INTRODUCTION

In the early sixties, the then Louisiana Department of Highways initiated an aggressive study to determine the extent of variability encountered in three broad categories of materials and construction - Asphaltic Concrete, Portland Cement Concrete (PCC) and Soil and Aggregate Base Course (*1, 2, 3*)*. The major thrust towards this study was to develop statistically based specifications commensurate with variability generally associated with the production processes of these three categories of materials and/or construction.

This initial effort resulted in simulation of asphaltic concrete specifications (*4*). Implementation of these specifications occurred in 1971 with subsequent evaluation of these specifications in 1975 (*5*). Portland Cement concrete (PCC) specifications were implemented in 1973 followed by their evaluation in 1979 (*6*).

In 1978, the Louisiana Department of Transportation and Development (DOTD) implemented a computerized system (the **MAT**erial **T**est Data Reporting System or, simply, the **MATT** system) of reporting and archiving material and construction test data (*7*). This implementation envisioned periodic evaluation of such archived data with a view to enhance the overall system of quality control (QC)/quality assurance (QA) on a continuing basis. However, such evaluation never materialized with volumes of MATT system data remaining unevaluated. It was not until 1996, almost 25 years after specification implementation and 20 years after the last such evaluation (*6*), that DOTD launched a formal study to determine the current status of QA/QC of asphaltic concrete materials and construction (*8*).

To continue this evaluation momentum, the DOTD awarded a contract to Southern University of Baton Rouge, through Request For Proposal (RFP) solicitation, to evaluate the overall QA/QC program of concrete construction and determine if specifications changes are needed to enhance concrete QA/QC program. This report discusses the accomplishments of Tasks 1 through 3 of Phase 1 of the study work plan. These tasks are defined in the next section under Objectives and Scope.

(*) - Underlined italic numbers in parenthesis refer to list of references

OBJECTIVES AND SCOPE

I Objectives

The broad objective of this study is to evaluate DOTD's MATT system data generated by statistically based specifications for paving and structural concrete. Specific objectives are:

1. Evaluate the MATT system data generated by current specifications on paving and structural concrete materials and construction;

2. Based on above evaluation, determine if specification changes are needed to enhance current QA/QC program; and

3. Evaluate the feasibility of using acceptance sampling using Percent Within Tolerance (PWL) concept.

4. Although not specifically required in the proposal, identify noise in MATT System data and make appropriate recommendations to rectify and enhance the system.

II Scope

In scope, the study will be limited to:

1. MATT system data since the implementation of the 1992 specifications;

2. Analysis and evaluation of slump, air content and compressive strength measurements of structural concrete;

3. Analysis and evaluation of thickness, strength and profile (smoothness) measurements of paving concrete.

WORK PLAN

The three objectives defined above are to be accomplished through two separate phases with three distinct tasks within each phase as follows:

Phase 1

Task 1. **Literature search** - Review literature pertinent to stated objectives

Task 2. **Evaluation of the current DOTD concrete specifications and test procedures -** In this task, Louisiana's current specifications on materials and construction are to be reviewed in light of other agencies requirements for acceptance. In that respect, there may be an overlap with Task 1, Literature Search.

Task 3. **Analysis of MATT system data -** This task is the crux of the study and involves review of master MATT system data files on paving and structural concrete, retrieval of pertinent records from these files, development of separate data base of these files, analysis and evaluation of acquired data and, lastly, submission of an interim report.

Phase 2 This phase is to commence upon DOTD approval to proceed based on findings and recommendations in interim report

Task 4. Development of proposed revised or additional criteria for QA/QC.

Task 5. Formulation of Percent Within Limits (PWL) specification and concurrent specification changes.

Task 6. Submit final report and associated material for implementation of recommendations.

Report Format -

This report is divided into ten sections. To better understand the results of the analysis, it is necessary to provide an understanding of the variability concept and its relationship to specifications.

This is discussed in the next section. The accomplishments of ***Task 1, Literature search*** and ***Task 2, Evaluation of Current Specifications*** are discussed in Section 5. Section 6 will discuss the data collection phase relative to database development from the MATT system files and an overview of the type of analysis and the tools used to analyze the data. Assessment of price adjustments is discussed in Section 7 followed by variability analysis in section 8. Section 9 deals with the operating characteristic curves of the current acceptance plans. Summary, conclusions and recommendations make up the last portion of this report.

BASIC STATISTICAL QUALITY CONTROL CONCEPTS

Frequency Distribution -

In this section some basic concepts of variability are presented to better understand the quality control and quality assurance procedures, and how these procedures relate to specifications. An appropriate starting point is the understanding of frequency distribution which is one of the most commonly used methods of describing pictorially variations of measurements from within a sample. In examining data of such type, it will be found that the individual data points group themselves about the central value so that there are roughly equal number of measurements on either side of this central value. The curve resulting from this distribution has the typical bell shape and is called the Normal Curve as shown in Figure 4.1. Figure 4.2 is an example of the actual distribution of structure concrete strength data collected for this study. In such curves small divergences occur more frequently than large ones. Also, these curves are unimodal, i.e., have one peak, and are symmetrical. This is one of the most important distributions and forms the basis for applying QA specifications. It is simple and can be defined in terms of two attributes - the mean and standard deviation. Understanding of these two properties, and some of the other properties associated with this normal distribution curve, is important since all these will be referred to later in the data analysis portion of this report.

Figure 4.1: A symmetrical or bell shaped curve

<u>The Mean</u> - This is a measure of central tendency of a group of measurements. It can be determined by summing the individual observations and dividing by the number of observations, thus:

Mean, $\overline{X} = \sum X_i / n$ where, X_i = individual observations, and
n = number of observations in a group.

Figure 4.2: Frequency distribution of compressive strength of concrete cores

The Standard Deviation - This property of the normal distribution signifies the spread or dispersion of a group of measurements from it's mean. It has the following form:

Standard Deviation, σ ***(sigma)*** $= \sqrt{\sum (X_i - \bar{X})^2/(n-1)}$ where, X_i and n are as before.

Thus, two curves can have the same mean and yet have different variability or spread for the same property. This is shown in Figure 4.3 where curve B has more spread than curve A. The standard deviation is expressed in the same unit as the unit representing the measured property.

The Variance - this measure is the basic measure of variability and is the square of the standard deviation.

Figure 4.3: Two normal curves with different variabilities

The Standard Error - this is the standard deviation of the mean of several samples and is estimated by:

$$\sigma_{\bar{x}} = \sigma / \sqrt{n}$$

On the basis of this relationship, it is apparent that the distribution of sample means will be narrower (less spread) than the individual measurements.

The Coefficient of Variation - This property is sometimes used as a relative measure of variability. It is expressed as a percent and is calculated thus:

$$CV = (\sigma / \bar{x}) \text{ x } 100$$

This measure is widely used in Portland Cement Concrete (PCC) strength evaluation to determine the magnitude of control maintained on concrete production *(9)*.

Skewness - As mentioned before, acceptance plans require that the samples representing the population be normally distributed. Although many construction characteristics have been shown to be normally distributed, it is not always obvious by mere observation of the distribution. Skewness is one measure of testing for normality (or non-normality). The measure of skewness is a pure number and may be either positive or negative. If the distribution has a longer tail toward the higher values (toward the right on the x-axis), it is said to have positive skew. If the longer tail extends towards the lower values, it is said to have negative skewness. Figure 4.4 shows the symmetrical bell shaped and the two types of skewed curves. It is important to determine if the skewness does in fact exist in the collected data since, as mentioned before, standard statistical methods used in QA/QC analysis are not applicable for skewed distribution. Most values of skewness are less than ±1 for a normally distributed property.

Figure 4.4: Symmetrical and skewed distributions

Relationship between Specifications and Statistical Parameters -

One of the most useful applications of the normal curve is in the development of specifications.

Since the normal curve is symmetric about the mean, the area under the curve is one. Because of the symmetry, 50% of the area will be above the mean and 50% below the mean. Furthermore, the proportion of area under the curve between any two values can be completely determined by the mean and standard deviation. The proportion of area under ±1, ±2, and ±3 standard deviations from the mean are shown in Figure 4.5.

The simplest form of specifications often use 2σ limits to specify tolerances for quality control and/or acceptance. Thus, for specification for slump of concrete that has a standard deviation of 0.8 inches, the limits could be the design slump plus and minus 1.6 inches. Under the assumption that the slump measurements are normally distributed, one can expect about five percent of the slumps to fall outside the two limits.

Types of Specifications -

Variability Known specifications

Most of the specifications developed in the early 60s and 70s were based on the ***variability known*** or ***sigma known*** concept. In these type of specifications acceptance and/or rejection was based on the mean of the measured characteristic. Such specifications are simple in nature and requires little, if any, statistical background for its application.

Figure 4.5: The percentages of areas within certain sigma (σ) limits

In these type specifications, two sigma units are generally used to specify the tolerance limits within which the measured characteristic, either individual or the mean, should fall for it to be accepted.

This type of specification works well if the variability can be maintained at the level originally used to develop the tolerance limits. Louisiana's current specifications are based on this ***variability known*** concept.

Variability Unknown Specifications -

Unlike the previous type specification where the historical (or assumed) standard deviation is used to accept the lot mean, this type of specification uses both the mean of sample size n (lot) and the standard deviation of the sample or lot. A major advantage of the ***unknown sigma*** sampling plan is that it induces an incentive for the contractor to reduce his process variability. A disadvantage is that it requires computation of standard deviation of each lot.

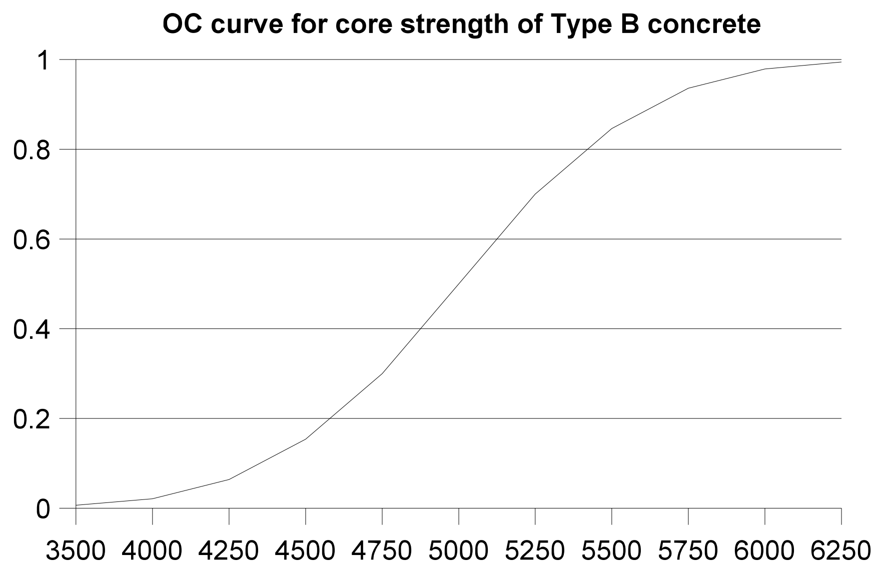
The acceptance plan for this type of specification is based on the quality level analysis suggested in the AASHTO guide specifications *(10)*. Briefly, this quality level analysis involves determination of two statistics - the mean and standard deviation of a lot of certain sample size n. From these two statistics and the governing specification limit(s) for the test property, Quality Level Indices (Q_U for upper quality index and Q_L for lower quality index) are calculated. The resulting values are checked against tabled values for the sample size to determine ***Percent Within Limits*** or ***PWL***. The lot, represented by the sample, is considered in conformance to the specifications if the ***PWL*** exceeds some preset value.

Acceptable Quality Level(AQL) and Rejectable Quality Level(RQL) -

In developing specifications, it is necessary to define exactly what is desired in terms of acceptable quality. This is the AQL or the acceptable quality level that yields product quality that should be accepted almost all of the time. Likewise, to guard against defective work, it is also necessary to define the quality that should be rejected almost all of the time. This is the RQL or the rejectable quality level. The levels at which AQL and RQL are selected depends on the criticality of the measured characteristic in terms of its performance.

Operating Characteristic (OC) Curve

The OC curve is a graphical representation of the acceptance plan developed from AQL and RQL. It is a presentation of the sampling technique which shows the relationship between the quality of the lot and the probability of its acceptance. An OC curve indicates how well a given plan discriminates between acceptable and non-acceptable lots. There is a relationship between AQL, RQL, and the OC curve. This is shown in Figure 4.6. The development of this curve is discussed in detail in section 8.



Prob of accept

Compressive strength, psi

Figure 4.6: A typical OC curve with AQL and RQL

LITERATURE SEARCH

The driving force in the development of statistically based specification was the Bureau of Public Roads (BPR) of the Federal Highway Administration (FHWA). One of their earlier publications (*11*) discussed the concepts of quality assurance for several major items of highway construction and materials. The major purpose of this publication was to introduce the application of the statistical concepts to highway agencies.

Unlike asphaltic concrete, the design, development and implementation of statistically based specifications for concrete has been a low key effort by states. As such, literature on the design and application of such specifications is not as widespread as for asphaltic concrete. A primary reason has been that the concrete industry has had good handle on the quality control of fresh concrete, relative to production, sampling and testing, through the assistance of American Concrete Institute (ACI) standards.

An important aspect of this literature search was the review of tests used by other states for quality assurance, and the statistical measures used for control and/or acceptance of concrete. The following information was extracted from TRIS, TRB, FHWA, AASHTO, and ACI.

States QA/QC Practices -

Louisiana was one of the pioneers in the development of statistically-based specifications on three major categories of materials and construction **- Asphaltic Concrete, Portland Cement Concrete(PCC), and Soil and Aggregate Base Courses** (*1*, *2*, *3*). For PCC, the specifications were developed in 1966 from historical data for compressive strength and slump of structural concrete and roadway core strength and thickness of paving concrete (*3*). Implementation of these specifications occurred in 1973. Roadway profile requirements for pavements were introduced at a later date.

State practices regarding specific concrete materials and construction properties (tests) for quality control/quality assurance are quite varied between states. For example, almost all states consider Air Content most important. Some give a higher rating to slump as it is considered an important reflection of water-cement ratio. Likewise, compressive strength and slab thickness are considered important parameters for pay factor considerations. Some states also consider flexure test as important as compressive strength. Results of such ratings of various concrete materials and construction tests by states were reported in the NCHRP Synthesis report and are shown in Table 5.1(*12*). A large majority of states consider most of the tests important (rating of 1).

It is interesting to note from the survey shown in Table 5.1 that most states considered air content of fresh concrete and slump more important than any other test. Likewise, a large number of states consider smoothness important to the comfort of the public but not to durability. Five states do not measure this property.

Another important aspect of the literature search has been the review of the states' practices relative to quality assurance tests they specify for pay factors. Table 5.2 lists such practices for states participating in the FHWA Pooled Fund Study (*13*). What type of statistical measures states use for control/acceptance of concrete? In some cases, these statistical measures for control and/or acceptance can range from the simple range, to some complex form of Quality Index determination. Within this range of parameters, states have a broad choice of using the mean, absolute deviation, running average, percent defective, percent within limits (PWL) and a host of other statistics. Table 5.3 (*11*) shows the choice of statistical parameters that the various states use in their QA/QC program.

