use of higher dosages (>25%) of GGBF slag	Do not add water to the mixture.	248
	Reduce the vibration energy to avoid bringing too much moisture to the surface; vibration at 5,000–8,000 vpm is sufficient for most well-graded mixtures.	
Over-sanded mixes	Increase the coarse aggregate.	176
Abrasion	Use a hard, wear-resistant aggregate.	50, 116
	Use a concrete mix with sufficient strength.	

Cracking

31. Cracking

Potential Cause(s)	Actions to Consider/Avoid	See Page
Applied loads	Keep construction traffic away from the slab edges; early loading by traffic or equipment causes higher edge stresses.	152, 157
	Keep public traffic away from the slab edges.	
Loss of support	Ensure that the subgrade and base have been properly prepared.	151, 157, 192, 237
	Ensure that the joints are properly filled and sealed where appropriate.	
Reflective cracks from stabilized bases	Isolate the slab from cracks in the base course by using bond breakers. (Acceptable bond breakers include two coats of wax-based curing compound, dusting of sand, bladed fines, asphalt emulsion, polyethylene sheets, and tar paper. Sheet goods are difficult to handle in windy or other harsh conditions.)	198
	Joint the base course to match the joints in the pavement.	
Slab/base bonding or high frictional restraint	Moisten the base course prior to paving (reduce the base temperature by evaporative cooling).	198
	Use a bond-breaking medium (see “Reflective cracks from stabilized bases,” immediately above)	
	If the base is open-graded, use a choker stone to prevent the penetration of concrete into the base’s surface voids.	
Mortar penetration into transverse joints (after hardening mortar prevents joint closure)	Mortar penetration occurs when paving against an existing previously placed lane; apply duct tape or other means to block the penetration of mortar into the transverse joints of the existing lane.	
Differential support condition created by frost heaving, soil settling, or expansive soils	Check base compaction, particularly above utility, culvert, and other trenches.	192, 196
	Proof roll the base.	
	Stabilize the subgrade soil.	
	Use selective grading techniques; cross-haul the soils to create smooth transitions between cut and fill sections and soil transitions.	
Misaligned dowel bars	Investigate whether the joints surrounding the crack have cracked and are functioning; misaligned or bonded dowels may prevent joint functioning, causing cracks.	218
	Designate personnel to ensure dowel alignment.	
Alkali-silica reactions	Avoid using reactive aggregates if possible.	31, 48, 141, 157, 179
	Use appropriate amounts of SCMs.	
	Use blended cements or SCMs proven to control ASR.	
	Use a low w/cm ratio.	
Chemical attack	Use a low w/cm ratio, maximum 0.45.	28, 157, 179
	Use an appropriate cementitious system for the environment.	
Frost related	Ensure that the air-void system of the in-place concrete is adequate.	49, 135, 136, 157, 179
	Use a low w/cm ratio.	
	Use frost-resistant aggregates.	
	Reduce the maximum particle size.	

Table 10-4. Assessing the Extent of Damage in Hardened Concrete

Problem	Nondestructive Testing Method(s)
1. Dowel bar alignment	Twin antenna radar Pulse induction (MIT-scan)
2. Pavement thickness	Impact-echo, radar
3. Pavement subgrade support and voiding	Impulse response Benkelman beam Falling weight deflectometer (FWD)
4. Concrete quality in pavement: a) Inclusions in pavement (clay balls) b) Honeycombing and poor concrete consolidation	Impulse radar Impulse response
5. Overlay debonding and separation: a) Traditional b) Advanced techniques	Hammer sounding Chain drag Impulse response Impact-echo, radar
6. Concrete strength	Rebound hammer (for comparative tests) Windsor probe

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Glossary (based on ACPA definitions)

A

AASHTO
American Association of State Highway and Transportation Officials

Absolute Specific Gravity
The ratio of the weight referred to in a vacuum of a given volume of material at a stated temperature to the weight referred to a vacuum of an equal volume of gas-free distilled water at the same temperature.

Absolute Volume (of ingredients of concrete or mortar)
The displacement volume of an ingredient of concrete or mortar; in the case of solids, the volume of the particles themselves, including their permeable or impermeable voids but excluding space between particles; in the case of fluids, the volume which they occupy.

Absorbed Moisture
The moisture held in a material and having physical properties not substantially different from those of ordinary water at the same temperature and pressure.

Absorbed Water
Water held on surfaces of a material by physical and chemical forces, and having physical properties substantially different from those of absorbed water or chemically combined water at the same temperature and pressure.

Absorption
The amount of water absorbed under specific conditions, usually expressed as a percentage of the dry weight of the material; the process by which the water is absorbed.

Acceleration
Increase in rate of hardening or strength development of concrete.

Accelerator
An admixture which, when added to concrete, mortar, or grout, increases the rate of hydration of hydraulic cement, shortens the time of set, or increases the rate of hardening or strength development.

ACI
American Concrete Institute

ACPA
American Concrete Pavement Association

ACR
Alkali-carbonate reaction

Admixture
A material other than water, aggregates, and portland cement (including air-entraining portland cement, and portland blast furnace slag cement) that is used as an ingredient of concrete and is added to the batch before and during the mixing operation.

Aggregate
Granular material, such as sand, gravel, crushed stone, crushed hydraulic-cement concrete, or iron blast furnace slag, used with a hydraulic cementing medium to produce either concrete or mortar.

Aggregate Blending
The process of intermixing two or more aggregates to produce a different set of properties, generally, but not exclusively, to improve grading.

Aggregate Gradation
The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings). See also Grading.

Aggregate Interlock
The projection of aggregate particles or portion of aggregate particles from one side of a joint or crack in concrete into recesses in the other side of the joint or crack so as to effect load transfer in compression and shear and maintain mutual alignment.

Aggregate, Angular
Aggregate particles that possess well-defined edges formed at the intersection of roughly planar faces.

Aggregate, Coarse
See Coarse Aggregate

Aggregate, Dense-graded
Aggregates graded to produce low void content and maximum weight when compacted.

Aggregate, Fine
See Fine Aggregate

Aggregate, Gap- graded
Aggregate so graded that certain intermediate sizes are substantially absent.

Aggregate, Maximum Size
See Maximum Size of Aggregate

Aggregate, Nominal Maximum Size
In specifications for and descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass; sometimes referred to as “maximum size (of aggregate).”

Aggregate, Open-graded
Concrete aggregate in which the voids are relatively large when the aggregate is compacted.

Agitating Truck
A vehicle in which freshly mixed concrete can be conveyed from the point of mixing to that of placing; while being agitated, the truck body can either be stationary and contain an agitator or it can be a drum rotated continuously so as to agitate the contents.

Agitation
The process of providing gentle motion in mixed concrete just sufficient to prevent segregation or loss of plasticity.

Air Content
The amount of air in mortar or concrete, exclusive of pore space in the aggregate particles, usually expressed as a percentage of total volume of mortar or concrete.

Air Void
A space in cement paste, mortar, or concrete filled with air; an entrapped air void is characteristically 1 mm (0.04 in.) or more in size and irregular in shape; an entrained air void is typically between 10µm and 1 mm (34 ft and .04 in.) in diameter and spherical (or nearly so).

Air-Entraining
The capabilities of a material or process to develop a system of minute bubbles of air in cement paste, mortar, or concrete during mixing.

Air-Entraining Agent
An addition for hydraulic cement or an admixture for concrete or mortar which causes air, usually in small quantity, to be incorporated in the form of minute bubbles in the concrete or mortar during mixing, usually to increase its workability and frost resistance.

Air-Entraining Cement
A cement that has an air-entraining agenda added during the grinding phase of manufacturing.

Air-Entrainment
The inclusion of air in the form of minute bubbles during the mixing of concrete or mortar.

Alkali-Aggregate Reaction
Chemical reaction in mortar or concrete between alkalis (sodium and potassium) released from portland cement or from other sources, and certain compounds present in the aggregates; under certain conditions, harmful expansion of the concrete or mortar may be produced.

Alkali-Carbonate Reaction
The reaction between the alkalies (sodium and potassium) in portland cement binder and certain carbonate rocks, particularly calcite dolomite and dolomitic limestones, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Alkali-Silica Reaction
The reaction between the alkalies (sodium and potassium) in portland cement binder and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acisic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

Artificial Turf
Surface texture achieved by inverting a section of artificial turf that is attached to a device that allows control of the time and rate of texturing.

Asphalt
A brown to black bituminous substance that is chiefly obtained as a residue of petroleum refining and that consists mostly of hydrocarbons.

ASR
See, Alkali-Silica Reaction

ASTM
American Society for Testing and Materials

B

Backer Rod
Foam cord that inserts into a joint sealant reservoir and is used to shape a liquid joint sealant and prevent sealant from adhering to or flowing out of the bottom of the reservoir.

Bag (of cement)
A quantity of cement; 42.6 kg in the United States, 39.7 kg in Canada; portland or air-entraining portland cement, or as indicated on the bag for other kinds of cement.

Ball Test
A test to determine the consistency of fresh concrete by measuring the depth of penetration of a steel ball. The apparatus is usually called a Kelly ball.

Bar
A member used to reinforce concrete, usually made of steel.

Barrel (of cement)
A unit of weight for cement: (170.6 kg) net, equivalent to 4 US bags for portland or air-entraining portland cements, or as indicated by the manufacturer for other kinds of cement. (In Canada, 158.8 kg. net per barrel.)

Base
The underlying stratum on which a concrete slab, such as a pavement, is placed.

