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16. Abstract
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Concrete mixes containing 10%, 20%, 30%, 40% and 60% fly ash were evaluated in the laboratory in combination with various cement contents. Type C fly ash was selected from three local sources which had been approved by the department for concrete mixes. Also, specifications were developed for using fly ash in a paving project.

In general, fly ash when used at replacement below 40% by weight of cement was found to be satisfactory in concrete. In areas that the maximum possible strength loss cannot exceed 10% of control, replacement rate of less than 25% is recommended. Increasing amounts of fly ash caused a reduction in compressive strength, especially when air-entraining agents were used or when the concrete was less than 28 days old. Retardation in the set times was also noticed with increasing amounts of fly ash. However, strength gains of up to 10% were noticed in some mixes after extended curing periods. There were no adverse effects observed on the plastic properties, freeze and thaw durability, modulus of elasticity, length change, abrasion resistance, or absorption characteristics of fly ash concrete at the replacement rates evaluated.

Based on the overall results of this study, no changes are recommended to the current fly ash concrete specifications developed earlier in this project.

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FLY ASH IN CONCRETE

FINAL REPORT

by

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RESEARCH REPORT NO. 221

RESEARCH PROJECT NO. 84-1C

Conducted by
LOUISIANA TRANSPORTATION RESEARCH CENTER
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

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AUGUST 1990

ABSTRACT

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Based on the overall results of this study, no changes are recommended to the current fly ash concrete specifications developed earlier in this project.

IMPLEMENTATION STATEMENT

Specifications were developed and implemented for fly ash concrete in Standard Specifications for state construction projects during the early part of this project. These specifications state that the contractor will be permitted partial substitution of an approved fly ash for portland cement mixes when using Type I, I(B) or Type II portland cement up to a maximum of 20% (by weight) for minor structures and pavements, and up to 15% (by weight) for structural concrete.

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INTRODUCTION

Fly ash is a fine residue material collected in the dust collection system from the burning of ground or pulverized coal by power plants. Fly ash mainly consists of the oxides of silicon, aluminum, and iron, with varying amounts of unburned carbon. Trace elements such as potassium, phosphorus, cobalt, molybdenum, boron, or manganese may also exist. The incombustible, inorganic particles of fly ash are usually spherical in shape and vary in size and density, although most are solid and contain iron compounds. The color of fly ash may vary from light tan to brown or from gray to black.

The composition of fly ash varies with the source of coal. At present two major classes of fly ash are identified and are related to the types of coal burned. These are designated Class F and Class C by the American Society of Testing and Materials (ASTM), and this differentiation is used in most current literature.

Class F fly ash is defined in ASTM Specification C-618 as the fly ash normally produced from burning bituminous coal [1]. Class F fly ash is not self-hardening but generally has pozzolanic properties. This means that in the presence of water, the fly ash particles react with calcium hydroxide (lime) to form cementitious products. The cementitious products formed are chemically similar to those present in hydrated portland cement. The pozzolanic reaction occurs slowly at normal ambient temperatures. It is reported that essentially all of the fly ash produced in the United States prior to 1985 was of this type.

Class C fly ash normally results from the burning of sub-bituminous coal and lignite such as are found in some of the western parts of the United States. Class C fly ash has pozzolanic properties but may also be self-hardening. That is when mixed with water, it hardens by hydration similar to portland cement. In most cases, this initial hardening occurs rather fast. These materials are referred to as being cementitious, and the degree of cementation generally varies with the calcium oxide (CaO) content of fly ash. Higher values of CaO denote higher cementation. This type of fly ash has become available in large quantities in the United States only in the past few years as the western coal fields have been opened. Although the degree of cementation is dependent on the total CaO content, ASTM C-618 contains no direct specification for the total CaO content. There is no specific test for the effect of cementation or any difference in the pozzolanic activity index tests or specification for the two classes of ash. The only major specification difference is the minimum limit of SiO_2 + Al_2O_3 + Fe_2O_3, which is 70% for Class F fly ash and 50% for Class C. This difference indirectly recognizes that the cementitious ashes contain appreciable CaO by allowing a lesser sum of silica, alumina, and iron oxides for Class C than for Class F. The need for reclassification based on CaO content has been proposed by some researchers.