Table 5.1: Summary of PCC Tests Ratings for Various States

Test	Number of States Giving Rating of a/				
	1	2	3	4	5
Physical Tests on Cement	31		10	1	
Chemical Tests on Cement	32		3		2
Aggregate Gradation for Concrete	22		17	1	1
Aggregate Soundness	35		3		1
Air-Content of Fresh Concrete	41		1		
Slump	30		7	3	
Cylinder Compressive Strength	25		9		2
Other Strengths					
Flexure Strength	11		6	2	1
Splitting Tensile Strength			2		
Thickness of Hardened Concrete	22	2	13		1
Pavement Smoothness b/	1	31	2		

a/ Rating: 1 - Very important - failure could affect durability
2 - Important to public comfort but probably no effect on durability
3 - Important for contractual compliance; however, "normal" deviations not likely to affect performance
4 - Important during construction phase only. Not important to performance
5 - Other purpose

b/- Five States do not measure this property

In Table 5.2, the majority of the states, including Louisiana, that are participating in the pooled fund study specify compressive strength and thickness of pavement as important criteria for pay purpose (pay factor). Of the 19 states listed, six states have three separate criteria for pay purpose and one state measures as many as four different properties for determination of final pay.

Although the states have a choice of several measures of statistical parameters on which to base acceptance and/or control of concrete construction, the most common measure that is specified is the ***mean***. This is shown in Table 5.3 from the pooled fund study (13). Other measure that is gaining widespread use is the ***Percent Within Limits*** or, simply, ***PWL***. Both these widely used concepts for acceptance have pluses and minuses as was discussed in the previous section. Other measures used by the states are also shown in this table.

Table 5.2: Concrete Properties Measured for Pay Factors by States

State	Measured Property							
	Density	Thickness	St Edge Index	Flexure Strength	Smoothness	Profile Index	Compressive Strength	Air Content
CO		X					X	
FL							X	
IA		X		X	X			
IL		X			X			
LA		X				X	X	
ME							X	X
MD		X				X		
MI							X	
MS		X					X	
NC	X	X	X	X				
NV		X				X	X	
NY	X	X						
OR		X			X		X	
PA		X					X	X
SC		X					X	
TX		X					X	
WA		X				X		
WI		X				X	X	
WY							X	X
19	2	15	1	2	3	5	13	3

From these three tables it is seen that Louisiana's testing requirements for assuring quality, and the statistical parameters used for acceptance of concrete construction follow the trend of majority of the states.

Table 5.3: Statistical Measures Used by States for Acceptance of

Concrete Construction

State	Running Avg	Percent Within Limits	Percent Defective	Avg Absolute Deviation	Mean	Mean & Std Dev	Quality Index	Range
CO							X	
FL					X			
IA							X	
IL	X				X			X
LA					X			
MD					X			
ME		X						
MI			X	X				
MS		X						
NC	X							X
NV	X			X	X			X
NY		X			X			
OR		X						
PA		X					X	
SC				X				
TX				X	X			
WA		X						
WI	X					X		X
WY		X					X	
19	4	7	1	4	7	1	4	4

Findings from the literature search on the most commonly defined tests for acceptance of concrete construction, as shown in Tables 5.2 and 5.3, are discussed below.

Variability of Portland Cement Concrete (PCC) Acceptance Tests

Cylinder and Pavement Core Strengths **-** Although strength is not always the most important characteristic of concrete, it is the one that is most often measured for acceptance and/or rejection of concrete production and construction. It is assumed to be indicative of the water-cement ratio and, accordingly, indicative of durability. The magnitude of variability in strength is, therefore, an indicator of the magnitude of variability of other characteristics.

Results of early studies by some states on compressive strengths variability are presented in Table 5.4 (*6*,*14*). These strength data show large standard deviation with average strengths well above the usual minimum of 3000 psi. Generally such wide variations are associated with lengthy production periods. It has also been observed that concrete used for incidental (minor structural) construction, where routine control is not as stringent as in major structural concrete production and placement, the variability is generally higher (*6*,*9*,*14*).

The variability in core strengths of concrete pavement can also show wide fluctuations than strength variability of 28-day cylinders for QC purposes. This is because the age of the cores can vary widely, from 30 days to as much as a year within the same project.

Table 5.4: Portland Cement Concrete Variations

State	Average Compressive Strength, psi a/	Type of Concrete	Standard Deviation, psi	Coefficient of Variation, cv
LA(*6*)	4842	General Structure	635	13.1
LA(*6*)	2982	Minor Structure	908	30.4
FL(*11*)	5054	General Structure	585	11.6
NY(*14*)	4410	“	756	17.3
IL(*14*)	4465	“	390	8.7
VA(*14*)	4840	“	660	13.6
ME(*14*)	5168	“	588	11.4
PA(*14*)	4647	“	699	15.1
LA(*6*)	5353	Paving (Cores)	1013	18.9
OH(*14*)	7403	“	1180	15.9
KS(*14*)	5166	“	689	13.3

a/ 28-day cylinder strengths for structural PCC
1 psi = 6.9 kpa

In addition to the material and sampling variation, there is testing variation that can contribute to large variation in compressive strengths. American Concrete Institute’s (ACI) 214-89 “Recommended Practice for Evaluation of Strength Results of Concrete” *(9)* provides some guidelines for determining the quality of a laboratory operation based on the within-test coefficient of variation. ACI 214-89 also provides guidelines for rating construction control for the total coefficient of variation values of compressive strengths. These rating values are shown in Table 5.5.

Table 5.5: ACI standards for concrete control

Class of Operation	CV for different control standards				
	Excellent	Very Good	Good	Fair	Poor
Over-all variation: General construction	Below 10.0		10 - 15	15 - 20	Above 20
Within-test variations: Field control	Below 3.0	3.0 - 4.0	4.0 - 5.0	5.0 - 6.0	Above 6.0

*** Variation in compressive strength between replicate cylinders tested by the same operator**

Pavement Thickness Variability **-** Large variations in pavement thickness are detrimental and uniformity in core thickness is important for better slab action and, therefore, prolonged pavement life. Variability in core thicknesses as reported by some states are shown in Table 5.6 (6,*14*,15). Statistically significant variations in thickness, between lots for a given project, have also been documented as shown in the same table. Uniformity in this quality characteristic is important to minimize early failures due to concentration of weaker points.

Table 5.6: Variation in PCC Pavement Thickness

State	Plan Thickness, in	Avg Thickness, in	Std Dev, in
LA(6)	8	8.52	0.50
LA	9	9.55	0.56
LA	10	10.35	0.41
OH(*14*)	9	9.21	0.32
OH	11	11.10	0.39
KS	9	9.21	0.32
GA	10	10.19	0.19
IL(*15*)	9	9.61(9.87)a/	0.24(0.17)
OH	8	8.11(8.21)	0.83(0.37)

a/ Between sub-lot values, 1 inch=25.4 mm

Pavement Smoothness Variability - Information on this construction property is limited since not very many states measure this property as indicated in Table 5.2. The method used to evaluate the ride quality has considerable influence on the variability of the measurements.

A study conducted at the University of Texas using the Ames profilograph showed standard deviation of 0.8 to 1.2 in/mile for the average of two results from the same profilograph (*14*). The report states that the overall variability is influenced by the operator of the profilograph variability and the interpreter variability.

Variability of Portland Cement Concrete (PCC) Control Tests

Slump - The slump test is more of a screening test to determine the consistency of the concrete mix. The results of these tests are a good indicator of mix uniformity. Results of studies by states have indicated that material variation contributes more to the overall variability than do sampling and testing (*11*). Depending on the range of specification requirements, the variability is generally between 0.5 to 0.8 inches for the cone method.

Air Content **-** Although a screening test, it is an important factor in the durability of pavements and bridge decks. Some states consider it important enough as acceptance test for pay purpose. Earlier studies by states showed that the air content using Chace meter gave somewhat higher contents than Pressure meter. The standard deviation ranges from 0.70 to 1.60 (*11*,*14*).

Summary

The purpose of this literature search was to identify the QA/QC tests and procedures states are using relative to Louisiana's QA/QC system. In that respect, it can be said that the current tests for acceptance of concrete construction, as defined in the standard specifications, follow the trend of majority of the states' system reviewed. Likewise, the statistical measures used by DOTD also follow majority of the states' measures for quality assurance and acceptance of concrete construction and tests. However, the review has also indicated the states' awareness of the need to minimize variability of individual lots. This is evident from Table 5.3 where there may be an increase in the number of states using the mean and standard deviation ***(sigma-unknown or PWL)*** concept for acceptance as an alternate to the more common statistical measure using the mean ***(sigma known)*** concept. The implementation of DOTD's Superpave asphaltic concrete specifications is based on this PWL concept and includes Quality Level Analysis for control and acceptance of mixes produced using Superpave design procedures. This quality level analysis is applied to validate job mix formulas, for project acceptance, and other QC procedures of contractors.

DATA COLLECTION AND ANALYSIS

In this section discussion relative to data collection, data base development and, finally, data analysis is presented. The governing DOTD's specifications applicable to data analysis are the 1992 specifications and are summarized in Appendix A *(16)*.

Data Collection -

As stated under scope in section 2, the analysis was to be confined to data collected during post 1992 specifications on structural and paving concrete. Further, this data was to be gathered from the computerized files of the DOTD's Material Test data reporting system (The MATT system) (*17)*. Since the MATT system is an on line system with data entered on daily basis, a cutoff date was set at August 1999. Thus, concrete test records generated by the 1992 specifications through the end of August 1999 formed the data base for analysis.

Data Base -

The data base developed for analysis consisted of three separate files as follows:

MATT A File - structural concrete strength tests file
MATT N File - paving concrete roadway core strength and thickness tests file
MATT I File - Paving concrete profile tests file

Since each record (a record being a set of data representing a unique entity such as a lot) has several items of information, only items pertinent to the analysis were included in the data base for each of the files defined above. Appendix B defines, for each record in the above three files, the various data fields that were included in the data base. The forms used for test data entry and the various material codes representing the various class and type of concrete are also shown in this appendix.

Table 6.1 lists the breakdown of number of projects, lots (records) and quantity of material for each of the three files. Table 6.2 is a further breakdown of the same information by districts. Thus, in Table 6.1 for structural concrete, there were 17,443 lots from 861 projects available for analysis. The total quantity of concrete distributed over these 17,443 lots was 680,624 cubic yards. Likewise, of the 680,624 cu yds of total concrete placed statewide, 93,918 cu yds was placed in district 02 distributed over 2064 lots and 114 projects as shown in Table 6.2.

Table 6.1: Concrete MATT System data file

MATT Files	No of Records (Observations)	No of Projects	No of Lots	Quantity cu yd/sq yd
Structural concrete file	17,443	861	17,443	680,624
Paving concrete core file	488	55	488	1,720.912
Paving concrete profile file	368	40	368	1,138,129

Table 6.2: MATT System data files by districts

Dist	MATT System for								
	Structure Concrete			Paving Concrete Core Strength and Thickness			Paving Concrete Profile Index		
	No of Proj	No of Records/Lots	Quant, cu yd	No of Proj	No of Records/Lots	Quant, sq yd	No of Proj	No of Records/Lots	Quant, sq yd
02	114	2064	93,918	9	51	161,416	2	28	87,773
03	91	2498	107,055	6	48	174,548	6	36	48,488
04	123	2019	59,799	8	45	134,734	9	26	40,355
05	107	1808	58,480	5	24	86,147	6	27	68,183
07	66	1072	54,939	7	65	235,903	4	20	39,573
08	131	3013	102,002	6	33	112,431	3	18	56,870
58	69	869	20,872	0	00	00	0	00	00
61	87	2418	104,304	11	162	589,555	7	111	401,767
62	73	1682	79,255	3	60	226,178	3	102	395,120
Total	861	17443	680,624	55	488	172,0912	40	368	1,138,129

1 sq yd= 0.836 sq m, 1 cu yd= 0.764 cu m

Data Analysis -

Preliminary to analysis, it was decided that only the data representing MATT file **Purpose Code "3"**, namely, **acceptance**, would be included in the analysis. Data representing extraneous purpose codes representing information, verification, etc., were deleted before creating temporary files for analysis. Also, whenever "noise" in the MATT data file was indicated (and it does exist in spite of data checks and edits), that record was deleted from the analysis. An example of such data would be the presence of zero value for strength (more about validity of data in the MATT system will be discussed under separate heading). Likewise, data representing special projects not governed by standard specifications were also deleted from the analysis.

The analysis is presented in two separate sections. The assessment of price adjustments for lots that were deficient in acceptance criteria is in the next section, and variability of data in the following section. The Operating Characteristic (OC) curve of the current acceptance plans will be the topic of a separate section including simulation of **PWL** type specifications on selective projects.

Whenever appropriate, reference will be made to the findings reported in the 1979 study *(6)*. Likewise, conclusions will be summarized after each topic discussion as deemed appropriate. All data access, management, analysis, and presentation was accomplished through the ***Statistical Analysis System (SAS)*** *(18)* package at the DOTD's computer division.

ASSESSMENT OF PRICE ADJUSTMENT

1. Structural Concrete -

Overview of Acceptance Criteria -

Louisiana's 1992 specifications require adjustment in unit price for lots that do not meet the requirements for 100% pay. The major acceptance criteria for this concrete, identified as class of concrete, is the 28-day compressive strength of cylinders fabricated at job sites by the DOTD's personnel and tested at the district laboratory. Depending on the use, different classes of concrete have different compressive strength requirements. The acceptance is based on the average strength of each lot, a lot being two batches with three cylinders per batch. The average of the two batches is the lot average for pay purpose. The schedule of payments for non conforming concrete is given in Appendix A.

Overall price reduction

Table 7.1 is the summary of pay reduction for non-conforming concrete. The table shows the breakdown of pay reduction by number of projects, lots and quantity. For comparison purpose, data from the 1979 evaluation is also shown *(6)*. Approximately 73% of the projects received 100% pay. On the basis of total lots submitted, about 2.1% had reduced pay. Since the unit of pay is in cubic yards, of importance is the amount of reduction by quantity which is only 1.4% of the total quantity. More than half of this reduction in pay was at the 98% level. Sixty two lots from 48 projects and 1449 cu yds (0.2%) were deficient at the 50% level. In the 1979 data, the deficiency at this level was 0.13%.

It is interesting to note that although the reduction in pay at the 95% and 80% is not in the acceptance payment schedule for structural concrete specifications (Appendix A), 32 lots from 18 projects representing some 958 cu yds had received payment at these levels. However, reduction in payment at these levels are defined for paving concrete, and, it is assumed that the class of concrete was substituted for paving concrete and cylinder strengths were used in lieu of roadway cores for acceptance. Also 246 cu yds were listed with 0% (zero) pay. This is unexplainable since no such pay level is defined in the acceptance schedule. Likewise, no explanation was given in the individual MATT test report for the lot.

Figure 7.1 is the bird's eye view of the data in Table 7.1. Also shown on this chart is the data from the 1979 study. The present data show a decrease in the quantity of concrete receiving reduced pay by almost 3.5% (1.4% versus 4.9%). The data evaluated in the 1979 report represented construction data from 1973 through 1977 on 561 projects and about 500,000 cu yds concrete.