Base Course
A layer of specified select material of planned thickness constructed on the subgrade or subbase below a pavement to serve one or more functions such as distributing loads, providing drainage, minimizing frost action, or facilitating pavement construction.

Batch
Quantity of concrete or mortar mixed at one time.

Batch Plant
Equipment used for batching concrete materials.

Batch Weights
The weights of the various materials (cement, water, the several sizes of aggregate, and admixtures) that compose a batch of concrete.

Batched Water
The mixing water added to a concrete or mortar mixture before or during the initial stages of mixing.

Batching
Weighing or volumetrically measuring and introducing into the mixer the ingredients for a batch of concrete or mortar.

Beam Test
A method of measuring the flexural strength (modulus of rupture) of concrete by testing a standard unreinforced beam.

Binder
See Cement Paste

Blast-Furnace Slag
The non-metallic byproduct, consisting essentially of silicates and aluminosilicates of lime and other bases, which is produced in a molten condition simultaneously with iron in a blast furnace.

Bleeding
The self-generated flow of mixing water within, or its emergence from, freshly placed concrete or mortar.

Bleeding Rate
The rate at which water is released from a paste or mortar by bleeding, usually expressed as cubic centimeters of water released each second from each square centimeter of surface.

Blended Cement
See Cement, Blended

Blended Hydraulic Cement
See Cement, Blended

Blistering
The irregular rising of a thin layer of placed mortar or concrete at the surface during or soon after completion of the finished operation.

Bond
The adhesion of concrete or mortar to reinforcement or other surfaces against which it is placed; the adhesion of cement paste to aggregate.

Bond Area
The interface area between two elements across which adhesion develops or may develop, as between concrete and reinforcing steel.

Bond Breaker
A material used to prevent adhesion of newly placed concrete from other material, such as a substrate.

Bond Hardness
The support (bond strength) that the metal matrix in a diamond saw blade segment provides to each diamond that is embedded within the matrix.

Bond Strength
Resistance to separation of mortar and concrete from reinforcing steel and other materials with which it is in contact; a collective expression for all forces such as adhesion, friction due to shrinkage, and longitudinal shear in the concrete engaged by the bar deformations that resist separation.

Bond Stress
The force of adhesion per unit area of contact between two surfaces such as concrete and reinforcing steel or any other material such as foundation rock.

Bonded Concrete Overlay
Thin layer of new concrete 5 to 10 cm (2 to 4 in.) placed onto slightly deteriorated existing concrete pavement with steps taken to prepare old surface to promote adherence of new concrete.

Bonding Agent
A substance applied to an existing surface to create a bond between it and a succeeding layer, as between a bonded overlay and existing concrete pavement.

Broom
The surface texture obtained by stroking a broom over freshly placed concrete. A sandy texture obtained by brushing the surface of freshly placed or slightly hardened concrete with a stiff broom.

Bulk Cement
Cement that is transported and delivered in bulk (usually in specially constructed vehicles) instead of in bags.

Bulk Density
The mass of a material (including solid particles and any contained water) per unit volume, including voids.

Bulk Specific Gravity
The ratio of the weight in air of a given volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the weight in air of an equal volume of distilled water at the same temperature.

Bulking Factor
Ratio of the volume of moist sand to the volume of the sand when dry.

Bull Float
A tool comprising a large, flat, rectangular piece of wood, aluminum, or magnesium usually 20 cm (8 in.) wide and 100 to 150 cm (39 to 60 in.) long, and a handle 1 to 5 m (1.1 to 5.5 yd) in length used to smooth unformed surfaces of freshly placed concrete.

Burlap
A coarse fabric of jute, hemp, or less commonly flax, for use as a water-retaining cover for curing concrete surfaces; also called Hessian.

Burlap Drag
Surface texture achieved by trailing moistened coarse burlap from a device that allows control of the time and rate of texturing.

C

Calcareous
Containing calcium carbonate, or less generally, containing the element calcium.

Calcium Chloride
A crystalline solid, $CaC1_2$; in various technical grades, used as a drying agent, as an accelerator of concrete, a deicing chemical, and for other purposes.

Calcium Lignosulfonate
An admixture, refined from papermaking wastes, employed in concrete to retard the set of cement, reduce water requirement and increase strength.

Caliche
Gravel, sand, or desert debris cement by porous calcium carbonate or other salts.

California Bearing Ratio
The ratio of the force per unit area required to penetrate a soil mass with a 19.4 cm^2 circular piston at the rate of 1.27 mm (.05 in.) per min to the force required for corresponding penetration of a standard crushed-rock base material; the ratio is usually determined at 2.5 mm (.10 in.) penetration.

California Profilograph
Rolling straight edge tool used for evaluating pavement profile (smoothness) consisting of a 25-ft frame with a sensing wheel located at the center of the frame that senses and records bumps and dips on graph paper or in a computer.

Capillary
In cement paste, any space not occupied by unhydrated cement or cement gel (air bubbles, whether entrained or entrapped, are not considered to be part of the cement paste).

Capillary Absorption
The action of surface tension forces which draws water into capillaries (i.e., in concrete) without appreciable external pressures.

Capillary Flow
Flow of moisture through a capillary pore system, such as concrete.

Capillary Space
In cement paste, any space not occupied by anhydrous cement or cement gel. (Air bubbles, whether entrained or entrapped, are not considered to be part of the cement paste.)

Carbonation
Reaction between carbon dioxide and the products of portland cement hydration to produce calcium carbonate.

Cast-In-Place
Concrete placed and finished in its final location.

Cement
See Portland Cement

Cement Content
Quantity of cement contained in a unit volume of concrete or mortar, ordinarily expressed as pounds, barrels, or bags per cubic yard.

Cement Factor
See Cement Content

Cement Paste
Constituent of concrete consisting of cement and water.

Cement, Blended
A hydraulic cement consisting essentially of an intimate and uniform blend of granulated blast-furnace slag and hydrated lime; or an intimate and uniform blend of portland cement and granulated blast-furnace slag cement and pozzolan, produced by intergrinding Portland cement clinker with the other materials or by blending Portland cement with the other materials, or a combination of intergrinding and blending.

Cement, Expansive
A special cement which, when mixed with water, forms a paste that tends to increase in volume at an early age; used to compensate for volume decrease due to drying shrinkage.

Cement, High Early-Strength
Cement characterized by producing earlier strength in mortar or concrete than regular cement, referred to in the United States as Type III.

Cement, Hydraulic
Cement that is capable of setting and hardening under water, such as normal portland cement.

Cement, Normal
General purpose portland cement, referred to in the United States as Type I.

Cement, Portland Pozzolan
A hydraulic cement consisting essentially of an intimate and uniform blend of portland cement or portland blast-furnace slag cement and fine pozzolan produced by intergrinding portland cement clinker and pozzolan, by blending portland cement or portland blast-furnace slag cement and finely divided pozzolan, or a combination of intergrinding and blending, in which the pozzolan constituent is within specified limits

Cement-Aggregate Ratio
The ratio, by weight or volume, of cement to aggregate.

Cementitious Materials
Substances that alone have hydraulic cementing properties (set and harden in the presence of water); includes ground, granulated blast-furnace slag, natural cement, hydraulic hydrated lime, and combinations of these and other materials.

Central Mixer
A stationary concrete mixer from which the fresh concrete is transported to the work.

Central-Mixed
Concrete that is completely mixed in a stationary mixer from which it is transported to the delivery point.

Chalking
A phenomenon of coatings, such as cement paint, manifested by the formation of a loose powder by deterioration of the paint at or just beneath the surface.

Coarse Aggregate
See Aggregate, Coarse

Coefficient of Thermal Expansion
Change in linear dimension per unit length or change in volume per unit volume per degree of temperature change.

Cohesion Loss
The loss of internal bond within a joint sealant material; noted by a noticeable tear along the surface and through the depth of the sealant.

Cohesiveness
The property of a concrete mix which enables the aggregate particles and cement paste matrix therein to remain in contact with each

other during mixing, handling, and placing operations; the "stick-togetherness" of the concrete at a given slump.

Combined Aggregate Grading
Particle size distribution of a mixture of fine and coarse aggregate.

Compacting Factor
The ratio obtained by dividing the observed weight of concrete which fills a container of standard size and shape when allowed to fall into it under standard conditions of test, by the weight of fully compacted concrete which fills the same container.

Compaction
The process whereby the volume of freshly placed mortar or concrete is reduced to the minimum practical space, usually by vibration, centrifugation, tamping, or some combination of these; to mold it within forms or molds and around embedded parts and reinforcement, and to eliminate voids other than entrained air. See also Consolidation.

Compression Test
Test made on a specimen of mortar or concrete to determine the compressive strength; in the United States, unless otherwise specified, compression tests of mortars are made on 50-mm (2-in.) cubes, and compression tests of concrete are made on cylinders 152 mm (6 in.) in diameter and 305 mm (12 in.) high.

Compressive Strength
The measured resistance of a concrete or mortar specimen to axial loading; expressed as pounds per square inch (psi) of cross-sectional area.

Concrete
A composite material that consists essentially of a binding medium in which is embedded particles or fragments of relatively inert material filler. In portland cement concrete, the binder is a mixture of portland cement and water; the filler may be any of a wide variety of natural or artificial aggregates.

Concrete Spreader
A machine designed to spread concrete from heaps already dumped in front of it, or to receive and spread concrete in a uniform layer.

Concrete, Normal-Weight
Concrete having a unit weight of approximately 2,400 kg/m^3 made with aggregates of normal weight.