Table 7.1: Summary of pay reduction for deficiency in structure concrete

Percent Pay	No of Projects (%)	No of Lots (%)	Quantity, cu yd	
			2000 Data (%)	1979 Data (%)*
98	106 *(12.3)*	187 *(1.1)*	5,312 *(0.8)*	16,696 *(3.5)*
95	14 *(1.6)*	22 *(0.1)*	633 *(0.1)*	1,259 *(0.3)*
90	52 *(6.0)*	67 *(0.4)*	1,766 *(0.3)*	4,631 *(1.0)*
80	4 *(0.5)*	10 *(0.0)*	325 *(0.0)*	239 *(0.0)*
50	48 *(5.6)*	62 *(0.4)*	1,449 *(0.2)*	610 *(0.1)*
0	8 *(1.0)*	13 *(0.1)*	246 *(0.0)*	****
Total with reduced pay	232 *(27.0)*	361 *(2.1)*	9,731 *(1.4)*a/	23,435 *(4.9)*
Total with 100% pay	629 *(73.0)*	17,082 *(97.9)*	670,893 *(98.6)*	454,085 *(95.1)*
Total constructed	861	17,443	680,624	477,520

*** - Represent class AA, A, R, & A minor concrete only, a/ includes 0% values, 1 cu yd=0.764 cu m**

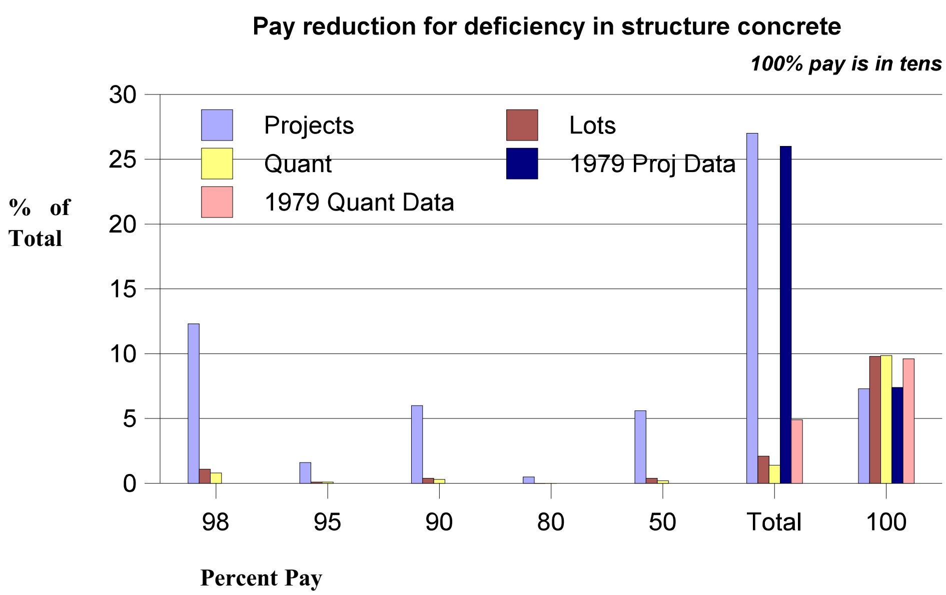


Figure 7.1: Overall distribution of price reduction for structural concrete

Price reduction by class of concrete -

To determine how this reduction in pay is distributed over different classes of concrete, Table 7.2 was prepared. The same data is charted in Figure 7.2 and 7.3. Of the total reduction in pay for quantity, about 85% is contributed by the most commonly used concrete, Class AA, A, R (minor)and A (minor). These four classes also represent about 80% of the total quantity used.

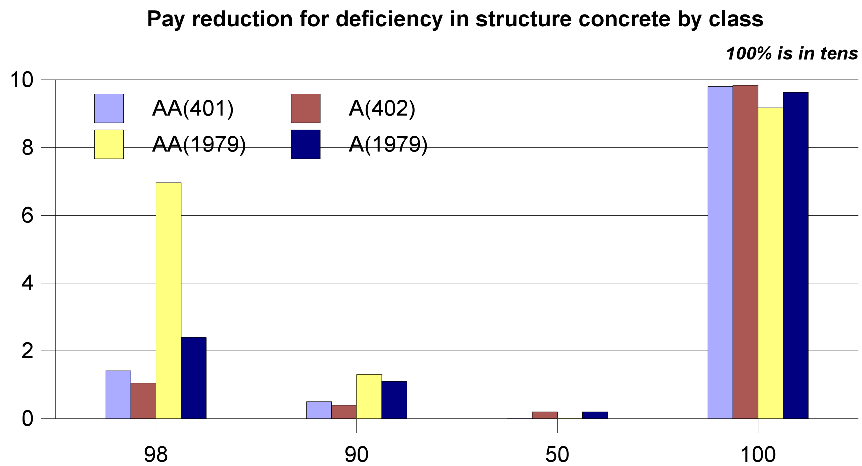
Comparison of this data to the 1979 data follow the same trend as was indicated in Table 7.2 for overall pay reduction. For AA concrete (Table 7.2 and Figure 7.2), only 1.98% of concrete was subjected to 98% pay versus 8.3% for the 1973-1977 construction data. For the same class, the percentage of quantity receiving pay at the 100% level has increased from 91.7% for 1973 - 1977 data to 98% for post 1992 construction data. For class A concrete 98.4% of the total quantity used for this class received 100% pay versus 96.3% for the 1979 data.

Table 7.2: Summary of Pay reduction by class and quantity

% Pay		Concrete Class and Quantity in cu yd (1 cu yd=0.764 cu m)							
		401	402	403-406	414-424	428 429	431 432	500s	Total
98	Quant	2930	1878	3	104		213	184	5312
	%	*(1.41)*	*(1.05)*	*(0.01)*	*(0.50)*		*(0.16)*	*(0.87)*	*(0.78)*
95	Quant	51		104	8	459	11		633
	%	*(0.02)*		*(0.43)*	*(0.04)*	*(0.62)*	*(0.01)*		*(0.09)*
90	Quant	1028	669	35	8		20	6	1766
	%	*(0.49)*	*(0.37)*	*(0.14)*	*(0.04)*		*(0.01)*	*(0.03)*	*(0.26)*
80	Quant					320	5		325
	%					*(0.43)*	*(0.0)*		*(0.05)*
50	Quant	26	270		284	115	652	102	1449
	%	*(0.01)*	*(0.15)*		*(1.36)*	*(0.15)*	*(0.49)*	*(0.48)*	*(0.21)*
0	Quant	82	71	74	16			3	246
	%	*(0.04)*	*(0.04)*	*(0.30)*	*(0.07)*			*(0.01)*	*(0.04)*

% Pay	Concrete Class and Quantity in cu yd (1 cu yd=0.764 cu m)							
Total quantity with reduction	**4117**	**2888**	**216**	**420**	**894**	**901**	**295**	**9731**
Total quantity	**208,075**	**179,240**	**24,468**	**20,817**	**74,579**	**133,837**	**21,266**	**680,624**
Percent for class (2000)	***1.98***	***1.61***	***0.88***	***2.02***	***1.20***	***0.67***	***1.39***	***(1.43)***
Percent for class (1979)	***(8.3)***	***(3.7)***	***(6.6)***			***(1.3)***		***(4.91)***

Figure 7.3 shows distribution of levels of pay reduction for minor concrete. The reduction for the two classes of minor concrete, R and M, was 0.88 and 0.67, respectively. For the same class of concrete, these reductions were 6.6% and 1.3%, respectively, for the 1979 evaluation. At the 50% level, R concrete had 1.4% versus 1.75% for the 1979 data.



% of Total

Percent Pay

Figure 7.2: Distribution of price reduction for class A & AA concrete

% of

Total

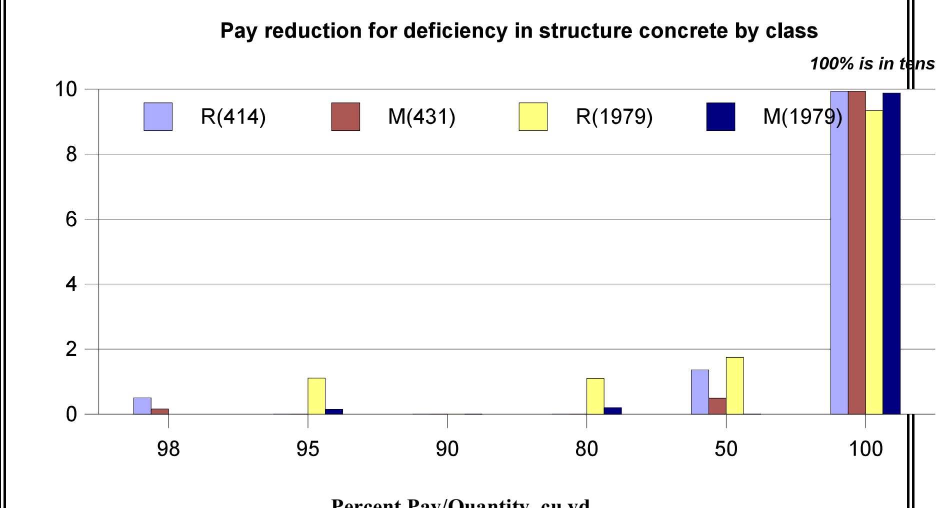
Percent Pay

Figure 7.3: Distribution of price reduction for minor concrete

<u>Price reduction by districts</u> -

Table 7.3 is a summary of pay reduction by districts. Projects in districts 2, 4, 6, and 8 have contributed more than half of the total reduction in pay. Whether the level of control maintained with respect to the mean and standard deviation has had any effect on this reduction will be evaluated in the variability portion of the analysis.

Table 7.3: Summary of Pay Reduction by district



Dist							
	98	95	90	80	50	0	Total

Dist	Percent Pay/Quantity, cu yd						
01	19	56	28	5	62	16	186
02	1,131	14	313	28	32	**	1517
03	1,026	41	80	****	153	77	1378
04	1,417	****	547	****	259	29	2252
05	****	2	11	79	144	122	358
06	934	****	446	****	225	**	1605
07	103	****	12	****	60	3	178
08	415	519	219	213	368	**	1734
09	268	****	110	****	147	**	524
Total	5,312	633	1,766	325	1,449	246	9731

1 cu yd=0.764 cu m

. Paving Concrete - ***Strength and Thickness***

Overview of Acceptance Criteria -

Concrete used for paving is classified according to type. The major acceptance criteria for this concrete is the 28-day compressive strength and thickness measured on roadway cores. Different types of concrete have compressive strength requirements according to whether air entrainment is used or not. The acceptance is based on the average strength and thickness of each lot, a lot being an identifiable area of pavement constructed. One core from each of five equal segments of the lot is obtained for strength and thickness measurements. The average of these two tests for the lot is evaluated for pay purpose. The schedule of payments for non conforming lots is summarized in Appendix A.

Overall price reduction -

Table 7.4 is a summary of pay reduction for non-conforming concrete. Graphical presentation is shown in Figure 7.4. Of the 55 projects evaluated, 14 or 25% show a reduction in price. In terms of lots, 20 lots had deficiency with 17 of these due to thickness deficiency. Of these 17 lots, seven were from one project. Evaluation of the thickness data of this project showed that the average lot thickness was too close to the plan thickness which resulted in several non-conforming lots. This will be discussed further in the variability section of the analysis.

Table 7.4: Summary of pay reduction for deficiency in Paving concrete

Percent Pay	No of Projects *(%)*	No of Lots *(%)*	Quantity, sq yd *(%)*
95	6 *(10.9)*	12 *(2.5)*	42,473 *(2.47)*
90	3 *(5.5)*	3 *(0.6)*	9,189 *(0.53)*
80	2 *(3.6)*	2 *(0.4)*	8,000 *(0.46)*
75	2 *(3.6)*	2 *(0.4)*	5,253 *(0.31)*
50	1 *(1.8)*	1 *(0.2)*	4,000 *(0.23)*
****	12*(21.8)*	58 *(11.9)*	166,106 *(9.65)*a/
Total with reduced pay	14 *(25.4)*	20 *(4.1)*	68,915 *(4.00)*
Total with 100% Pay	41 *(74.6)*	411 *(95.9)*	1,651,997 *(96.0)*
Total constructed	55	488	1,720,912

a/ included in 100% pay   1 sq yd = 0.836 sq m

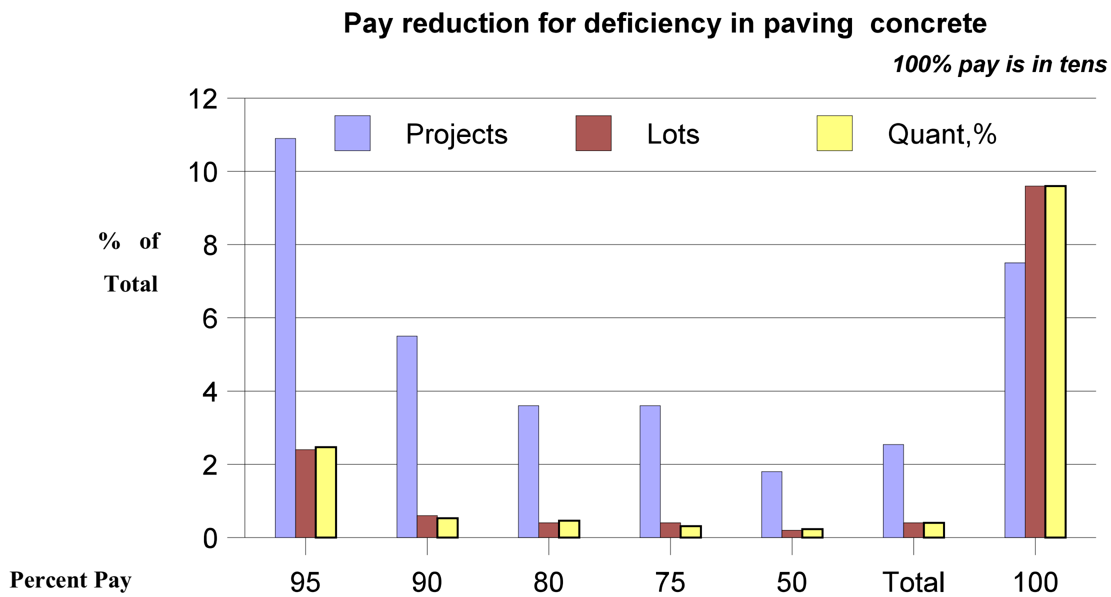


Figure 7.4: Distribution of price reduction for paving concrete

The overall reduction as a result of these deficiencies was 4% of the total quantity with more than half at the 95% level.

The low number of lots (three) with strength deficiency can be attributed to the age of concrete cores at testing time which in most cases exceed the specified minimum curing age of 28 days by as much as 10 to 15 times. In a number of cases, this age was recorded in excess of 200 days. This generally results in higher strengths than would otherwise be indicated at or around the specified curing period.