Concrete, Reinforced
Concrete construction that contains mesh or steel bars embedded in it.

Consistency
The relative mobility or ability of fresh concrete or mortar to flow. The usual measures of consistency are slump or ball penetration for concrete and flow for mortar.

Consolidate
Compaction usually accomplished by vibration of newly placed concrete to minimum practical volume, to mold it within form shapes or around embedded parts and reinforcement, and to reduce void content to a practical minimum.

Consolidation
The process of inducing a closer arrangement of the solid particles in freshly mixed concrete or mortar during placement by the reduction of voids, usually by vibration, centrifugation, tamping, or some combination of these actions; also applicable to similar manipulation of other cementitious mixtures, soils, aggregates, or the like. See also Compaction.

Construction Joint
The junction of two successive placements of concrete, typically with a keyway or reinforcement across the joint.

Continuously Reinforced Pavement
A pavement with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints.

Contract
Decrease in length or volume. See also Expansion, Shrinkage, Swelling.

Contraction Joint
A plane, usually vertical, separating concrete in a structure of pavement, at a designated location such as to prevent formation of objectionable shrinkage cracks elsewhere in the concrete. Reinforcing steel is discontinuous.

Control Joint
See Contraction Joint

Core
A cylindrical specimen of standard diameter drilled from a structure or rock foundation to be bested in compression or examined petrographically.

Corner Break
A portion of the slab separated by a crack that intersects the adjacent transverse or longitudinal joints at about a 45° angle with the direction of traffic. The length of the sides is usually from 0.3 meters to one-half of the slab width on each side of the crack.

Course
In concrete construction, a horizontal layer of concrete, usually one of several making up a lift; in masonry construction, a horizontal layer of block or brick. See also Lift.

CPCD
Concrete pavement contraction design; term used in Texas for jointed plain concrete pavement (see JPCP).

Crack Saw
Small three-wheeled specialty saw useful for tracing the wandering nature of a transverse or longitudinal crack; usually contains a pivot wheel and requires a small diameter crack sawing blade.

Cracking
The process of contraction or the reflection of stress in the pavement.

Crazing
Minute surface pattern cracks in mortar or concrete due to unequal shrinkage or contraction on drying or cooling.

CRC Pavement (CRCP)
Continuously reinforced concrete pavement; see Continuously Reinforced Pavement.

Cross Section
The section of a body perpendicular to a given axis of the body; a drawing showing such a section.

Crushed Gravel
The product resulting from the artificial crushing of gravel with a specified minimum percentage of fragments having one or more faces resulting from fracture. See also Coarse Aggregate.

Crushed Stone
The product resulting from the artificial crushing of rocks, boulders, or large cobblestones, substantially all faces of which possess well-defined edges and have resulted from the crushing operation.

Crusher-Run Aggregate
Aggregate that has been broken in a mechanical crusher and has not been subjected to any subsequent screening process.

Cubic Yard
Normal commercial units of measure of concrete volume, equal to 27 ft^3.

Cure
Maintenance of temperature and humidity for freshly placed concrete during some definite period following placing and finishing to ensure proper hydration of the cement and proper hardening of the concrete.

Curing
The maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that desired properties may develop.

Curing Blanket
A built-up covering of sacks, matting, Hessian, straw, waterproof paper, or other suitable material placed over freshly finished concrete. See also Burlap.

Curing Compound
A liquid that can be applied as a coating to the surface of newly placed concrete to retard the loss of water or, in the case of pigmented compounds, also to reflect heat so as to provide an opportunity for the concrete to develop its properties in a favorable temperature and moisture environment. See also Curing.

D

Damp
Either moderate absorption or moderate covering of moisture; implies less wetness than that connoted by “wet,” and slightly wetter than that connoted by “moist.” See also Moist and Wet.

Deformed Bar
A reinforcing bar with a manufactured pattern of surface ridges that provide a locking anchorage with surrounding concrete.

Deformed Reinforcement
Metal bars, wire, or fabric with a manufactured pattern of surface ridges that provide a locking anchorage with surrounding concrete.

Density
Mass per unit volume; by common usage in relation to concrete, weight per unit volume, also referred to as unit weight.

Density (dry)
The mass per unit volume of a dry substance at a stated temperature. See also Specific Gravity.

Density Control
Control of density of concrete in field construction to ensure that specified values as determined by standard tests are obtained.

Design Strength
Load capacity of a member computed on the basis of allowable stresses assumed in design.

Deterioration
1) Physical manifestation of failure (e.g., cracking delamination, flaking, pitting, scaling, spalling, staining) caused by environmental or internal autogenous influences on rock and hardened concrete as well as other materials.

2) Decomposition of material during either testing or exposure to service. See also Disintegration and Weathering.

Diamond Grinding
The process used to remove the upper surface of a concrete pavement to remove bumps and restore pavement rideability; also, equipment using many diamond-impregnated saw blades on a shaft or arbor to shave the surface of concrete slabs.

Dispersing Agent
Admixtures capable of increasing the fluidity of pastes, mortar or concretes by reduction of inter-particle attraction.

Distress
Physical manifestation of deterioration and distortion in a concrete structure as the result of stress, chemical action, and/or physical action.

Dolomite
A mineral having a specific crystal structure and consisting of calcium carbonate and magnesium carbonate in equivalent chemical amounts (54.27 and 45.73 percent by weight, respectively); a rock containing dolomite as the principal constituent.

Dowel
1) A load transfer device, commonly a plain round steel bar, which extends into two adjoining portions of a concrete construction, as at a joint in a pavement slab, so as to transfer shear loads.

2) A deformed reinforcing bar intended to transmit tension, compression, or shear through a construction joint.

Dowel Bar (Dowelbar)
See Dowel

Dowel Bar Retrofit (DBR)
See Retrofit Dowel Bars

Dowel Basket
See Load-Transfer Assembly

Drainage
The interception and removal of water from, on, or under an area or roadway; the process of removing surplus ground or surface water artificially; a general term for gravity flow of liquids in conduits.

Dry Process
In the manufacture of cement, the process in which the raw materials are ground, conveyed, blended, and stored in a dry condition. See also Wet Process.

Dry Mix
Concrete, mortar, or plaster mixture, commonly sold in bags, containing all components except water; also a concrete of near zero slump.

Dry Mixing
Blending of the solid materials for mortar or concrete prior to adding the mixing water.

Drying Shrinkage
Contraction caused by drying.

Durability
The ability of concrete to remain unchanged while in service; resistance to weathering action, chemical attack, and abrasion.

Dynamic Load
A variable load; i.e., not static, such as a moving live load, earthquake, or wind.

Dynamic Loading
Loading from units (particularly machinery) which, by virtue of their movement or vibration, impose stresses in excess of those imposed by their dead load.

E

Early Strength
Strength of concrete developed soon after placement, usually during the first 72 hours.

Early-Entry Dry Saw
Lightweight saw equipped with a blade that does not require water for cooling and that allows sawing concrete sooner than with conventional wet-diamond sawing equipment.

Econocrete
Portland cement concrete designed for a specific application and environment and, in general, making use of local commercially produced aggregates. These aggregates do not necessarily meet conventional quality standards for aggregates used in pavements.

Edge Form
Formwork used to limit the horizontal spread of fresh concrete on flat surfaces, such as pavements or floors.

Edger
A finishing tool used on the edges of fresh concrete to provide a rounded edge.

Efflorescence
Deposit of calcium carbonate (or other salts), usually white in color, appearing upon the surface or found within the near-surface pores of concrete. The salts deposit on concrete upon evaporation of water that carries the dissolved salts through the concrete toward exposed surfaces.

Entrained Air
Round, uniformly distributed, microscopic, non-coalescing air bubbles entrained by the use of air-entraining agents; usually less than 1 mm (.04 in.) in size.

Entrapped Air
Air in concrete that is not purposely entrained. Entrapped air is generally considered to be large voids (larger than 1 mm [.04 in.]).

Equivalent Single Axle Loads (ESALs)
Summation of equivalent 18,000-pound single axle loads used to combine mixed traffic to design traffic for the design period.

Evaporable Water
Water set in cement paste present in capillaries or held by surface forces; measured as that removable by drying under specified conditions.

Expansion
Increase in length or volume. See also Autogenous Volume Change, Contraction, Moisture Movement, Shrinkage, and Volume Change.

Expansion Joint
See Isolation Joint

Exposed Aggregate
Surface texture where cement paste is washed away from concrete slab surface to expose durable chip-size aggregates for the riding surface.

Exposed Concrete
Concrete surfaces formed so as to yield an acceptable texture and finish for permanent exposure to view. See also Architectural Concrete.

External Vibrator
See Vibration

F

False Set
The rapid development of rigidity in a freshly mixed portland cement paste, mortar, or concrete without the evolution of much heat, which rigidity can be dispelled and plasticity regained by further mixing without addition of water; premature stiffening, hesitation set, early stiffening, and rubber set are terms referring to the same phenomenon, but false set is the preferred designation.

Fast-Track
Series of techniques to accelerate concrete pavement construction.

Faulting
Differential vertical displacement of a slab or other member adjacent to a joint or crack.

FHWA
Federal Highway Administration

Fibrous Concrete
Concrete containing dispersed, randomly oriented fibers.

Field-Cured Cylinders
Test cylinders cured as nearly as practicable in the same manner as the concrete in the structure to indicate when supporting forms may be removed, additional construction loads may be imposed, or the structure may be placed in service.