There were some lots with missing pay values (shown as asterisks under percent pay column). Once again, no valid reason could be determined from individual reports. However, these were included as being paid 100%.

In the 1979 evaluation, 97% of the concrete (Type B) had reduced pay. The three percent that received reduced pay was due to non-conforming thickness. The evaluation was based on 1.69 million square yards concrete distributed over 73 projects.

3. Paving Concrete - Profile Testing

<u>Overview of Acceptance Criteria</u> -

Acceptance of pavement is on lot basis with lot defined as for strength and thickness acceptance criteria. Using an approved profilograph, the profile index is determined longitudinally in each wheel path of each travel lane to determine the smoothness of pavement. Lots not meeting the specified tolerance for smoothness, after corrections are made, are paid at reduced price. The schedule of payment for non conforming lots is summarized in Appendix A.

<u>Overall price reduction</u> -

Table 7.5 is an overview of pay assessment for lots not meeting the stated requirements for smoothness criteria. Figure 7.5 is a chart of the tabled data. Only six of the 368 lots did not meet the requirement for 100% pay. In terms of quantity, this amounts to about 4%. No comparative data from the 1979 evaluation is available.

One of the reasons for such low number of non conforming lots is that the contractor, during quality control testing, is required to correct deficiencies in excess of specified values before submission for acceptance testing.

Table 7.5: Summary of pay reduction for deficiency in Profile Index

Percent Pay	No of Projects *(%)*	No of Lots *(%)*	Quantity, sq yd *(%)*
98	2 *(5.0)*	3 *(0.8)*	9671 *(2.47)*
95	2 *(5.0)*	2 *(0.5)*	3573 *(0.53)*
80	1 *(2.5)*	1 *(0.3)*	2315 *(0.46)*
50	0 *(0.0)*	0 *(0.0)*	0 *(0.23)*
****	8 *(20.0)*	25 *(6.8)*	59,788 *(9.65)*a/
Total with reduced pay	5 *(12.5)*	6 *(1.6)*	15,559 *(4.00)*
Total with 100% Pay	35 *(87.5)*	362 *(98.4)*	1,122,570 *(98.6)*
Total constructed	40	368	1,138,129

a/ included in 100% pay 1 sq yd=0.836 sq m

Summary of Price Adjustments -

The discussion presented in the preceding sections can be summarized in the following statements:

- On the basis of total quantity of structural concrete, the average reduction in final pay was 0.2%, or an average payment per project of 99.8%. This substantiates the average pay of 99.7% for the 1979 projects.

- Compared to the 1979 data evaluation, there has been an increase in the quantity of structural concrete receiving 100% pay. In terms of reduced pay (less than 100%), only 1.4% of the total quantity used in structures was subjected to reduction in price. This reduction was 4.9% for the 1979 data.

- Because of the large volume of concrete used in Class AA and A, 72% (7005 cu yds) of the total concrete that received reduced pay (9731 cu yds) was for this class of concrete. For the 1979 data, the reduction for this class was 92% (21,741 cu yds) of the total of 23,435 cu yds.

- Of the total concrete that had pay reduction, about 15% was at the 50% level compared to 2.6% for the 1979 data.

- The average price reduction in final pay for paving concrete was 0.5%, or an average payment of 99.5% per project. The average payment for the 1979 projects was 99.9%.

- Most of deficiency in paving concrete stems from non-conforming thickness. Furthermore, because of extended curing period allowed before testing for strength, practically none of the concrete showed deficiency in strength requirement. Similar trend was noticed in the 1979 evaluation. The overall reduction was 4% of the total square yards laid with more than half at the 95% reduction level.

- Four percent of the pavement tested for surface smoothness showed profile index exceeding the stated requirements.

VARIABILITY OF DATA

In Section 5, it was shown that for a normally distributed property, about 95% of the data can be expected to fall between $\pm 2\sigma$ limits from the mean, and almost 100% of values would be included within $\pm 3\sigma$ from the mean. On the basis of this property of the normal distribution, there exists a definite relationship between specifications and statistical parameters. If the specification tolerances were developed from some known standards of the mean and the standard deviation, any deviation on the process control from this known standard is likely to change the probability of acceptance and/or rejection of the product.

This section discusses the variability of the various criteria defined for control and acceptance of concrete construction, and comparison of this variability to known standards defined by the governing specifications. In the tables that follow, N represent total number of observations and Nlot, number of lots.

1. *Structural Concrete Strength Variability* -

Statewide Variability by Class of Concrete

Tables 8.1 and 8.1a show the variability of compressive strength of different classes of concrete. The data represents values pooled over all projects and lots for that class. The tabled data on variability are plotted in Figures 8.1 through 8.3. The plots are for the most commonly used concrete class.

Most of the data follow normal distribution as indicated by the skewness values of less than absolute one. The closeness to the normal distribution is also indicated by the frequency distribution plots of strengths by class of concrete. These distributions are shown in Appendix C.

Based on the ACI rating standards of Table 5.5, the coefficient of variation indicates that the level of production and field control was good for most classes of concrete. This measure of variability is useful in comparing data from multiple sets of measurements with different units or widely differing means. Three classes of concrete, 428, 429, and 431 show fair level of control and class R concrete, poor. The large magnitude of the coefficient of variation for class R concrete is due to the minimal inspection exercised over its production and field control.

Strength variability on projects that were let under the Metric system of specifications is shown in

Table 8.1: Statewide overall & lot variability in compressive strength of different classes of structure concrete (EU)

Concrete Class (MATT Code)	N *NLot*	Quant, cu. yd	Mean, psi	Std Dev, psi	CV	Min, psi	Max , psi	Range, psi	Skewness	Kurtosis
AA (401)	23,861 *4,411*	208,076	5285 *5294*	738 *709*	14.0 *13.4*	1510 *2398*	8610 *8233*	7100 *5835*	0.4 *0.4*	0.8 *0.8*
A (402)	36,193 *7083*	179,240	5358 *5350*	779 *753*	14.5 *14.1*	31 *33*	9405 *9143*	9374 *9110*	0.4 *0.4*	1.0 *1.1*
D (403)	99 *17*	4,298	5040 *5027*	559 *509*	11.1 *10.1*	3340 *4120*	5860 *5755*	2520 *1635*	-0.8 *-0.3*	0.3 *-1.1*
P (404)	87 *15*	221	5313 *5354*	765 *770*	14.4 *14.4*	4050 *4249*	7350 *6993*	3300 *2744*	0.6 *0.7*	0.0 *0.3*
S (406)	1416 *259*	19,949	5770 *5727*	758 *725*	13.1 *12.7*	3463 *3623*	9400 *8805*	5937 *5182*	0.4 *0.4*	1.5 *1.3*
R (414) minor	1305 *403*	17,709	3208 *3170*	1002 *972*	31.2 *30.7*	1130 *1463*	8341 *8105*	7211 *6642*	1.3 *1.3*	2.3 *2.5*
AAM (421)	113 *23*	996	5305 *5313*	577 *618*	10.9 *11.6*	3700 *3757*	6950 *6440*	3250 *2683*	-0.3 *-0.3*	0.6 *0.8*
AM (422)	297 *65*	1,900	5757 *5710*	476 *438*	8.3 *7.7*	4471 *4507*	7120 *7043*	2649 *2536*	0.1 *0.1*	0.1 *0.8*
PM (424)	81 *27*	212	6944 *6944*	882 *859*	12.7 *12.4*	3554 *4132*	9022 *8659*	5468 *4527*	-1.2 *-1.3*	3.1 *3.6*
Pvt-air (428)	3240 *757*	54,701	5525 *5508*	903 *887*	16.3 *16.1*	2620 *2640*	9035 *8237*	6415 *5597*	0.1 *-0.0*	0.3 *0.3*
Pvt-no air (429)	198 *52*	19,878	5114 *4984*	947 *867*	18.5 *17.4*	3428 *3535*	7860 *7318*	4432 *3783*	0.7 *0.8*	-0.2 *0.1*
M (431)	10,285 *3220*	130,754	4990 *4987*	825 *803*	16.5 *16.1*	354 *2332*	8738 *7996*	8384 *5664*	0.3 *0.3*	0.7 *0.5*
F (432)	366 *109*	3,083	4593 *4629*	612 *571*	13.3 *12.3*	2844 *3188*	5897 *5840*	3053 *2652*	-0.4 *-0.4*	-0.2 *-0.1*
No pile (434)	24 *4*	134	5402 *5402*	433 *476*	8.0 *8.8*	4804 *4981*	6306 *6057*	1502 *1076*	0.7 *1.2*	-0.8 *0.9*
(460)	225 *38*	18,210	5924 *5925*	463 *425*	7.8 *7.2*	4878 *5081*	7526 *7089*	2648 *2008*	0.6 *0.6*	0.8 *0.9*

1 psi=6.89kPa

Table 8.1a. Class AA and A fall in the fair category with class R showing poor level as was indicated under the English system. According to charts 8.1 through 8.3, the values for different measures of

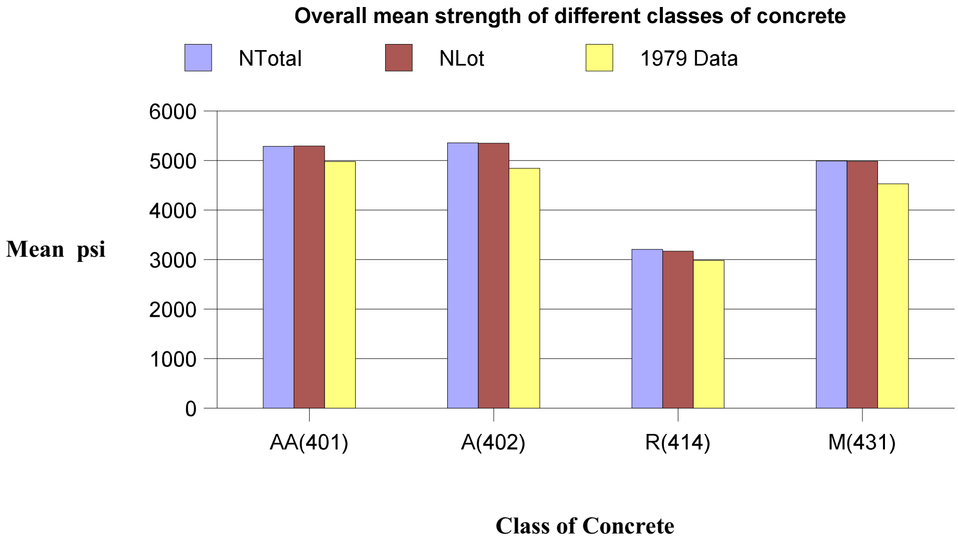


Figure 8.1: Overall mean strength of different classes of concrete

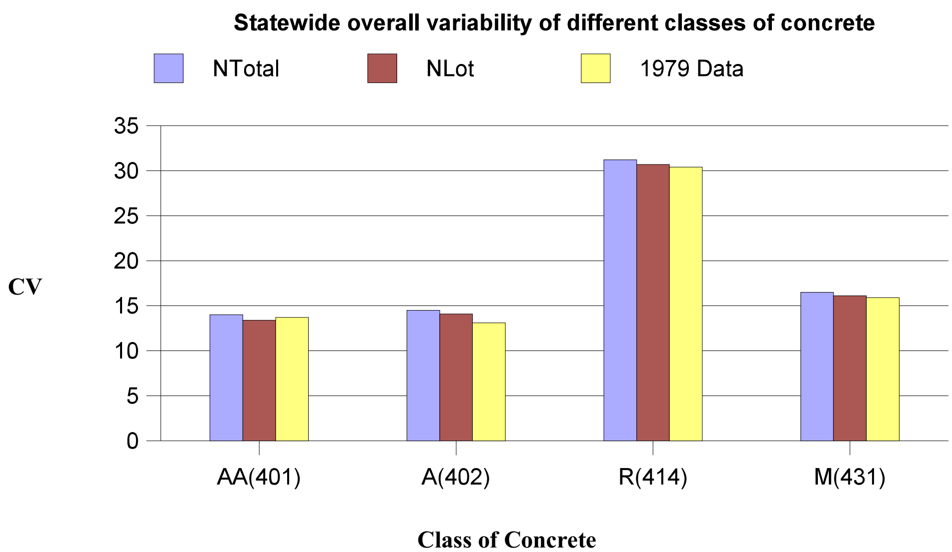


Figure 8.2: Overall coefficient of variation of different classes of concrete

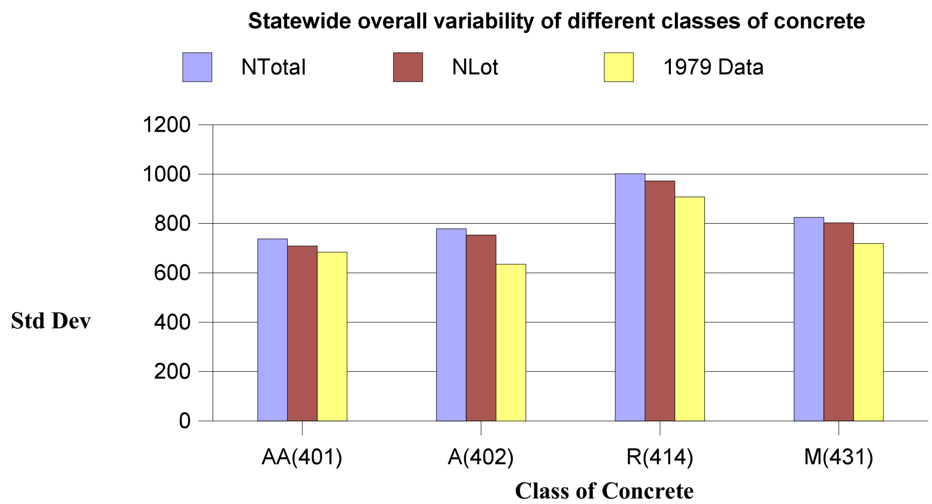


Figure 8.3: Overall standard deviation of different classes of concrete

variability are higher than those indicated by the projects evaluated in 1979. There is an increase in the mean strength across all classes of concrete with the corresponding increase in standard deviation also. This trend (increase variability with increase in the mean) is not uncommon although less desirable. Sometimes the influence of time (lengthy production periods lasting from few days to several months) as a source of variation contributes to the overall variation. This results in a constant change in process control which is reflected in the variability of the measurements. As was mentioned before, any deviation in the process control from the known standard is likely to change the probability of acceptance and/or rejection of the product. To determine the effect of this deviation (increase in the standard deviation and the mean), Table 8.2 was prepared.

The table shows actual number of samples versus predicted number of non-conforming samples for the four classes of concrete. The predicted numbers were calculated using the variability data of Table 8.1 and the theoretical area under the normal curve. The values are for the individual and average strength requirements defined in the specifications for the class of concrete and shown in column 2. There is a close agreement between the predicted and actual number of measurements indicating adequate level of standard maintained with respect to the mean and standard deviation.

Table 8.1a: Statewide overall & lot variability in compressive strength of different classes of structure concrete (MU)

Conc Class (MATT Code)	N *NLot*	Quant, cu m	Mean, MPa	Std Dev, MPa	CV	Min, MPa	Max, MPa	Range, MPa	Skewness	Kurtosis
AA (501)	657	2308	35.1	6.6	18.7	19.9	55.6	35.7	0.8	0.5
	129		*34.6*	*6.1*	*17.5*	*21.9*	*51.2*	*30.3*	*1.0*	*1.0*
A (502)	2,466	7996	37.1	5.7	15.4	17.7	73.3	55.6	0.7	1.2
	507		*36.8*	*5.6*	*15.2*	*18.3*	*55.8*	*27.5*	*0.7*	*0.9*
P (504)	38	134	40.4	4.7	11.7	30.4	49.2	18.8	-0.2	-0.6
	13		*41.6*	*4.7*	*11.4*	*31.6*	*48.0*	*16.4*	*-0.9*	*0.5*
S(506)	39	184	41.2	2.6	6.3	35.3	45.2	9.9	-0.6	-0.4
	7		*41.1*	*2.3*	*5.5*	*36.6*	*43.5*	*6.9*	*-1.4*	*2.6*
R(514)	36	194	18.7	5.6	30.1	9.7	29.9	20.2	0.3	-0.9
	11		*18.1*	*5.6*	*31.1*	*9.9*	*29.1*	*19.2*	*0.5*	*-0.1*
Pvt air(528)	578	6046	42.9	7.0	16.4	28.5	62.0	33.5	0.3	-0.7
	126		*42.1*	*6.5*	*15.4*	*30.6*	*58.2*	*27.6*	*0.4*	*-0.6*
Pvt noair(529)	12	154	34.8	3.1	9.0	29.2	38.0	8.8	-1.1	-0.2
	4		*34.8*	*3.3*	*9.6*	*29.9*	*37.2*	*7.3*	*-1.6*	*3.3*
M(531)	429	4250	32.7	5.7	17.3	18.0	56.6	38.6	0.7	1.7
	144		*32.7*	*5.6*	*17.1*	*18.7*	*54.9*	*36.2*	*0.8*	*1.8*

1 psi=6.89 kPa

Table 8.2: Predicted versus actual number of samples outside the limits for compressive strength of Structural Concrete

Concrete Class (MATT Code)	PSI's less than	Actual number (%) less than indicated PSI	Predicted number (%) based on Mean and Std Dev (from Table 8.1)
AA(401)	3200	40 (0.17)	57 (0.24)
	4200	*181 (4.10)*	*271(6.16)*
A(402)	3000	47 (0.13)	47 (0.13)
	3800	*82 (1.16)*	*142 (2.0)*
R(414) minor	1800	31 (2.38)	105 (8.0)
	1800	*9 (2.21)*	*32 (7.93)*
M(431) minor	3000	61(0.59)	82(0.80)
	3000	*16((0.50)*	*22(0.68)*

1 psi=6.89 kPa

District wide Variability by Class of Concrete

Table 8.3 is listing of statistical parameters detailed according to district and class. Figures 8.4 through 8.7 are graphical representation of the tabled data. The data follow the same trend as for statewide variability - increase mean with associated increase in standard deviation. However, based on the ACI rating of Table 5.5, most of the districts show good field control for all classes of concrete except class R which, as before, indicate poor control.

Although the standard deviation shows an increase from the 1979 data in most cases, the contractor was able to maintain the process mean much higher than the minimum required for 100%. As a result, the percentage of expected failure was much higher than the actual failure for some of the districts that had high percentage of quantity with reduced pay (02, 04, 06, and 08). For these districts, the expected failure was between 1.5% to 2.0% compared to actual pay reduction of less than one percent.

District wide Within-test variability

Variation in concrete occurs from two sources: batch-to-batch variation due to concrete materials (mixture) and within-test sources of variation. The data in Table 8.4 and Figure 8.8 show this within-test variability for the nine districts. ACI has developed variability standards that can be expected for compressive strength tests on projects subject to different degrees of control. Referring to Table 5.5, it is seen that the coefficient of variation in excess of 6.0 relative to field control indicates poor testing control. Based on these standards, none of the districts fall in that category with majority showing very good control and two showing excellent control. District 04 seems to have excellent control regardless of the class of concrete. With the exception of one district, similar trend was indicated in the 1979 data. Well maintained equipment with periodic calibration and well defined sampling and testing procedures are prerequisites to maintaining good test standards.

Table 8.3: District wide overall & lot variability in compressive strength of

Class A , AA & R (minor) structure concrete

Dist	Concrete Class (MATT Code)															
	AA (401)				A (402)				R (Minor) (414)				A (Minor) (431)			
	N *NLot*	Mean, psi	Std	CV	N *NLot*	Mean, psi	Std	CV	N *NLot*	Mean, psi	Std	CV	N *NLot*	Mean, psi	Std	CV
01	2714 *531*	5630 *5611*	669 *652*	11.9 *11.6*	4132 *781*	5744 *5732*	619 *597*	10.8 *10.4*	148 *46*	2917 *2837*	1007 *1034*	34.5 *35.2*	1514 *493*	5432 *5444*	894 *855*	16.5 *15.7*
02	4907 *958*	5477 *5487*	788 *755*	14.4 *13.8*	5236 *998*	5480 *5464*	761 *736*	13.9 *13.5*	57 *19*	3148 *3148*	619 *622*	19.7 *19.8*	1043 *341*	4946 *4936*	762 *741*	15.4 *15.0*
03	984 *189*	5104 *5069*	677 *660*	13.3 *13.0*	4112 *924*	5422 *5414*	771 *766*	14.2 *14.1*	273 *88*	3113 *3033*	934 *791*	30.0 *26.1*	985 *284*	4990 *5035*	695 673	13.9 *13.4*
04	1629 *272*	4681 *4681*	515 *489*	11.0 *10.4*	4909 *896*	4845 *4867*	556 *538*	11.5 *11.0*	227 *73*	3691 *3653*	1002 *1002*	27.2 *27.4*	1173 *370*	4562 *4571*	628 *616*	13.8 *13.5*
05	1553 *282*	5777 *5750*	891 *852*	15.4 *14.8*	1547 *293*	6121 *6106*	735 *725*	12.0 *11.9*	15 *5*	3155 *3155*	1081 *1164*	34.3 *36.9*	1262 *341*	5559 *5557*	847 *837*	15.2 *15.1*
06	6472 *1206*	5191 *5201*	578 *547*	11.1 *10.5*	6860 *1403*	5338 *5319*	543 *519*	10.2 *9.7*	177 *58*	3212 *3227*	1045 *1049*	32.5 *32.5*	557 *184*	4894 *4887*	669 *664*	13.7 *13.6*
07	1758 *294*	4848 *4846*	498 *478*	10.3 *9.9*	2590 *452*	4877 *4890*	570 *597*	11.7 *12.2*	120 *27*	3363 *3332*	889 *848*	26.4 *25.4*	207 *60*	4765 *4818*	699 *677*	14.7 *14.0*
08	1380 *260*	5175 *5172*	737 *708*	14.2 *13.7*	2937 *613*	5096 *5084*	768 *746*	15.1 *14.7*	138 *39*	2870 *2749*	986 *981*	34.3 *35.7*	2661 *862*	4722 *4723*	720 *701*	15.2 *14.8*
09	2464 *419*	5308 *5304*	747 *705*	14.1 *13.3*	3870 *722*	5617 *5566*	1018 *974*	18.1 *17.5*	150 *48*	3149 *3099*	1007 *981*	32.0 *31.6*	883 *285*	4955 *4967*	743 *729*	15.0 *14.7*

1 psi-6.89 kPa

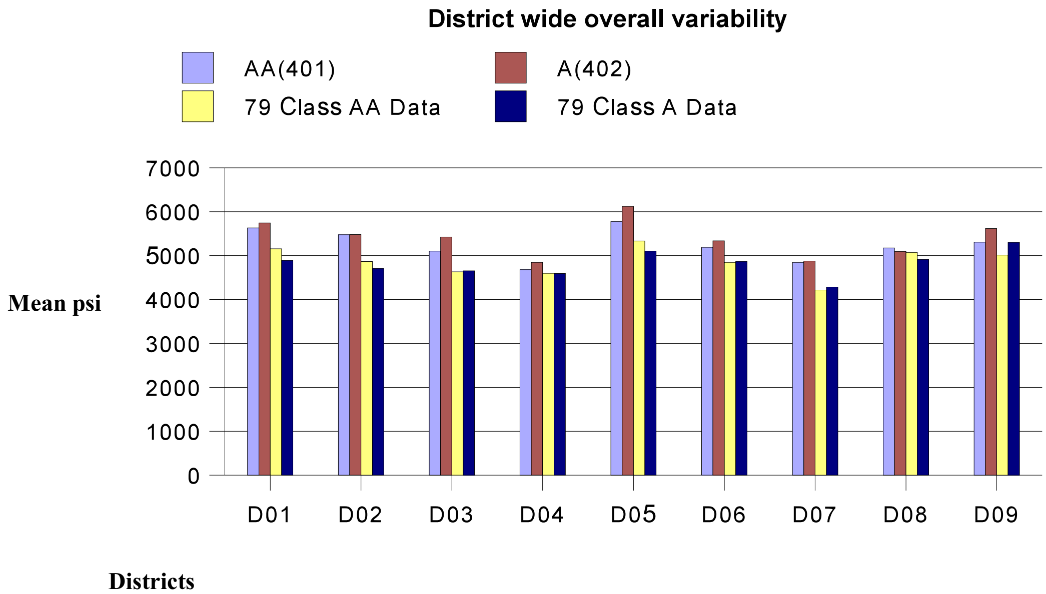


Figure 8.4: District wide mean strength of class A & AA concrete

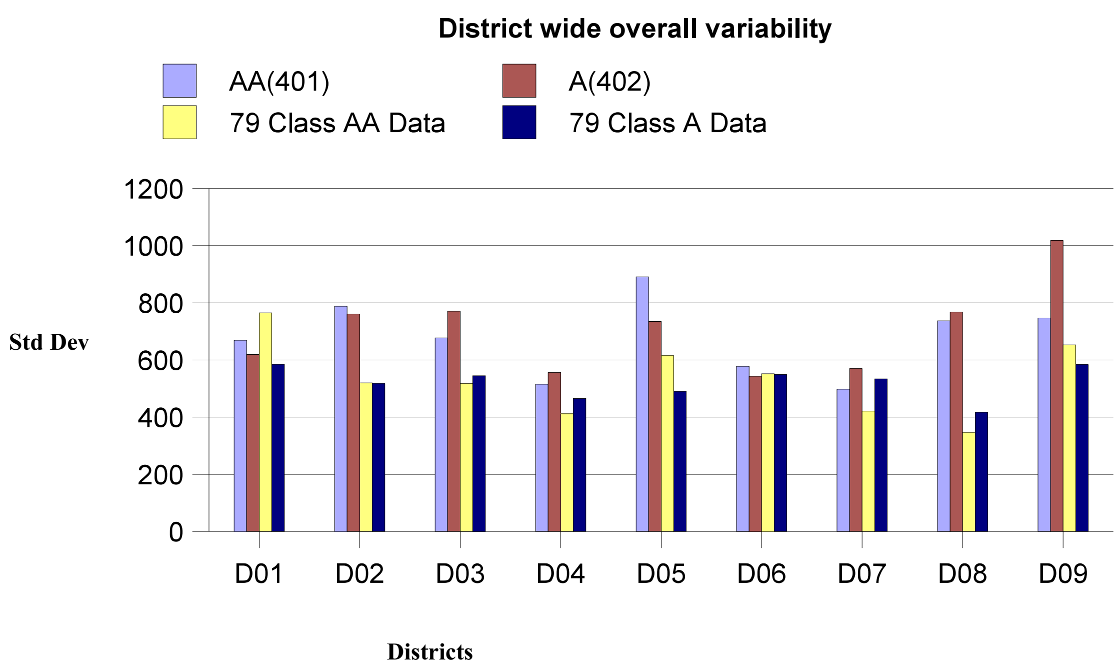


Figure 8.5: District wide standard deviation of class A & AA concrete

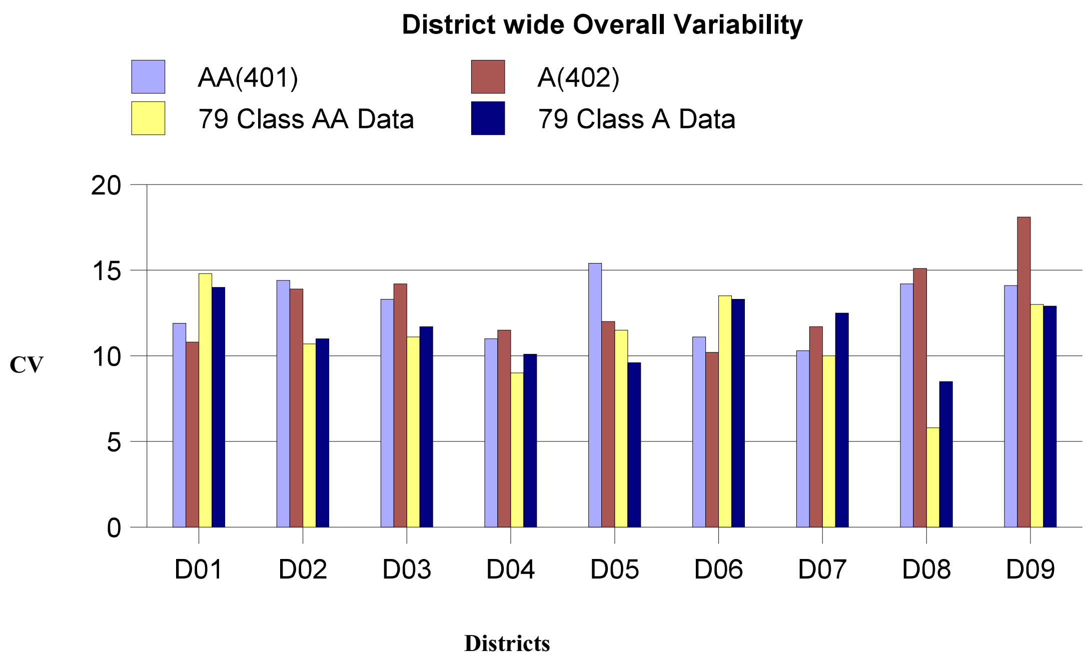


Figure 8.6: District wide coefficient of variation of class A & AA concrete

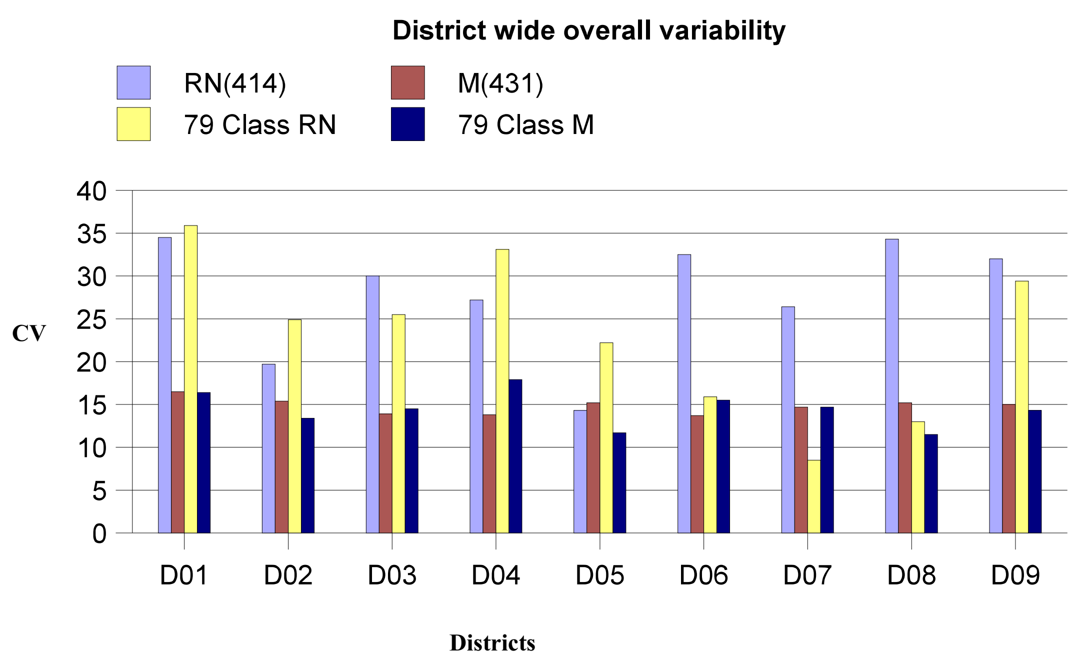


Figure 8.7: District wide coefficient of variation for minor concrete

Table 8.4: District wide test variability in compressive strength of Class A , AA & R (minor) structure concrete