Final Set
A degree of stiffening of a mixture of cement and water greater than initial set, generally stated as an empirical value indicating the time in hours and minutes required for a cement paste to stiffen sufficiently to resist to an established degree, the penetration of a weighted test needle; also applicable to concrete and mortar mixtures with use of suitable test procedures. See also Initial Set.

Final Setting Time
The time required for a freshly mixed cement paste, mortar, or concrete to achieve final set. See also Initial Setting Time.

Fine Aggregate
Aggregate passing the 9.5-mm (3/8-in.) sieve and almost entirely passing the 4.75-mm (#4) sieve and predominantly retained on the 75-mm (#200) sieve.

Finish
The texture of a surface after compacting and finishing operations has been performed.

Finishing
Leveling, smoothing, compacting, and otherwise treating surfaces of fresh or recently placed concrete or mortar to produce desired appearance and service. See also Float and Trowel.

Finishing Machine
A power-operated machine used to give the desired surface texture to a concrete slab.

Fixed Form Paving
A type of concrete paving process that involves the use of fixed forms to uniformly control the edge and alignment of the pavement.

Flash Set
The rapid development of rigidity in a freshly mixed portland cement paste, mortar, or concrete, usually with the evolution of considerable heat, which rigidity cannot be dispelled nor can the plasticity be regained by further mixing without addition of water; also referred to as quick set or grab set.

Flexible Pavement
A pavement structure that maintains intimate contact with and distributes loads to the subgrade and depends on aggregate interlock, particle friction, and cohesion for stability; cementing agents, where used, are generally bituminous (asphaltic) materials as contrasted to portland cement in the case of rigid pavement. See also Rigid Pavement.

Flexural Strength
A property of a material or structural member that indicates its ability to resist failure in bending. See also Modulus of Rupture.

Float
A tool (not a darby) usually of wood, aluminum, or magnesium, used in finishing operations to impart a relatively even but still open texture to an unformed fresh concrete surface.

Float Finish
A rather rough concrete surface texture obtained by finishing with a float.

Floating
Process of using a tool, usually wood, aluminum, or magnesium, in finishing operations to impart a relatively even but still open texture to an unformed fresh concrete surface.

Flow
1) Time dependent irrecoverable deformation. See Rheology.

2) A measure of the consistency of freshly mixed concrete, mortar, or cement paste in terms of the increase in diameter of a molded truncated cone specimen after jigging a specified number of times.

Flow Cone Test
Test that measures the time necessary for a known quantity of grout to completely flow out of and empty a standard sized cone; usually used in slab stabilization to determine the water quantity necessary for stabilization grout.

Fly Ash
The finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the fire box through the boiler by flu gasses; used as mineral admixture in concrete mixtures.

Form
A temporary structure or mold for the support of concrete while it is setting and gaining sufficient strength to be self-supporting.

Free Moisture
Moisture having essentially the properties of pure water in bulk; moisture not absorbed by aggregate. See also Surface Moisture.

Free Water
See Free Moisture and Surface Moisture

Full-Depth Patching
Removing and replacing at least a portion of a concrete slab to the bottom of the concrete, in order to restore areas of deterioration.

Full-Depth Repair
See Full-Depth Patching

G

Gap-Graded Concrete
Concrete containing a gap-graded aggregate.

Gradation
See Grading

Grading
The distribution of particles of granular material among various sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sizes (sieve openings) or the percentages between certain ranges of sizes (sieve openings).

Gravel
Granular material predominantly retained on the 4.75 mm (#4)

sieve and resulting from natural disintegration and abrasion of rock or processing of weakly bound conglomerate.

Green Concrete
Concrete that has set but not appreciably hardened.

Green Sawing
The process of controlling random cracking by sawing uniform joint spacing in early age concrete, without tearing or dislocating the aggregate in the mix.

Grooving
The process used to cut slots into a concrete pavement surface to provide channels for water to escape beneath tires and to promote skid resistance.

Gross Vehicle Load
The weight of a vehicle plus the weight of any load thereon.

Gross Volume (of concrete mixers)
In the case of a revolving-drum mixer, the total interior volume of the revolving portion of the mixer drum; in the case of an open-top mixer, the total volume of the trough or pan calculated on the basis that no vertical dimension of the container exceeds twice the radius of the circular section below the axis of the central shaft.

H

Hairline Cracking
Barely visible cracks in random pattern in an exposed concrete surface which do not extend to the full depth or thickness of the concrete, and which are due primarily to drying shrinkage.

Hardening
When portland cement is mixed with enough water to form a paste, the compounds of the cement react with water to form cementitious products that adhere to each other and to the intermixed sand and stone particles and become very hard. As long as moisture is present, the reaction may continue for years, adding continually to the strength of the mixture.

Harsh Mixture
A concrete mixture that lacks desired workability and consistency due to a deficiency of mortar.

Harshness
Deficient workability and cohesiveness caused by insufficient sand or cement, or by improperly graded aggregate.

Header
A transverse construction joint installed at the end of a paving operation or other placement interruptions. To a contractor, a header is the location at which paving will resume on the next day.

Heat of Hydration
Heat evolved by chemical reactions of a substance with water, such as that evolved during the setting and hardening of portland cement.

Heavy-Weight Aggregate
An aggregate of very high unit weight, such as barium, boron, or iron ore, steel shot or punchings, which forms a high density mortar of concrete when bound together with hardened cement paste.

Heavy-Weight Concrete
Concrete in which heavy aggregate is used to increase the density of the concrete; unit weights in the range of 165 to 330 lb/ft^3 are attained.

High Range Water-Reducing Admixture
See Water-Reducing Admixture (high range)

High Early-Strength Cement
See Cement, High Early-Strength

High Early-Strength Concrete
Concrete that, through the use of high-early-strength cement or admixtures, is capable of attaining specified strength at an earlier age than normal concrete.

Honeycomb
Concrete that, due to lack of the proper amount of fines or vibration, contains abundant interconnected large voids or cavities; concrete that contains honeycombs was improperly consolidated.

Horizontal-Axis Mixer
Concrete mixers of the revolving drum type in which the drum rotates about a horizontal axis.

Hot-Pour Sealant
Joint sealing materials that require heating for installation, usually consisting of a base of asphalt or coal tar.

Hydrated Lime
A dry powder obtained by treating quicklime with sufficient water to convert it to calcium hydroxide.

Hydration
The chemical reaction between cement and water which causes concrete to harden.

Hydraulic Cement
A cement that is capable of setting and hardening under water due to the chemical interaction of the water and the constituents of the cement.

Hydroplaning
To go out of steering control by skimming the surface of a wet road.

I

Incentive
Barely visible cracks in random pattern in an exposed concrete surface which do not extend to the full depth or thickness of the concrete, and which are due primarily to drying shrinkage.

Inclined-Axis Mixer
A truck with a revolving drum that rotates about an axis inclined to the bed of the truck chassis.

Incompressibles
Small concrete fragments, stones, sand or other hard materials that enter a joint sealant, joint reservoir, or other concrete pavement discontinuity.

Initial Set
A degree of stiffening of a mixture of cement and water less than

final set, generally stated as an empirical value indicating the time in hours and minutes required for cement paste to stiffen sufficiently to resist to an established degree the penetration of a weighted test needle; also applicable to concrete or mortar with use of suitable test procedures. See also Final Set.

Initial Setting Time
The time required for a freshly mixed cement paste to acquire an arbitrary degree of stiffness as determined by specific test.

Inlay
A form of reconstruction where new concrete is placed into an area of removed pavement; The removal may be an individual lane, all lanes between the shoulders or only partly through a slab.

Isolation Joint
A pavement joint that allows relative movement in three directions and avoids formation of cracks elsewhere in the concrete and through which all or part of the bonded reinforcement is interrupted. Large closure movement to prevent development of lateral compression between adjacent concrete slabs; usually used to isolate a bridge.

J

Joint
A plane of weakness to control contraction cracking in concrete pavements. A joint can be initiated in plastic concrete or green concrete and shaped with later process.

Joint Depth
The measurement of a saw cut from the top of the slab to the bottom of the cut.

Joint Deterioration
See Spalling, Compression

Joint Filler
Compressible material used to fill a joint to prevent the infiltration of debris and to provide support for sealant.

Joint Sealant
Compressible material used to minimize water and solid debris infiltration into the sealant reservoir and joint.

Joint Shape Factor
Ratio of the vertical to horizontal dimension of the joint sealant reservoir.

Joint, Construction
See Construction Joint

Joint, Contraction
See Contraction Joint

Joint, Expansion
See Expansion Joint

Jointed Plain Concrete Pavement (JPCP)
Pavement containing enough joints to control all natural cracks expected in the concrete; steel tiebars are generally used at longitudinal joints to prevent joint opening, and dowel bars may be used to enhance load transfer at transverse contraction joints depending upon the expected traffic.

Jointed Reinforced Concrete Pavement (JRCP)
Pavement containing some joints and embedded steel mesh reinforcement (sometimes called distributed steel) to control expected cracks; steel mesh is discontinued at transverse joint locations.

K

Keyway
A recess or groove in one lift or placement of concrete, which is filled with concrete of the next lift, giving shear strength to the joint. See also Tongue and Groove.

L

Laitance
A layer of weak material containing cement and fines from aggregates, brought to the top of overwet concrete, the amount of which is generally increased by overworking and over-manipulating concrete at the surface by improper finishing.

Layer
See Course

Lean Concrete
Concrete of low cement content.

Life-Cycle Cost Analysis
The process used to compare projects based on their initial cost, future cost and salvage value, which accounts for the time value of money.

Lift
The concrete placed between two consecutive horizontal construction joints, usually consisting of several layers or courses.

Liquid Sealant
Sealant materials that install in liquid form and cool or cure to their final properties; rely on long-term adhesion to the joint reservoir faces.

Load Transfer Device
See Dowel

Load Transfer Efficiency
The ability of a joint or crack to transfer a portion of a load applied on the side of the joint or crack to the other side of the joint or crack.

Load Transfer Restoration (LTR)
See Retrofit Dowel Bars

Load-Transfer Assembly
Most commonly, the basket or carriage designed to support or link dowel bars during concreting operations so as to hold them in place, in the desired alignment.

Longitudinal Broom
Surface texture achieved in similar manner as transverse broom, except that broom is pulled in a line parallel to the pavement centerline.

Longitudinal Joint
A joint parallel to the long dimension of a structure or pavement.

Longitudinal Reinforcement
Reinforcement essentially parallel to the long axis of a concrete member or pavement.

Longitudinal Tine
Surface texture achieved by a hand held or mechanical device equipped with a rake-like tining head that moves in a line parallel to the pavement centerline.

Lot
A defined quantity.

M

M-E PDG
Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavements (NCHRP 2004).

Map Cracking
1) Intersecting cracks that extend below the surface of hardened concrete; caused by shrinkage of the drying surface concrete which is restrained by concrete at greater depths where either little or no shrinkage occurs; vary in width from fine and barely visible to open and well-defined.

2) The chief symptom of chemical reaction between alkalis in cement and mineral constituents in aggregate within hardened concrete; due to differential rate of volume change in different portions of the concrete; cracking is usually random and on a fairly large scale, and in severe instances the cracks may reach a width of ½-in. See also Crazing and Pattern Cracking.

Maximum Size Aggregate
The largest size aggregate particles present in sufficient quantity to affect properties of a concrete mixture.

Membrane Curing
A process that involves either liquid sealing compound (e.g., bituminous and paraffinic emulsions, coal tar cut-backs, pigmented and non-pigmented resin suspensions, or suspensions of wax and drying oil) or non-liquid protective coating (e.g., sheet plastics or “waterproof” paper), both of which types function as films to restrict evaporation of mixing water from the fresh concrete surface.

Mesh
The number of openings (including fractions thereof) per unit of length in either a screen or sieve in which the openings are 6 mm (¼-in.) or less.

Mesh Reinforcement
See Welded-Wire Fabric Reinforcement

Method and Material Specification
Specification that directs the contractor to use specified materials in definite proportions and specific types of equipment and methods to place the material.

Mix
The act or process of mixing; also mixture of materials, such as mortar or concrete.

Mix Design
See Proportioning

Mixer
A machine used for blending the constituents of concrete, grout, mortar, cement paste, or other mixture.

Mixer, Batch
See Batch Mixer

Mixer, Transit
See Truck Mixer

Mixing Cycle
The time taken for a complete cycle in a batch mixer; i.e., the time elapsing between successive repetitions of the same operation (e.g., successive discharges of the mixer).

Mixing Plant
See Batch Plant

Mixing Speed
Rotation rate of a mixer drum or of the paddles in an open-top, pan, or trough mixer, when mixing a batch; expressed in revolutions per minute (rpm), or in peripheral feet per minute of a point on the circumference at maximum diameter.

Mixing Time
The period during which the mixer is combining the ingredients for a batch of concrete. For stationary mixers, the time is measured from the completion of batching cement and aggregate until the beginning of discharge. For truck mixers, mixing is given in term of the number of revolutions of the drum at mixing speed.

Mixing Water
The water in freshly mixed sand-cement grout, mortar, or concrete, exclusive of any previously absorbed by the aggregate (e.g., water considered in the computation of the net water-cement ratio). See also Batched Water and Surface Moisture.

Mixture
The assembled, blended, commingled ingredients of mortar, concrete, or the like, or the proportions for their assembly.

Modulus of Rupture
A measure of the ultimate load-carrying capacity of a beam, sometimes referred to as “rupture modulus” or “rupture strength.” It is calculated for apparent tensile stress in the extreme fiber of a transverse test specimen under the load that produces rupture. See also Flexural Strength.

Moist
Slightly damp but not quite dry to the touch; the term “wet” implies visible free water, “damp” implies less wetness than “wet,” and “moist” implies not quite dry. See also Damp and Wet.

Moisture Barrier
A vapor barrier.

Moisture Content of Aggregate
The ratio, expressed as a percentage, of the weight of water in a given granular mass to the dry weight of the mass.

Moisture-Free
The condition of a material that has been dried in air until there is no further significant change in its mass. See also Ovendry.

Mortar
Concrete with essentially no aggregate larger than about 3/16 inch.

Mud Balls
Balls of clay or silt ("mud").

N

Natural Sand
Sand resulting from natural disintegration and abrasion of rock. See also Sand and Aggregate, Fine.

NCHRP
National Cooperative Highway Research Program

NHI
National Highway Institute

Nominal Maximum Size (of aggregate)
In specifications for and descriptions of aggregate, the smallest sieve opening through which the entire amount of the aggregate is permitted to pass; sometimes referred to as "maximum size (of aggregate)."

Non-Agitating Unit
A truck-mounted container for transporting central-mixed concrete that is not equipped to provide agitation (slow mixing) during delivery; a dump truck.

Non-Air-Entrained Concrete
Concrete in which neither an air-entraining admixture nor an air-entraining cement has been used.

No-Slump Concrete
Concrete with a slump of 6 mm (¼-in.) or less. See also Zero-Slump Concrete.

NRMCA
National Ready Mixed Concrete Association

O

Open-Graded Subbase
Unstabilized layer consisting of crushed aggregates with a reduced amount of fines to promote drainage.

Ovendry
The condition resulting from having been dried to essentially constant weight, in an oven, at a temperature that has been fixed, usually between 105 and 115ºC (221 and 239ºF).

Overlay
The addition of a new material layer onto an existing pavement surface. See also Resurfacing

Overlay, Bonded
See Bonded Concrete Overlay

Overlay, Unbonded
See Unbonded Concrete Overlay

Overlay, UTW
See Ultra-Thin Whitetopping

Overlay, Whitetopping
See Whitetopping

Over-Sanded
Containing more sand than would be required for adequate workability and satisfactory finishing characteristics.

Over-Vibrated
Concrete vibrated more than is necessary for good consolidation and elimination of entrapped air.

Over-Wet
The consistency of concrete when it contains more mixing water and hence is of greater slump than is necessary for ready consolidation.

P

Particle-Size Distribution
The division of particles of a graded material among various sizes; for concrete materials, usually expressed in terms of cumulative percentages larger or smaller than each of a series of diameters or the percentages within certain ranges of diameter, as determined by sieving.

Paste
Constituent of concrete consisting of cement and water.

Pattern Cracking
Fine openings on concrete surfaces in the form of a pattern; resulting from a decrease in volume of the material near the surface, an increase in volume of the material below the surface, or both.

Pavement (concrete)
A layer of concrete over such areas as roads, sidewalks, canals, airfields, and those used for storage or parking. See also Rigid Pavement.

Pavement Structure
The combination of surface courses and base/subbase courses placed on a prepared subgrade to support the traffic load.

Paving Train
An assemblage of equipment designed to place and finish a concrete pavement.

PCA
Portland Cement Association

PCC
Portland cement concrete

Pea Gravel
Screened gravel the particle sizes of which range between 3/16 and 3/8 inch in diameter.

Percent Fines
Amount, expressed as a percentage, of material in aggregate finer than a given sieve, usually the 75-mm (#200) sieve; also, the amount of fine aggregate in a concrete mixture expressed as a percent by absolute volume of the total amount of aggregate.

Performance-Based Specification
Specification that describes the desired levels of fundamental engineering properties (for example, resilient modulus and/or fatigue properties) that are predictors of performance and appear in primary prediction relationships (i.e., models that can be used to predict pavement stress, distress, or performance from combinations of predictors that represent traffic, environmental, roadbed, and structural conditions).

Performance-Related Specification
Specification that describes the desired levels of key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance. These characteristics (for example, strength of concrete cores) are amenable to acceptance testing at the time of construction.

Permeable Subbase
Layer consisting of crushed aggregates with a reduced amount of fines to promote drainage and stabilized with portland cement or bituminous cement.

Phasing
The sequences used by a contractor to build elements of a project.

Pitting
A localized disintegration taking the form of cavities at the surface of concrete.

Placement
The process of placing and consolidating concrete; a quantity of concrete placed and finished during a continuous operation; also inappropriately referred to as "pouring."

Placing
The deposition, distribution, and consolidation of freshly mixed concrete in the place where it is to harden; also inappropriately referred to as "pouring."

Plain Bar
A reinforcing bar without surface deformations, or one having deformations that do not conform to the applicable requirements.

Plain Concrete
Concrete without reinforcement.

Plain Pavement
Concrete pavement with relatively short joint spacing and without dowels or reinforcement.

Plane of Weakness
The plane along which a body under stress will tend to fracture; may exist by design, by accident, or because of the nature of the structure and its loading.

Plastic
Condition of freshly mixed cement paste, mortar, or concrete such that deformation will be sustained continuously in any direction without rupture; in common usage, concrete with slump of 80 to 100 mm (3 to 4 in.).