Dist	Concrete Class (MATT Code)											
	AA(401)				A (402)				R (Minor)(414)			
	NLot	Mean psi	Mean Range, psi	CV a/	NLot	Mean	Mean Range	CV	NLot	Mean	Mean Range	CV
01	531	5613	372	3.9	788	5728	331	3.4	47	2933	182	3.7
02	958	5498	295	3.1	998	5471	301	3.2	19	3148	185	3.5
03	189	5081	276	3.2	924	5420	296	3.2	88	3036	155	3.0
04	272	4690	200	2.5	896	4871	140	1.6	73	3651	117	1.9
05	282	5752	334	3.4	293	6103	335	3.2	5	3155	194	3.6
06	1206	5213	246	2.8	1404	5324	197	2.2	58	3226	194	3.6
07	294	4844	198	2.4	452	4884	186	2.3	27	3361	222	3.9
08	260	5163	357	4.1	613	5074	318	3.7	39	2752	181	3.9
09	419	5311	308	3.4	723	5569	311	3.3	48	3101	159	3.0

1 psi = 6.89kPa   a/ - mean range/(1.69)(mean psi)

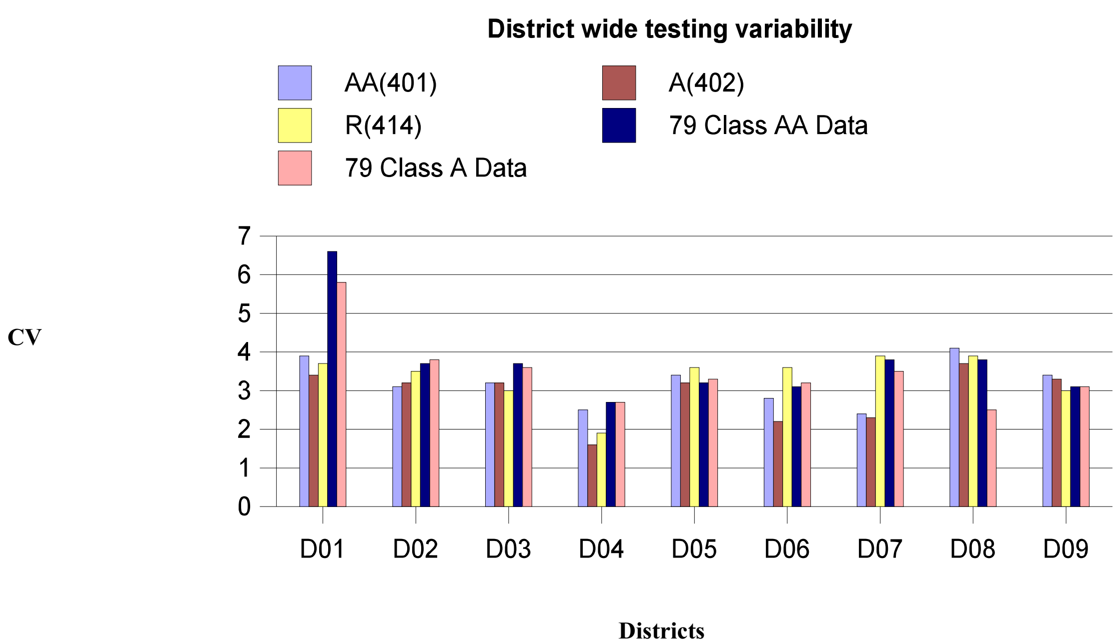


Figure:8.8: District wide within-test variability for different classes of concrete

2. Paving Concrete Variability

Statewide Variability of Strength of Roadway Cores

Table 8.5 shows overall variability of compressive strength of roadway cores. The data are from 488 lots representing over 1.7 million square yards of concrete distributed over 55 projects. Figures 8.9 and 8.10 show this data in graphical form for the mean and coefficient of variation, respectively. With the exception of data for Type D concrete, most of the data follow normal distribution as indicated by the skewness values and the near shape of the frequency distribution of this data as shown in Appendix D.

The variability presented as coefficient of variation is in line with the 1979 data. However, this is somewhat higher than data reviewed from some national studies (see Table 5.4). The lengthy construction periods for some of these paving projects and the long curing period, more than 10 to 15 times the required minimum of 28 days, before testing also contributes to this variability. However, because of the high level at which the mean was maintained, very few lots (only 3) failed to meet the minimum requirement for 100% pay. This is shown in Table 8.6 which compares the predicted versus actual number of samples outside the stated limits for individual and mean strength.

Table 8.5: Statewide overall & lot variability in compressive strength of roadway cores

Concrete Type (MATT Code)		N *NLot*	Quant, sq yd	Mean, psi	Std Dev, psi	CV	Min, psi	Max , psi	Range, psi	Skewness
B(451)	Air	764 *158*	521889	6057 *6091*	1114 *967*	18.4 *15.9*	3280 *3904*	9940 *8806*	6660 *4902*	0.43 *0.66*
	No Air	390 *78*	260487	6679 *6681*	1200 *1047*	18.0 *15.7*	3660 *4322*	9656 *8955*	5996 *4633*	0.06 *0.06*
A(452) a/	Air	95 *19*	66872	5376 *5353*	1031 *786*	19.2 *14.7*	2980 *3827*	8800 *6506*	5820 *2679*	-0.20 *-0.42*
	No Air	85 *17*	40364	5921 *5921*	1036 *650*	17.5 *11.0*	3531 *4886*	8894 *6971*	5363 *2085*	0.41 *0.02.*
D(454)	Air	1038 *210*	785272	5434 *5431*	1341 *1232*	24.7 *22.7*	2400 *3364*	10559 *9617*	8159 *6253*	1.34 *1.62*
	No Air	75 *15*	46028	5759 *5759*	667 *441*	11.6 *7.7*	3906 *5066*	7193 *6722*	3287 *1656*	-0.13 *0.38*

1 sq yd=0.836 sq m

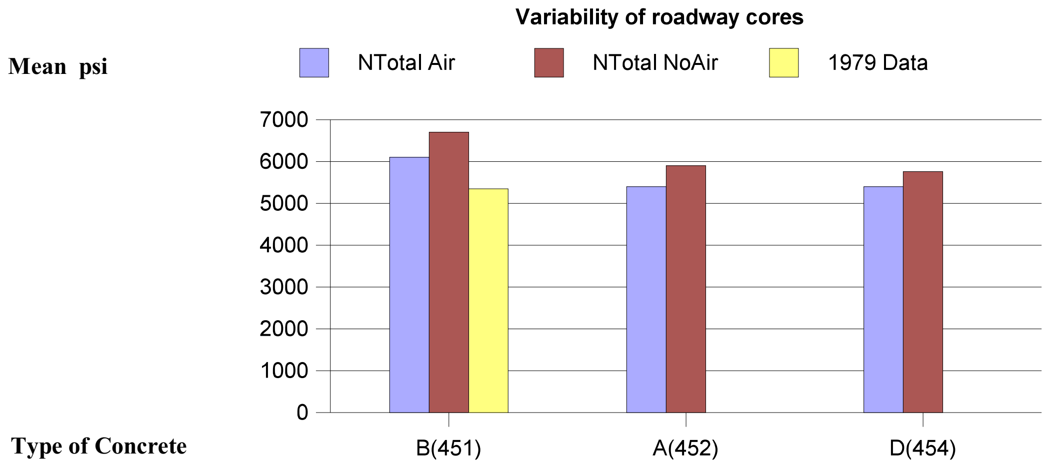


Figure 8.9: Overall mean strength of roadway cores

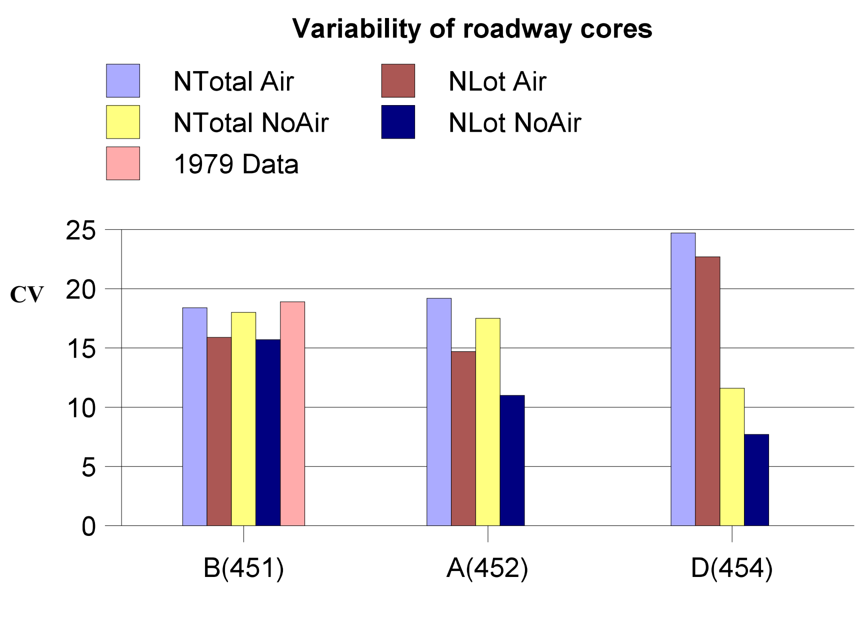


Figure 8.10: Overall coefficient of variation of strength of roadway cores

Table 8.6: Predicted versus actual number of samples outside the limits for compressive strength of roadway cores

Concrete Type (MATT Code)		PSI's less than	Actual number (%) less than indicated PSI	Predicted number (%) based on Mean and Std Dev (from Table 8.5)
B(451)	air	3600	0	10 (1.4)
	no air	*4000*	*0*	*5 (1.3)*
A(452) a/	air	3600	0	4 (4.3)
	no air	*4000*	*0*	*3 (3.2)*
D(454)	air	3600	3 (0.3)	88 (8.5)
	no air	*4000*	*0*	*0 (0.4)*

1 psi=6.89 kPa

To see if there is a relationship between curing period and strength, Figure 8.11 was prepared. The plot is for individuals core strengths of type B paving concrete without air entrainment. As seen, there is too much scatter to indicate any discernable trends.

PSI

Average age in days

Figure 8.11: Scatter of age versus compressive strength of cores

Statewide Variability of Thickness of Roadway Cores

Figures 8.12 and 8.13 show standard deviation and mean, respectively, of data listed in Table 8.7 for roadway thickness. The thickness represent values measured on the same roadway cores tested for strength.

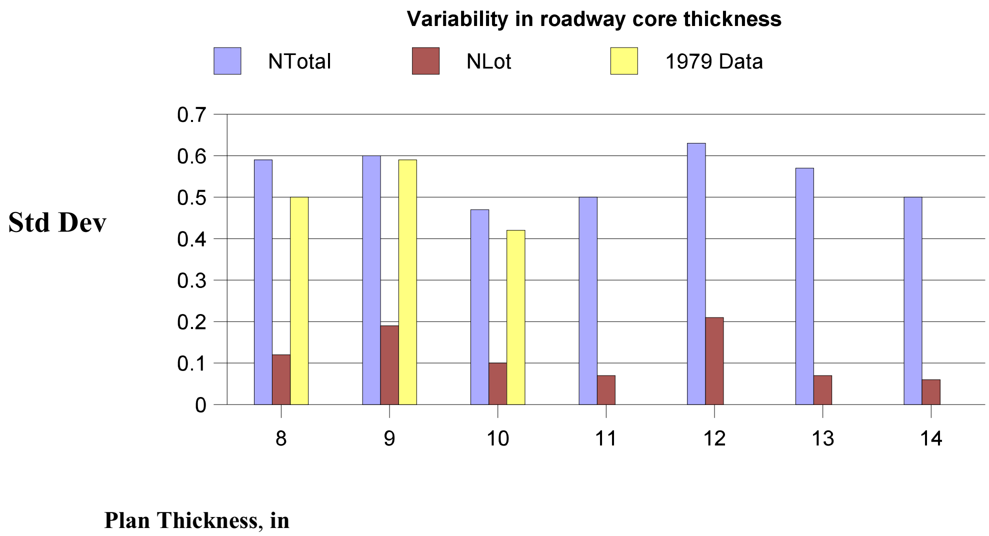


Figure 8.12: Standard deviation of roadway thickness

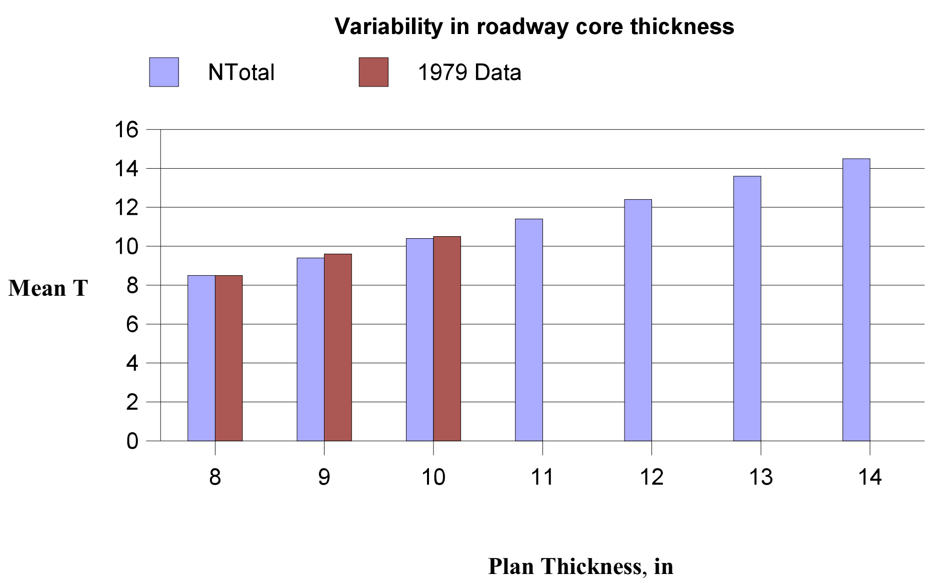


Figure 8.13: Mean thickness of roadway cores

Although the mean value of thickness for the 8-, 9-, and 10-inch plan thickness has remained the same, the variability has increased by almost 0.1 inch from the 1979 data. The norm as reported by some states (Table 5.6) is around 0.25 to 0.35 inches. Further, the lot mean thickness is so close to the plan thickness that some lots are likely to fail the tolerance requirement for acceptance.