Plastic Consistency
A condition of freshly mixed concrete such that it is readily remoldable and workable, cohesive, and has an ample content of cement and fines, but is not over-wet.

Plastic Cracking
Cracking that occurs in the surface of fresh concrete soon after it is placed and while it is still plastic.

Plastic Deformation
Deformation that does not disappear when the force causing the deformation is removed.

Plastic Shrinkage Cracking
Cracks, usually parallel and only a few inches deep and several feet long, in the surface of concrete pavement that are the result of rapid moisture loss through evaporation.

Plasticity
That property of fresh concrete or mortar which determines its resistance to deformation or its ease of molding.

Plasticizer
A material that increases the plasticity of a fresh cement paste, mortar, or concrete.

Pneumatic
Moved or worked by air pressure.

Popout
Pit or crater in the surface of concrete resulting from cracking of the mortar due to expansive forces associated with a particle of unsound aggregate or a contaminating material, such as wood or glass.

Porosity
The ratio, usually expressed as a percentage, of the volume of voids in a material to the total volume of the material, including voids.

Portland Cement
A commercial product which when mixed with water alone or in combination with sand, stone, or similar materials, has the property of combining with water, slowly, to form a hard solid mass. Physically, portland cement is a finely pulverized clinker produced by burning mixtures containing lime, iron, alumina, and silica at high temperature and in definite proportions, and then intergrinding gypsum to give the properties desired.

Portland Cement Concrete
A composite material that consists essentially of a binding medium (portland cement and water) within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate course aggregate.

Portland-Pozzolan Cement
See Cement, Portland Pozzolan

Pozzolan
A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Pozzolan-Cement Grout
Common slab stabilization grout consisting of water, portland cement and pozzolan; usually fly ash.

Preformed Compression Seal
Joint sealant that is manufactured ready for installation and is held

in a joint by lateral pressure exerted against the reservoir by the seal after being compressed during installation.

Preservation
The process of maintaining a structure in its present condition and arresting further deterioration. See also Rehabilitation, Repair, and Restoration.

Pressure-Relief
Cut made in a concrete pavement to relieve compressive forces of thermal expansion during hot weather.

Process Control
Those quality assurance actions and considerations necessary to assess production and construction processes so as to control the level of quality being produced in the end product. This includes sampling and testing to monitor the process but usually does not include acceptance sampling and testing.

Profile Index
Smoothness qualifying factor determined from profilograph trace. Calculated by dividing the sum of the total counts above the blanking band for each segment by the sum of the segment length.

Profile Line
On a profile trace, line drawn by hand on the field trace to average out spikes and minor deviations caused by rocks, texturing, dirt or transverse grooving.

Project Scoping
An early planning step in the development of a project where all project requirements are defined and a plan is developed to address them.

Proportioning
Selection of proportions of ingredients for mortar or concrete to make the most economical use of available materials to produce mortar or concrete of the required properties.

PSI
1) Pounds per square inch; a measure of the compressive, tensile or flexural strength of concrete as determined by appropriate test.

2) In pavements, the Performance Serviceability Index.

Pumping
The forceful displacement of a mixture of soil and water that occurs under slab joints, cracks and pavement edges which are depressed and released quickly by high-speed heavy vehicle loads; occurs when concrete pavements are placed directly on fine-grained, plastic soils or erodible subbase materials.

Punchout
In continuously reinforced concrete pavement, the area enclosed by two closely spaced transverse cracks, a short longitudinal crack, and the edge of the pavement or longitudinal joint, when exhibiting spalling, shattering, or faulting. Also, area between Y cracks exhibiting this same deterioration.

Q

QA/QC
See, Quality Assurance and Quality Control

Quality Assurance
Planned and systematic actions by an owner or his representative to provide confidence that a product or facility meet applicable standards of good practice. This involves continued evaluation of design, plan and specification development, contract advertisement and award, construction, and maintenance, and the interactions of these activities.

Quality Assurance/Quality Control Specification
Statistically based specification that is a combination of end result and material and method specifications. The contractor is responsible for quality control (process control), and the highway agency is responsible for acceptance of the product.

Quality Control
Actions taken by a producer or contractor to provide control over what is being done and what is being provided so that the applicable standards of good practice for the work are followed.

R

Radius of Relative Stiffness
A character or property of a concrete slab which measures the stiffness of the slab in relation to that of the subgrade; it is expressed by the equation:

$$l = \sqrt[4]{\frac{E_c h^3}{12(1-\mu^2)k}}$$

Random Crack
See Uncontrolled Crack

Raveling
Displacement of aggregate or paste near the slab surface from sawing; normally indicates that concrete strength is too low for sawing.

Reactive Aggregate
Aggregate containing certain silica or carbonate compounds that are capable of reacting with alkalis in portland cement, in some cases producing damaging expansion of concrete.

Ready-Mixed Concrete
Concrete manufactured for delivery to a purchaser in a plastic and unhardened state.

Rebar
Abbreviation for "reinforcing bar." See Reinforcement.

Rebound Hammer
An apparatus that provides a rapid indication of the mechanical properties of concrete based on the distance of rebound of a spring-driven missile.

Reconstruction
The process of removing an existing pavement from its grade and replacing it with a completely new pavement.

Recycled Concrete
Concrete that has been processed for use, usually as aggregate.

Recycling
The act of processing existing pavement material into usable material for a layer within a new pavement structure.

Rehabilitation
The process of repairing or modifying a structure to a desired useful condition. See also Preservation, Repair, and Restoration.

Reinforced Concrete
Concrete containing adequate reinforcement (prestressed or not prestressed) and designed on the assumption that the two materials act together in resisting forces.

Reinforcement
Bars, wires, strands, and other slender members embedded in concrete in such a manner that the reinforcement and the concrete act together in resisting forces.

Reinforcement, Transverse
Reinforcement at right angles to the longitudinal reinforcement; may be main or secondary reinforcement.

Relative Humidity
The ratio of the quantity of water vapor actually present to the amount present in a saturated atmosphere at a given temperature; expressed as a percentage.

Release Agent
Material used to prevent bonding of concrete to a surface. See also Bond Breaker.

Remoldability
The readiness with which freshly mixed concrete responds to a remolding effort, such as jigging or vibration, causing it to reshape its mass around reinforcement and to conform to the shape of the form. See also Flow.

Repair
To replace or correct deteriorated, damaged, or faulty materials, components, or elements of a structure. See also Preservation, Rehabilitation, and Restoration.

Reservoir
The part of a concrete joint that normally holds a sealant material. Usually a widening saw cut above the initial saw cut.

Restoration
The process of reestablishing the materials, form, and appearance of a structure to those of a particular era of the structure. See also Preservation, Rehabilitation, and Repair.

Resurfacing
The addition of a new material layer onto an existing pavement surface for the purposes of correcting a functional factor, such as smoothness or texture.

Retardation
Reduction in the rate of hardening or strength development of fresh concrete, mortar, or grout; i.e., an increase in the time required to reach initial and final set.

Retarder
An admixture that delays the setting of cement and hence of mixtures such as mortar or concrete containing cement.

Retempering
Addition of water and remixing of concrete or mortar that has lost enough workability to become unplaceable or unusable. See also Tempering.

Retrofit Dowel Bars
Dowels that install into slots cut into the surface of an existing concrete pavement.

Revibration
A second vibration applied to fresh concrete, preferably as long after the first vibration as the concrete will still respond properly.

Rheology
The science of dealing with flow of materials, including studies of deformation of hardened concrete, the handling and placing of freshly mixed concrete, and the behavior of slurries, pastes, and the like.

Ribbon Loading
Method of batching concrete in which the solid ingredients, and sometimes the water, enter the mixer simultaneously.

Rich Mixture
A concrete mixture containing a large amount of cement.

Rigid Pavement
Pavement that will provide high bending resistance and distribute loads to the foundation over a comparatively large area.

Rock Pocket
A portion of hardened concrete consisting of a concentration of coarse aggregate that is deficient in mortar; caused by separation during placement or insufficient consolidation, or both; see Honeycomb.

Rod
A specified length of metal, circular in cross section with one end rounded; used to compact concrete or mortar test specimens.

Rod, Tamping
A straight steel rod of circular cross section having one or both ends rounded to a hemispherical tip.

Rodability
The susceptibility of fresh concrete or mortar to compaction by means of a tamping rod.

Rodding
Compaction of concrete by means of a tamping rod. See also Rod, Tamping, and Rodability.

S

Sack
See Bag

Sample
A group of units, or portion of material, taken from a larger collection of units or quantity of material, which serves to provide information that can be used as a basis for action on the larger quantity or on the production process; the term is also used in the sense of a sample of observations.

Sampling, Continuous
Sampling without interruptions throughout an operation or for a predetermined time.

Sampling, Intermittent
Sampling successively for limited periods of time throughout an operation or for a predetermined period of time. The duration of sample periods and of the intervals between are not necessarily regular and are not specified.

Sand
The fine granular material (usually less than 3/16 inch in diameter) resulting from the natural disintegration of rock, or from the crushing of friable sandstone.

Sand Grout
Grout mixture containing water, portland cement, and sand.

Sand Streak
A streak of exposed fine aggregate in the surface of formed concrete caused by bleeding.

Saturated Surface-Dry
Condition of an aggregate particle or other porous solid when the permeable voids are filled with water but there is no water on the exposed surface.

Saturated Surface-Dry (SSD) Particle Density
The mass of the saturated surface-dry aggregate divided by its displaced volume in water or in concrete. (Also called Bulk Specific Gravity).