Table 8.7: Statewide overall and lot variability in thickness of roadway cores

Plan T	N *NLot*	Quant, sq yd	Mean T, in	Std Dev	CV	Min	Max	Range	Skewness
8	524 *106*	365,543	8.5 *8.1*	0.59 *0.12*	7.0 *1.4*	7.0 *7.8*	11.7 *8.3*	4.7 *0.5*	1.4 *-1.1*
9	451 *91*	322,468	9.4 *9.1*	0.60 *0.19*	6.4 *2.1*	7.2 *7.9*	12.0 *9.3*	4.8 *1.4*	0.8 *-3.3*
10	496 *100*	343,207	10.4 *10.1*	0.47 *0.10*	4.6 *1.0*	9.1 *9.8*	12.9 *10.3*	3.8 *0.5*	1.4 *-1.1*
11	149 *33*	82,977	11.4 *11.2*	0.50 *0.07*	4.3 *0.6*	10.5 *11.0*	13.5 *11.3*	3.0 *0.3*	1.6 *-0.9*
12	35 *7*	18,914	12.4 *12.1*	0.63 *0.21*	5.1 *1.7*	10.5 *11.7*	13.8 *12.3*	3.3 *0.6*	-0.7 *-2.2*
13	355 *71*	266,622	13.6 *13.2*	0.57 *0.07*	4.2 *0.5*	11.3 *13.0*	15.4 *13.3*	4.1 *0.3*	0.3 *-1.5*
14	372 *76*	290,383	14.5 *14.2*	0.50 *0.06*	3.5 *0.4*	13.2 *14.0*	16.6 *14.3*	3.4 *0.3*	1.34 *-1.3*

1 in = 25.4 mm , 1 sq yd = 0.836 sq m

Recall that of the 20 lots that had failed to meet the minimum requirement for 100% pay (Table 7.4), 17 were for the lots with thickness deficiency and 16 of these were for lots with 8 and 9 inch plan thickness. Based on the mean and standard deviation of the lots with these plan thicknesses, about 18% would be the expected number to fail the minimum requirement for 8-inch thickness. The observed number was six. Similar numbers for 9-inch thickness are 25 expected versus 10 observed. The point that is being made here is the importance of maintaining the mean and standard deviation at a level that would minimize nonconformance.

The variation in materials and construction has significant effect on performance. As variation in strength and thickness (and some other properties) increase along a given lot, the variation in distress over time may increase. This would result in increased maintenance and rehabilitation costs.

Pavement Smoothness Variability

Data on smoothness is measured by the 25-ft California type Profilograph over each wheel path of each lane. Acceptance requirements are based on design speed and roadway classification, whether urban or rural. The results are reported as Average Profile Index, or API, in inches per mile per lot. Appendix A lists the specification tolerances for this criteria. The variability data on API is shown in Table 8.8. Also shown is the International Roughness Index (IRI). Frequency distribution is shown in Appendix E.

Table 8.8: Statewide variability of average profile index (API)

Categ	Type	NLot	Mean, in/mi	Std Dev	CV	Min	Max	Range	Skewness
none	API	131	7.9	6.3	78.6	0.1	25.9	25.8	0.73
	IRI	153	31.9	57.0	178.7	-	158.3	158.3	1.26
1	API	65	1.9	2.6	134.7	0	14.6	14.6	2.91
	IRI	67	102.9	29.6	28.7	-	153.7	153.7	-2.40
2	API	7	7.3	4.2	58.0	1.8	12.8	11.0	-0.19
	IRI	7	132.1	11.7	8.8	117.9	149.9	32.0	0.09
3	API	30	10.6	5.5	51.7	0	21.8	21.8	0.07
	IRI	34	47.4	63.0	133.1	-	164.3	164.3	0.83

1 in=25.4 mm 1 mile=1.609 km

No comparative data is available to judge how well the level of control is maintained on this measurement. However, a Texas study (*14)* showed a standard deviation between 0.8 to 1.2 in/mile for the average of two results from the same profilograph. The report states that the overall variability is influenced by the operator variability and the interpreter variability. Review of individual project data show the variability to vary from less than one to 6.9 in/mile. In light of this Texas study, the overall variability may be somewhat higher. Future such evaluation may be necessary to develop standard for control on variability.

Quality Control Tests

Slump and air content are two properties that are traditionally measured as screening tests to determine the consistency and durability. The results of these tests are required to be plotted on control charts by the contractor. Table 8.9 and 8.10 show variability data for the two control tests for structure concrete and paving concrete, respectively. Figure 8.14 and 8.15 show graphical representation of the data.

Table 8.9: Statewide overall & lot variability in slump and air content of

different classes of structure concrete

Concrete Class (MATT Code)	N *NLot*	Mean	Std Dev	CV	Min	Max	Range	Skewness
SLUMP, in								
AA(401)	7185	3.55	0.82	23.1	0.5	9.0	8.5	-1.4
	4280	*3.56*	*0.78*	*22.9*	*0.5*	*9.0*	*8.5*	*-1.6*
A(402)	10065	3.58	0.86	20.1	0.5	9.0	8.5	0.9
	6335	*3.57*	*0.69*	*19.3*	*0.8*	*9.0*	*8.2*	*0.8*
R(414) minor	319	3.55	0.71	19.9	1.0	5.0	4.0	-0.8
	296	*3.55*	*0.71*	*20.0*	*1.0*	*5.0*	*4.0*	*-0.9*
M(431)	2530	3.27	0.89	27.4	0.5	8.0	7.5	-0.5
	2426	*3.26*	*0.89*	*27.3*	*0.5*	*8.0*	*7.5*	*-0.5*
AIR , %								
AA(401)	6989	4.75	0.57	11.6	0.5	7.0	7.0	0.1
	4152	*4.75*	*0.52*	*10.9*	*2.5*	*7.0*	*7.0*	*0.1*
A(402)	956	4.70	0.62	14.4	1.0	7.0	7.0	-1.2
	651	*4.70*	*0.60*	*56.3*	*1.0*	*7.0*	*7.0*	*-1.4*
R(414) minor	24	4.77	0.66	12.7	3.0	6.0	6.0	-1.3
	17	*4.70*	*0.65*	*59.8*	*3.0*	*6.0*	*6.0*	*-0.8*
M(431)	664	4.84	0.70	15.4	0.5	7.0	7.0	-1.4
	651	*4.80*	*0.67*	*26.0*	*0.5*	*6.5*	*6.5*	*-1.5*

1 in= 25.4 mm

The mean and standard deviation of slump data is substantiated by the 1966 data from field studies for both structure and paving concrete *(3)*. The skewness indicates most of the data to follow normal distribution with the exception of class 401. This happens when there is a frequent shift in the mix design which results in more than one peak in the distribution. The frequency distribution of slump measurements can be found in Appendices C and D.

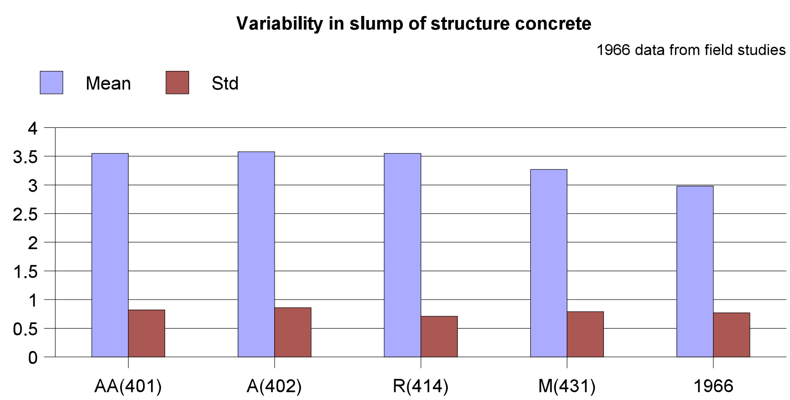
Previous studies have indicated the variability in slump measurements in the 0.5- to 0.8-inch range and the air content to vary between 0.70 to 1.60 percent *(11,14)*. The present data show somewhat higher

Table 8.10: Statewide overall & lot variability in slump and air content of different types of paving concrete

Concrete Type (MATT Code)	N *NLot*	Mean	Std Dev	CV	Min	Max	Range	Skewness
SLUMP, in								
B(451)	678	2.24	0.98	43.8	1.0	4.5	3.5	0.6
	171	*2.25*	*0.92*	*41.0*	*1.0*	*4.0*	*3.0*	*0.7*
A(452) a/	71	3.05	1.18	38.7	1.0	6.0	5.0	-0.3
	26	*3.27*	*1.09*	*33.4*	*1.0*	*5.6*	*4.6*	*-0.5*
D(454)	366	2.14	0.97	45.5	1.0	4.5	3.5	0.96
	117	*2.13*	*0.91*	*42.6*	*1.2*	*4.0*	*2.8*	*1.0*
AIR , %								
B(451)	579	4.69	0.92	19.6	0.0	7.0	7.0	-1.5
	146	*4.69*	*0.77*	*16.4*	*0.0*	*6.1*	*6.1*	*-3.0*
A(452)	23	4.65	0.65	13.9	3.5	5.5	2.0	0.1
	7	*4.73*	*0.50*	*10.6*	*4.1*	*5.3*	*1.2*	*-0.4*
D(454)	346	4.75	0.82	17.3	3.0	6.5	3.5	-0.1
	109	*4.81*	*0.70*	*14.7*	*3.3*	*6.1*	*2.8*	*-0.3*

1 in=25.4 mm

Std Dev



Concrete Class

Figure 8.14: Statewide variability in slump of structure concrete

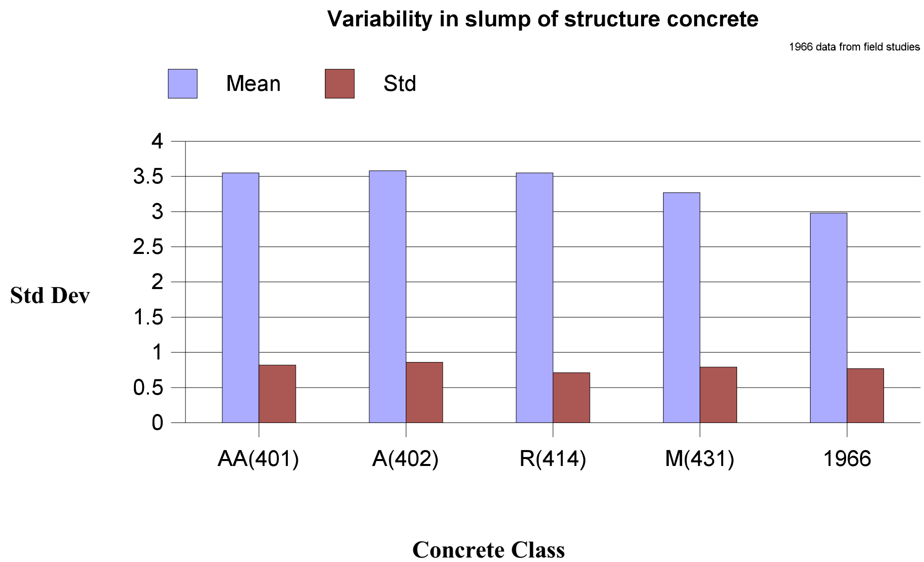


Figure 8.15: Statewide variability in slump of structure concrete

variability than indicated by these references. However, in many test results, much of the measured variation could be attributed to sampling and testing methods and procedures, and therefore the real variation may not be as large as results indicate *(3)*.

Summary of Variability Analysis -

Variation of what is considered good construction has been shown by the research summarized here. Based on this analysis, the following observations can be made:

- Most of the data on measured characteristics follow normal distribution.

- Since the first evaluation of the statistically-based specifications in 1979, there has been an increase in the magnitude of the overall mean and the standard deviation for each class of structure concrete. Such higher variability is generally associated with higher mean value of the measured characteristic.

- Since the average strength is maintained at a level well above the minimum requirement for the concrete, the actual number of nonconforming concrete is well below the predicted number based on the mean and standard deviation.

- Based on the ACI standards for field quality control, almost all classes of concrete indicated good control. For within-test variability control, most of the districts fall in the good to excellent category.

- For type B paving concrete, there has been an increase in the magnitude of the mean core strength compared to the 1979 data. However, the magnitude of variation has remained somewhat same.

- The magnitude of statewide variability in thickness, including within lot variability, show an increase from the 1979 data. The overall mean thickness for each plan thickness has remained the same.

- The overall variability in profilograph measurements (API) is higher than some of the values reported elsewhere.

- The variability of the quality control tests, slump and air content, are within the norm reported in previous studies.

Operating Characteristic (OC) Curves

OC Curve for Variability Known Sampling Plan-

As was defined in section 4, the Operating Characteristic (OC) curve is nothing more than a graphical presentation of a sampling plan which shows the relationship between the quality of a lot and the probability of its acceptance or rejection. The OC curve indicates how well a given plan discriminates between acceptable and non acceptable lots. In this section, OC curves for current acceptance plan for paving concrete core strength and thickness are presented.

OC Curve for Core Compressive Strength -

To develop an OC curve for the present acceptance plan, it is necessary to assign values to AQL and RQL (see section 4 for definition of these two terms)

AQL=98% - this is the acceptable quality level that should be accepted almost all of the time it is submitted
RQL=95% - this the rejectable quality level that should be rejected almost all of the time it is submitted
Mean=6057 psi (for type B concrete with air from Table 8.5)
Standard deviation σ=1114 psi
n=5
K, the acceptance value=Mean - 0.92σ (see reference 2 for determination of K), or K =5032 psi or 5000 psi

To see how this plan operates on lots of other means, an OC curve is constructed from data in Table 9.1. Because of the mathematical relationship between AQL, RQL and n, any change in n will change the OC curve.

The OC curve for the above plan indicates that lots with 28-day compressive strength of 5000 psi are submitted, about 50% of the lots would be accepted and 50% would be rejected. On the other hand, if the lots submitted have 6000 psi or more, almost all would be accepted. The plan is based on known sigma scheme which in essence assumes that the sigma will remain constant. This is not always the case and any change in sigma upwards will have a greater risk of accepting poor material. Increasing sample size n increases the slope of the curve thereby making the curve more discriminating. However, more samples means more cost. A balance should be in terms of cost and protection. Such curves can be developed for other types of paving concrete.

Table 9.1: Calculation of OC Curve for core strength

Mean $\bar{X}$, psi	$t = (k - \bar{X})\sqrt{n} / \sigma$	Probability of acceptance
3500	3.049	.0011
3750	2.541	0.0065
4000	2.032	0.0212
4250	1.5246	.0640
4500	1.0164	0.1539
4750	.5082	0.2810
5000	0.0	.5000
5250	.5082	.7190
5500	1.0164	.8461
5750	1.5246	.9360
6000	2.032	.9788
6250	2.541	.9945

1 psi=6.89 kPa **t in the formula is 't' distribution**

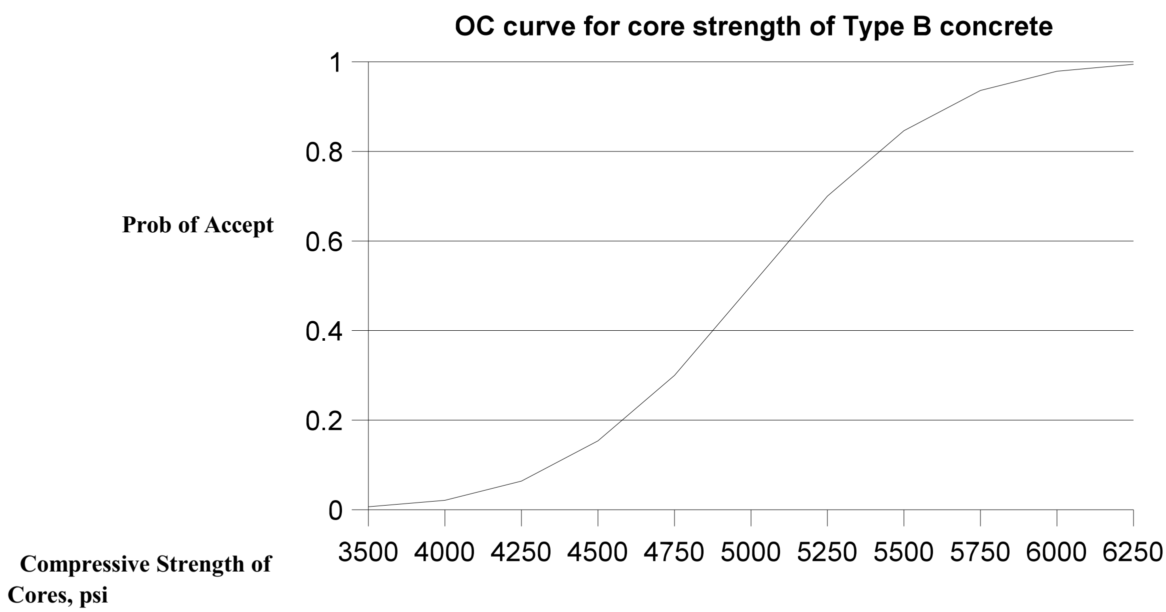


Figure 9.1: OC Curve for compressive strength of Type B paving concrete

<u>**OC Curve for Thickness of Paving Concrete**</u>

An existing acceptance plan for pavement thickness requires that n = 5 cores be taken at random location from each 4000 sq yd of pavement. Following is the OC curve for 9-inch plan thickness of pavement. Using the same risks for AQL and RQL and the statewide mean and standard deviation from Table 8.7, the OC curve for this plan would be:

AQL=98% - this is the acceptable quality level that should be accepted almost all of the time it is submitted
RQL=95% - this the rejectable quality level that should be rejected almost all of the time it is submitted
Mean=9.4 in (for 9-in thickness from Table 8.5)
Standard deviation σ=0.60
n=5
K, the acceptance value=Mean - 0.92σ (see reference 2 for determination of K), or K =8.85 in.

Table 9.2: Calculation of OC Curve for core thickness

Mean $\bar{X}$, in	t=(k - $\bar{X}$) √n / σ	Probability of acceptance
8.2	2.422	.0078
8.3	2.049	.0202
8.4	1.6771	.0465
8.5	1.3044	.0968
8.6	.9317	.1762
8.7	.5590	.2877
8.8	.1863	.4286
8.85	.5000	.5000
8.9	.1863	.5714
9.0	.5590	.7123
9.1	.9317	.8238
9.2	1.3044	.9032
9.3	1.6771	.9535
9.4	2.049	.9798

1 in=25.4 mm   t in the formula is 't' distribution

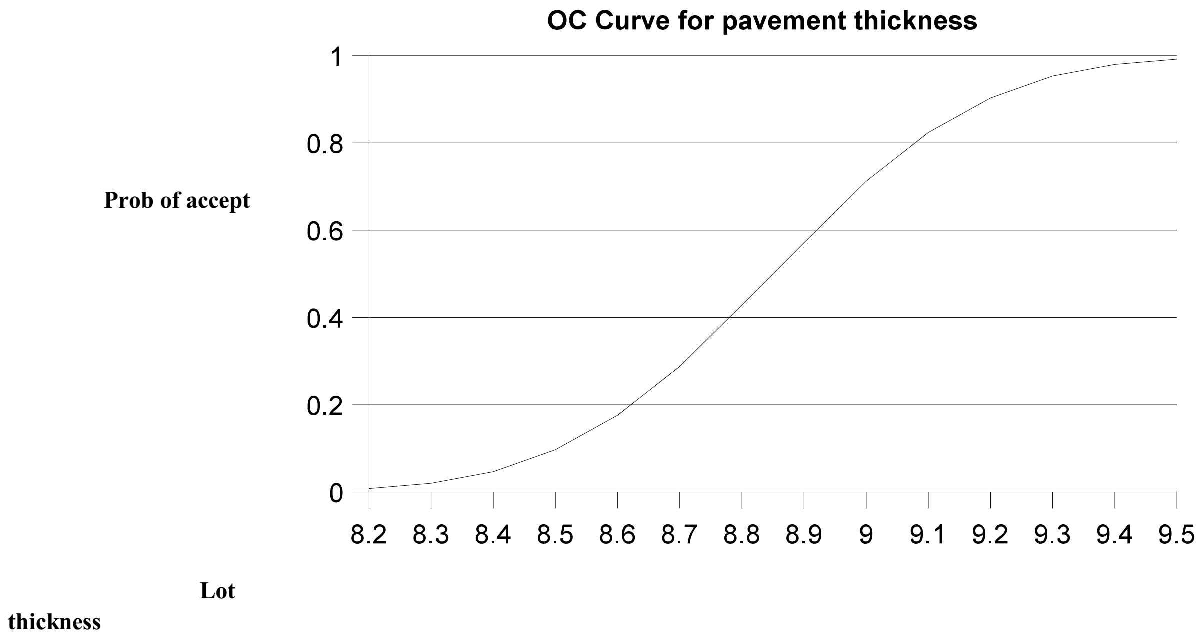


Figure 9.2: OC Curve for thickness of paving concrete cores

In the development of the above OC curve, it was assumed that the standard deviation and the arithmetic mean of the population is known. When the lot standard deviation is unknown the procedure is much the same, except that a sample estimate of σ is substituted for population σ.

From the above curve, it can be said that if a lot with a thickness of 8.6 inches is submitted to this plan the probability of accepting this lot is about 20%. It should be mentioned that the above relationship between compressive strength or thickness and probability of acceptance has some meaning when several lots are considered. Essentially what is being interpreted here is that if a number of lots of 8.6 inch thickness are submitted to this plan, approximately 20% of them will be accepted and 80% will be rejected.

The DOTD's present plan of accept/reject is similar to the one illustrated here except that the decision to accept or reject is based on the magnitude of deviation of mean thickness of the lot from the plan thickness. Two characteristics of the OC curves are worth mentioning again. First, increasing n increases the slope of the curve thereby making it more discriminating (better protection). Second, increasing K, the acceptance number, displaces the OC curve to the right and results in accepting more material.

Variability Unknown Sampling Plan (Sigma Unknown) - PWL Specifications

The PWL specifications are based on criteria in which the decision is based on the sample average in combination with a sample variability. As was mentioned before, such plans are referred to as ***unknown-sigma*** plan. The current DOTD acceptance plan for concrete is based on ***known-sigma***. In such plans acceptance is based on the sample average.

Unknown sigma plans are generally employed when inspection and acceptance of some new product is necessary and there is no basis for estimating the variability of this new product. The DOTD specifications on Superpave falls in that category. As more data becomes available and proper statistical control is indicated (either through ***Sigma*** or ***Range*** chart), it may make sense to switch to a known-sigma plan. An incidental advantage of using known-sigma plan is a reduction in sample size. Likewise, **if the statistical control of the dispersion of the measured characteristic shows lack of control, a switch to unknown sigma plan may be the choice to induce tighter control on the variability**. However, for better estimate of sigma, this plan requires larger sample size for making decision on acceptance.

Briefly, the unknown sigma acceptance plan is based on quality level analysis which involves determination of two statistics - the mean and standard deviation of a lot of certain sample size n. From these two statistics and the governing specification limit(s) for the test property, Quality Level Indices (Q_U for upper quality index and Q_L for lower quality index) are calculated. The resulting values are checked against tabled values for the sample size to determine ***Percent Within Limits*** or ***PWL***. The lot, represented by the sample, is considered in conformance to the specifications if the ***PWL*** exceeds some preset value.

Although the present DOTD acceptance plan for variables (sigma known) is adequate in that it is able to discriminate between acceptable and rejectable material, the sigma unknown type plan may be an alternative if it is felt that the magnitude of variation may be high and that better control is needed to minimize this variability. Such plans are particularly suited for acceptance of tests on completed pavement such as compaction, compressive strength of roadway cores, thickness, etc. To see how such a plan would work if applied to present data, all paving concrete projects were simulated using quality level analysis for strength and thickness. The major purpose of this simulation was to show the sensitivity of such a plan to large changes in variability.

For these projects, Q_L (since only lower tolerance is specified) was calculated to determine PWL from the tabled values. For the lot to be considered acceptable (100% pay), the value of Q_L should be greater than 1.20. Negative values of Q_L means the measured value was less than the lower tolerance specified for that measurement. The results of this simulation is presented in Appendix F. The last two columns in the table show a '1' for accept and a '0' for reject.

Application of PWL concept increased the number of lots deficient in strength requirement from three, under the present (variability known) acceptance plan, to 26 under this PWL plan. Likewise, 31 lots were found to be unacceptable under this plan versus 17 under the current plan for thickness requirement.

Some lots with average strength as high as 5500 psi would have received reduced pay because of large magnitude of variability. In some cases, the range in psi values within a lot has been as high as 4000 psi. In the case of thickness, a range as large as 3.5 inches has been observed within a lot. Such wide ranges within a segment of pavement can result in weak areas resulting in less than desired pavement life.
The PWL concept induces the contractor to control his variability to a level that would minimize reduction in pay, and provide more uniform and longer lasting product.

Summary, Conclusions and Recommendations

Summary -

_______This study evaluated the extent of variability in the test properties of structural and paving concrete materials and construction. This evaluation was based on over 25,000 lots distributed over some 900 projects during a period of seven years - 1992 to 1999. The major thrust of this evaluation was to determine how well concrete construction, both structure and paving, is controlled on various acceptance criteria and the assessment of specifications in terms of price adjustments. The data for the study was collected from the DOTD's MATT system files. The analysis and evaluation can be summarized as follows:

Assessment of Price Reduction

1. On the basis of total quantity of concrete used on the projects, the overall average reduction in price due to deficiency in acceptance criteria was 0.2% for structure concrete and 0.5% for paving concrete. This substantiates the results from such previous evaluation of 1979.

2. Seventy two percent of the reduction was for class AA and A concrete and most of this occurred at a level one scale below the 100% level (95 or 98%). Fifteen percent was at the 50% level.

3. For paving concrete 85% of the reduction was due to nonconforming thickness measurements. The overall reduction was 4% of total square yards laid with more than half at the 95% level.

4. Only 4% of the pavement tested for surface smoothness failed the stated requirement.

5. All in all, the price reduction has been minimal and within the expected frequency.

Assessment of Variability

_______Most of the price reduction discussed above can be traced to the level of control maintained during production and/or construction process. Because of the definite relationship between specification and statistical parameters, failure to maintain adequate control on the mean and standard deviation will necessarily increase the failure ratio for fixed process variability. Results of the variability analysis are summarized below:

1. Most of the data on measured characteristics for the acceptance and control criteria follow normal distribution.

2. Based on the ACI standards of concrete control, good field control is indicated by all concrete except minor Class R concrete. This substantiates the 1979 evaluation.

3. All districts showed good to excellent control proficiency in the testing phase of concrete control.

4. The strength of all classes of structure concrete is maintained at a higher level than was noted soon after implementation of the statistically based specifications in 1973. However, there is some decline in the level of control on variability.

5. As a result of longer than specified minimum curing period for strength testing, there has been an increase in the magnitude of the average core strength. However, there has also been an increase in the within lot variability.

6. There is a decline in the thickness variability as measured by the cores. Likewise, the within lot variability also show lack of control.

7. Adequate control is maintained on the slump and air content tests.

8. The OC curves for the present variability known acceptance plan for paving concrete tests are able to distinguish acceptable and unacceptable concrete.

***<u>Recommendations</u>* -**

Based on the above statements, the following recommendations are offered for consideration:

- To provide continuous feedback on the level of control maintained at all level of concrete production, increase the frequency of evaluation such as the one conducted here on a routine basis. The MATT system is geared towards satisfying this feedback requirements. Such a feedback would provide, to those responsible for monitoring the project, information relative to the level of control maintained on the mean and variability of the process, the failure ratio, and, as a guideline, the level at which the process control should be maintained to improve the product and reduce the risk of pay reduction.

- To monitor the process on routine basis, develop analysis modules, such as the ones developed in this study, using SAS system package. The modules can be used by the districts and/or project engineers to routinely monitor the level of control on regular (daily, weekly) basis. There are no tools available to do this on routine basis.

- Because of the large within-lot variability in strength and thickness measurements, consideration should be given to developing a variability unknown type acceptance plan for paving concrete criteria, similar to the present plan for Superpave. Such a plan induces the seller to maintain better control on the variability of his product.

- Another approach to reducing the within-lot variation in thickness would be to require a control chart for the Range, if thickness of plastic concrete can be measured during paving operation. This may be a better alternative since the charts give early warning on the process that is about to go out-of-control. Likewise, the curing time should be kept close to 28 days for strength testing.

- During the development of data base for analysis, anomalies were observed in the MATT system. Considerable time was spent to create a database free of invalid data. A major type of 'noise' in the data was the presence of zero(0) in the strength slump and air content fields. When air is not used, the field has to be left blank rather than the value '0'. To minimize such invalid entry, data entry into the MATT system should be constrained with more edit checks. Likewise, provision should be made to identify concrete specified versus its use, similar to the provision in the MATT system for asphaltic concrete.

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APPENDIX A
Specifications

APPENDIX B

Test Forms, Record Layout & Material Codes

APPENDIX C

Frequency Distribution of Structure Concrete Data

APPENDIX D

Frequency Distribution of Paving Concrete Data

APPENDIX E

Frequency Distribution of Profile Index & IRI

APPENDIX G

Simulation of PWL Specification