Saturation
1) In general, the condition of the coexistence in stable equilibrium of either a vapor and a liquid or a vapor and solid phase of the same substance at the same temperature.

2) As applied to aggregate or concrete, the condition such that no more liquid can be held or placed within it.

Saw Blade, Abrasive
Concrete sawing medium that uses non-diamond abrasion elements. These blades do not need water to cool, but water is sometimes used.

Saw Blade, Diamond
Concrete sawing medium that uses industrial diamonds as the primary abrasion element. Blades are cooled with water to protect the host metal from melting and prematurely dislodging the diamonds.

Saw Cut
A cut in hardened concrete utilizing diamond or silicone-carbide blades or discs.

Sawed Joint
A joint cut in hardened concrete, generally not to the full depth of the member, by means of special equipment.

Sawing
Cutting of joints in hardened concrete by means of special equipment utilizing diamond or silicon carbide blades or discs; cut goes only part way through the slab.

Scaling
Flaking or peeling away of the near-surface portion of hydraulic cement concrete or mortar.

Schmidt Hammer (trade name), Swiss Hammer, or Rebound Hammer
A device used to estimate the compressive strength of hardened concrete by measuring surface hardness.

Scoping
See Project Scoping

Screed
1) To strike off concrete lying above the desired plane or shape.

2) A tool for striking off the concrete surface, sometimes referred to as a Strikeoff.

Screed Guide
Firmly established grade strips or side forms for unformed concrete that will guide the strikeoff in producing the desired plane or shape.

Screeding
The operation of forming a surface by the use of screed guides and a strikeoff. See also Strikeoff.

Sealant
See Joint Sealant and Membrane Curing

Sealant Reservoir
The saw kerf or formed slot in which a joint sealant is placed. Many times this refers to a cut made to widen the original saw cut made for a contraction joint.

Sealing
The process of filling the sawed joint with material to minimize intrusion into the joint of water and incompressible materials.

Sealing Compound
See Joint Sealant and Membrane Curing

Secondary Sawing
The sawing that takes place to establish shape in the joint. Many times this shape is the reservoir of the joint.

Segregation
The tendency, as concrete is caused to flow laterally, for coarse aggregate and drier material to remain behind and for mortar and wetter material to flow ahead. This also occurs in a vertical direction when wet concrete is over-vibrated, the mortar and wetter material rising to the top. In the vertical direction, segregation may also be called Stratification.

Semiautomatic Batcher
A batcher equipped with gates or valves that are separately opened manually to allow the material to be weighed but which are closed automatically when the designated weight of each material has been reached.

Separation
The tendency, as concrete is caused to pass from the unconfined ends of chutes or conveyor belts, for coarse aggregate to separate from the concrete and accumulate at one side; the tendency, as processed aggregate leaves the ends of conveyor belts, chutes, or similar devices with confining sides, for the larger aggregate to separate from the mass and accumulate at one side; the tendency for solids to separate from the water by gravitational settlement. See also Bleeding and Segregation.

Set
The condition reached by a cement paste, mortar, or concrete when it has lost plasticity to an arbitrary degree, usually measured in terms of resistance to penetration or deformation. Initial set refers to first stiffening. Final set refers to attainment of significant rigidity.

Set-Accelerating Admixture
See Accelerator

Set-Retarding Admixture
See Retarder

Setting of Cement
Development of rigidity of cement paste, mortar, or concrete as a result of hydration of the cement. The paste formed when cement is mixed with water remains plastic for a short time. During this stage it is still possible to disturb the material and remix without injury, but as the reaction between the cement and water continues, the mass loses its plasticity. This early period in the hardening is called the "setting period," although there is not a well-defined break in the hardening process.

Setting Time
The time required for a specimen of concrete, mortar or cement paste, prepared and tested under standardized conditions, to attain a specified degree of rigidity.

Settlement
Sinking of solid particles in grout, mortar, or fresh concrete, after placement and before initial set. See also Bleeding.

Settlement Shrinkage
A reduction in volume of concrete prior to the final set of cementitious mixtures; caused by settling of the solids and decreases in volume due to the chemical combination of water with cement. See Plastic Shrinkage.

Shrinkage
Decrease in length or volume.

Shrinkage Crack
Crack from restraint of volume reduction due to shrinkage or temperature contraction; usually occurring within the first few days after placement.

Shrinkage Cracking
Cracking of a slab due to failure in tension caused by external or internal restraints as reduction in moisture content develops.

Shrink-Mixed Concrete
Ready-mixed concrete mixed partially in a stationary mixer and then mixed in a truck mixer.

Sieve
A metallic plate or sheet, a woven-wire cloth, or other similar device, with regularly spaced apertures of uniform size, mounted in a suitable frame or holder for use in separating granular material according to size.

Sieve Analysis
The classification of particles, particularly of aggregates, according to sizes as determined with a series of sieves of different openings.

Silicone
A resin, characterized by water-repellent properties, in which the main polymer chain consists of alternating silicon and oxygen atoms, with carbon-containing side groups; silicones may be used in joint sealing compounds, caulking or coating compounds, or admixtures for concrete.

Silicone Sealant
Liquid joint sealant consisting of silicone-based material.

Skid Resistance
A measure of the frictional characteristics of a surface.

Slipform Paving
A type of concrete paving process that involves extruding the concrete through a machine to provide a uniform dimension of concrete paving.

Slipform
A form that is pulled or raised as concrete is placed; may move in a generally horizontal direction to lay concrete evenly for highway paving or on slopes and inverts of canals, tunnels, and siphons; or vertically to form walls, bins, or silos.

Slump
A measure of consistency of freshly mixed concrete, equal to the subsidence measured to the nearest 6 mm (¼-in.) of the molded specimen immediately after removal of the slump cone.

Slump Cone
A mold in the form of the lateral surface of the frustum of a cone with a base diameter of 203 mm (8 in.), top diameter 102 mm (4 in.), and height 305 mm (12 in.), used to fabricate a specimen of freshly mixed concrete for the slump test.

Slump Loss
The amount by which the slump of freshly mixed concrete changes during a period of time after an initial slump test was made on a sample or samples thereof.

Slump Test
The procedure for measuring slump.

Slurry
Mixture of water and concrete particles resulting from concrete sawing or grinding.

Solid Volume
See Absolute Volume

Sounding
Process of tapping concrete slab surface with metal object, listening for tone from the impact, to determine areas of delamination.

Soundness
In the case of a cement, freedom from large expansion after setting. In the case of aggregate, the ability to withstand aggressive conditions to which concrete containing it might be exposed, particularly those due to weather.

Spalling, Compression
Cracking, breaking, chipping, or fraying of slab edges within 0.6 meter of a transverse joint.

Spalling, Sliver
Chipping of concrete edge along a joint sealant; usually within 12 mm of the joint edge.

Spalling, Surface
Cracking, breaking, chipping, or fraying of slab surface; usually within a confined area less than 0.5 square meters.

Specific Gravity
The ratio of the weight in air of a given volume of material at a stated temperature to the weight in air of an equal volume of distilled water at the same temperature.

Specific Gravity Factor
The ratio of the weight of aggregates (including all moisture), as introduced into the mixer, to the effective volume displaced by the aggregates.

Split Batch Charging
Method of charging a mixer in which the solid ingredients do not all enter the mixer together; cement, and sometimes different sizes of aggregate, may be added separately.

Spud Vibrator
A vibrator used for consolidating concrete, having a vibrating casing or head that is used by insertion into freshly placed concrete.

Standard Deviation
The root mean square deviation of individual values from their average.

Static Load
The weight of a single stationary body or the combined weights of all stationary bodies in a structure (such as the load of a stationary vehicle on a roadway); during construction, the combined weight of forms, stringers, joists, reinforcing bars, and the actual concrete to be placed.

Stationary Hopper
A container used to receive and temporarily store freshly mixed concrete.

Storage Hopper
See Stationary Hopper

Straight-Edging
Process of using a rigid, straight piece of either wood or metal to strike off or screed a concrete surface to proper grade or to check the planeness of a finished surface.

Stratification
The separation of over-wet or over-vibrated concrete into horizontal layers with increasingly lighter material toward the top; water, laitance, mortar, and coarse aggregate will tend to occupy successively lower positions (in that order).

Strength
A generic term for the ability of a material to resist strain or rupture induced by external forces. See also Compressive Strength, Flexural Strength, and Tensile Strength.

Stress
Intensity of internal force (i.e., force per unit area) exerted by either of two adjacent parts of a body on the other across an imagined plane of separation; when the forces are parallel to the plane, the stress is called shear stress; when the forces are normal to the plane the stress is called normal stress; when the normal stress is directed toward the part on which it acts it is called compressive stress; when it is directed away from the part on which it acts it is called tensile stress.

Strikeoff
To remove concrete in excess of that required to fill the form evenly or bring the surface to grade; performed with a straightedged piece of wood or metal by means of a forward sawing movement or by a power operated tool appropriate for this purpose; also the name applied to the tool. See also Screed and Screeding.

Structural Capacity
Expression of the ability of a pavement to carry traffic loads; Expressed as number of equivalent single axle loads in AASHTO design methodology.

Subbase
A layer in a pavement system between the subgrade and base course or between the subgrade and a portland cement concrete pavement.

Subgrade
The soil prepared and compacted to support a structure or a pavement system. Also sometimes called grade.

Sulfate Attack
Chemical or physical reaction between certain constituents in cement and sulfates in the soil or groundwater; sufficient attack may disrupt concrete that is susceptible to it.

Sulfate Resistance
The ability of aggregate, cement paste, or mixtures thereof to withstand chemical attack by sulfate ion in solution.

Superplasticizer
See Water-Reducing Admixture (high range)

Supplementary Cementitious Material
Mineral admixtures consisting of powdered or pulverized materials, which are added to concrete before or during mixing to improve or change some of the plastic or hardened properties of Portland cement concrete. Materials are generally natural or by-products of other manufacturing processes.

Surface Moisture
Water retained on surfaces of aggregates capable of mixing with portland cement in concrete; distinguished from absorbed moisture, which is contained inside the aggregate particles.

Surface Retarder
A retarder used by application to a form or to the surface of newly placed concrete to delay setting of the cement to facilitate construction joint cleanup or to facilitate production of exposed, aggregate finish.

Surface Tension
That property, due to molecular forces, that exists in the surface film of all liquids and tends to prevent the liquid from spreading.

Surface Texture
Degree of roughness or irregularity of the exterior surfaces of aggregate particles or hardened concrete.

Surface Vibrator
A vibrator used for consolidating concrete by application to the top surface of a mass of freshly mixed concrete; four principal types exist: vibrating screeds, pan vibrators, plate or grid vibratory tampers, and vibratory roller screeds.

Surface Voids
Cavities visible on the surface of a solid.

Surface Water
See Surface Moisture

Swelling
Increase in length or volume. See also Contraction and Expansion.

T

Tamper
1) An implement used to consolidate concrete or mortar in molds or forms.

2) A hand-operated device for compacting floor topping or other unformed concrete by impact from the dropped device in preparation for strikeoff and finishing; contact surface often consists of a screen or a grid of bars to force coarse aggregates below the surface to prevent interference with floating or troweling.

Tamping
The operation of compacting freshly placed concrete by repeated blows or penetrations with a tamping device.

Temper
The addition of water and mixing of concrete or mortar as necessary to bring it initially to the desired consistency. See also Retempering.

Tensile Strength
Maximum stress that a material is capable of resisting under axial tensile loading based on the cross-sectional area of the specimen before loading.

Terminal Joint
Joint used in continuously reinforced concrete pavement (see CRCP) to transition to another pavement type or to a bridge structure.

Texturing
The process of producing a special texture on either unhardened or hardened concrete.

Thermal Expansion
Expansion caused by increase in temperature.

Thermal Movement
Change of dimension of concrete or masonry resulting from change of temperatures. See also Contraction and Expansion.

Thermal Shock
The subjection of newly hardened concrete to a rapid change in temperature which may be expected to have a potentially deleterious effect.

Tiebar
Bar at right angles to and tied to reinforcement to keep it in place; deformed bar extending across a construction joint to prevent separation of adjoining slabs.

Time of Haul
In production of ready-mixed concrete, the period from first contact between mixing water and cement until completion of discharge of the freshly mixed concrete.

Time of Set
Time required after addition of water to cement for cement paste, mortars, or concretes to attain a certain arbitrary degree of hardness or strength.

Time of Setting
See Initial Setting Time and Final Setting Time.

TMMB
Truck Mixer Manufacturers' Bureau; most truck mixers carry TMMB rating plates.

Tongue and Groove
A joint in which a protruding rib on the edge of one side fits into a groove in the edge of the other side, abbreviated "T & G." See also Keyway.

Topping
1) A layer of high quality concrete placed to form a floor surface on a concrete base.

2) A dry-shake application of a special material to produce particular surface characteristics.

Transit-mixed Concrete
Concrete, the mixing of which is wholly or principally accomplished in a truck mixer. See Truck-Mixed Concrete.

Transverse Broom
Surface texture obtained using either a hand broom or mechanical broom that lightly drags the stiff bristles across the surface.

Transverse Crack
Crack that develops at a right angle to the long direction of the member.

Transverse Joint
A joint normal to the longitudinal dimension of a structure.

Transverse Reinforcement
See Reinforcement, Transverse.

Transverse Tine
Surface texture achieved by a hand held or mechanical device equipped with a rake-like tining head that moves laterally across the width of the paving surface.

TRB
Transportation Research Board

Trial Batch
A batch of concrete used for establishing or checking proportions.

Trowel
A flat, broad-bladed steel hand tool used in the final stages of finishing operations to impart a relatively smooth surface to concrete floors and other unformed concrete surfaces; also, a flat triangular-bladed tool used for applying mortar to masonry.

Truck-Mixed Concrete
Concrete, the mixing of which is accomplished in a truck mixer.

Truck Mixer
A concrete mixer suitable for mounting on a truck chassis and capable of mixing concrete in transit. See also Horizontal-Axis Mixer, Inclined-Axis Mixer, and Agitator.

U

Ultra-Thin Whitetopping
Thin layer of new concrete (2-4 inches), usually high strength and fiber-reinforced, placed over a prepared surface of distressed asphalt

Unbonded Concrete Overlay
Overlay of new concrete placed onto distressed existing concrete pavement with a layer of asphalt or other medium between the new and old concrete surface to separate them.

Uncontrolled Crack
A crack that is located within a slab away from the sawed joints.

Under-Sanded
A concrete mixture that is deficient in sand content; a condition associated with poor workability or finishing characteristics.

Unit Water Content
The quantity of water per unit volume of freshly mixed concrete, often expressed as pounds or gallons per cubic yard. It is the quantity of water on which the water-cement ratio is based and does not include water absorbed by the aggregate.

Unit Weight
See Bulk Density and Specific Gravity

Unreinforced Concrete
See Plain Concrete

Unsound Aggregate
An aggregate or individual particles of an aggregate capable of causing or contributing to deterioration or disintegration of concrete under anticipated conditions of service.

Uplift Beam
Beam-like movement detection device used to monitor slab lift during slab stabilization.

V

Vibrated Concrete
Concrete compacted by vibration during and after placing.

Vibration
Energetic agitation of concrete produced by a mechanical oscillating device at moderately high frequency to assist consolidation and compaction.

Vibration Limit
That time at which fresh concrete has hardened sufficiently to prevent its becoming mobile when subject to vibration.

Vibration, External
External vibration employs vibrating devices attached at strategic positions on the forms and is particularly applicable to manufacture of precast items and for vibration of tunnel-lining forms; in manufacture of concrete products, external vibration or impact may be applied to a casting table.

Vibration, Internal
Internal vibration employs one or more vibrating elements that can be inserted into the concrete at selected locations, and is more generally applicable to in-place construction.

Vibration, Surface
Surface vibration employs a portable horizontal platform on which a vibrating element is mounted.

Vibrator
An oscillating machine used to agitate fresh concrete so as to eliminate gross voids, including entrapped air but no entrained air, and produce intimate contact with form surfaces and embedded materials.

Vibratory Plate Compactor
Motorized, one-man tool consisting of a vibrating square plate that transmits energy to compact granular mate rials.

Volume Batching
The measuring of the constituent materials for mortar or concrete by volume.

W

Wash (or Flush) Water
Water carried on a truck mixer in a special tank for flushing the interior of the mixer after discharge of the concrete.

Water-Cement Ratio
The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of portland cement in a concrete or mortar mixture; preferably stated as a decimal by weight.

Water-Cementitious Materials Ratio
The ratio of the amount of water, exclusive only of that absorbed by the aggregates, to the amount of portland cement and other cementitious material (fly ash, pozzolan, etc.) in a concrete or mortar mixture; preferably stated as a decimal by weight.

Water-Gain
See Bleeding

Water-Reducing Admixture
A material that either increases slump of freshly mixed mortar or concrete without increasing water content or maintains a workability with a reduced amount of water, the effect being due to factors other than air entrainment; also known as water reducer.

Water-Reducing Admixture (High Range)
A water-reducing admixture capable of producing large water or great flowability without causing undue set retardation or entrainment of air in mortar or concrete.

Weathering
Changes in color, texture, strength, chemical composition or other properties of a natural or artificial material due to the action of the weather.

Weight Batching
Measuring the constituent materials for mortar or concrete by weight.

Welded-Wire Fabric Reinforcement
Welded-wire fabric in either sheets or rolls, used to reinforce concrete.

Well-Graded Aggregate
Aggregate having a particle size distribution that will produce maximum density; i.e., minimum void space.

Wet
Covered with visible free moisture; not dry. See also Damp and Moist.

Wet Process
In the manufacture of cement, the process in which the raw materials are ground, blended, mixed, and pumped while mixed with water; the wet process is chosen where raw materials are extremely wet and sticky, which would make drying before crushing and grinding difficult.

Whitetopping
Concrete overlay pavement placed on an existing asphalt pavement.

Whitetopping, Conventional
Overlay of new concrete, greater than 4 inches thick, placed onto existing asphalt pavement with no particular steps taken to ensure bonding or debonding.

Whitetopping, Ultra-Thin
See Ultra-Thin Whitetopping

Wire Mesh
See Welded Wire Fabric

Workability
That property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished.

Working Crack
A crack in a concrete pavement slab that undergoes significant deflection and thermal opening and closing movements; Typically oriented transverse to the pavement centerline and near a non-functioning transverse contraction joint.

Y

Yield
The volume of fresh concrete produced from a known quantity of ingredients; the total weight of ingredients divided by the unit weight of the freshly mixed concrete.

Zero-Slump Concrete
Concrete of stiff or extremely dry consistency showing no measurable slump after removal of the slump cone. See also Slump and No-Slump Concrete.

Abbreviated Index

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