Fly ash has found considerable use as an additive in applications such as soil stabilization, pavement base and surface courses, brick, building block, lightweight aggregate and concrete. Research on the pozzolanic action of fly ash has been published as early as 1914 in Engineering News Record. Critical evaluation of the properties of fly ash concrete began in late 1930's, with many of the early investigations conducted at the University of California - Berkeley by Raymond Davis and others who compared the performance of fly ash with volcanic ash as a concrete admixture [(2)]. These studies, together with the production of finer, more reactive ashes due to the development of more efficient collecting systems, encouraged others to experiment with fly ash. Much of the significant pioneering work in the field of fly ash concrete was conducted in the 1940's and early 1950's. Although there are numerous reports on the laboratory evaluation of fly ash, the information available on field usage is rather limited and sometimes conflicting. For example, some contractors claim that fly ash seemed to finish easier due to its lubricating qualities, while others reported fly ash produced a "sticky" concrete which made finishing more difficult. Many investigators have reported that partial replacement of portland cement by some fly ashes in mortars and concretes reduces their water requirements for flow or workability. This phenomenon is commonly believed to be a result of the spherical shape and smooth surface of many of the fly ash particles. However, water reduction obtained by fly ash does not necessarily produce a concrete which can be finished easier.

The limited amount of field data on the usage of fly ash concrete may reflect the disadvantages associated with its use. Prior to the EPA requirement of fly ash utilization in concrete, its use was even more limited. This is believed to be due to the lack of significant economic incentives by states to contractors, such as initial capital investment for required separate silos or storage bins for fly ash, and increased quality control testing. Halstead of the Virginia Highway and Transportation Research Council conducted two national surveys in 1980 and 1986 regarding the utilization of fly ash by highway agencies as a part of NCHRP Synthesis Report 127, "Use of Fly Ash in Concrete" [3],[4]. These surveys are summarized in Table 1, Appendix C. The consensus reached from these surveys indicates that almost all states now permit the use of fly ash meeting ASTM C-618 or AASHTO M295 requirements. In several cases, the maximum limit for loss on ignition is lower than either of these specifications. In most cases, sources of fly ash must be prequalified and certification of compliance to the specification is required. Generally, the amount of fly ash allowed is about 15% replacement. No problems with air-entrainment occur when loss on ignition values are in the 1.0 to 1.5 percent range. Use of an admixture is not allowed in some cases, while some states use water reduction admixtures to make possible lower water-cement ratios and thus compensate for the loss of early strength from a smaller amount of cement. The advantages reported by highway agencies include better workability, lower heat of hydration, sulfate resistance, and higher ultimate strength. The most frequent disadvantages reported include increased testing and quality control problems, lack of knowledge of field personnel, non-uniformity of fly ash, lack of cost-effectiveness since the lower cost of ingredients is not passed on to states, non-availability of good fly ash, and control of the air content.

The ability to achieve the proper air-void characteristics when air-entraining agents are used in fly ash concrete and the subsequent concrete durability performance has been the subject of many debates among researchers. The general opinion held by many highway agency personnel and contractors is that fly ash concrete is both slow to gain strength and less durable at early ages than conventional concrete. This opinion has resulted in restrictions on the use of fly ash during the cold season in some states. However, the work done by Head and Sajadi at the University of West Virginia concluded that during the early age of concrete when specimens were from 1 to 7 days old, all fly ash concrete tested in laboratory freeze and thaw performed at least as well as conventional concrete [(5)].

The work conducted by Lloyd and Young of Oklahoma State University also reported that fly ash concrete exhibited high resistance to freeze and thaw deterioration and that the air-void system of hardened concrete appeared to be unaffected by the fly ash [(6)].

In a report written by Carrasquillo, Tikalshy, and Olek of University of Texas at Austin, the use of fly ash was shown to be more durable and economical than plain concrete containing no fly ash [(7)].

Passage of the 1976 Resource Conservation and Recovery Act (RCRA) and the decision made by the Environmental Protection Agency (EPA) to establish guidelines for federal procurement of concrete containing fly ash resulted in a renewed interest in the utilization of fly ash as an ingredient for making portland cement concrete [8].

In 1985, FHWA required that all affected agencies revise their specifications, standards, and procedures to remove any discrimination against the use of fly ash in concrete unless such use was found to be technically inappropriate in a particular application. Therefore, this project was initiated by the Louisiana Transportation Research Center to evaluate the physical properties of portland cement concrete containing various amounts of Type C fly ash. Type C fly ash is the predominant source of fly ash in the state of Louisiana.

PURPOSE AND SCOPE

The purpose of this study was to:

1. Determine the suitability of locally produced fly ash sources for use in concrete mixes.

2. Determine the maximum amount of fly ash that can be used to produce a satisfactory concrete product.

3. Develop guidelines and specifications for the use of fly ash in concrete.

The scope of this project was limited to standard laboratory testing for determining workability, setting time, strength, freeze and thaw durability, abrasion and absorption of fly ash concrete. The variables selected for evaluation included cement content (6, 7 bags per cubic yard of concrete), fly ash replacement rate (10%, 20%, 30%, 40% and 60% by weight of cement), air entraining admixtures, sources of fly ash (three local sources of Type C fly ash and one source of Type F fly ash). Additionally, a 4 bag mix, with and without air, was investigated for one source of fly ash.

METHDOLOGY

Three sources of Type C fly ash were selected to be evaluated in this project. These producers were: Bayou Ash from Big Cajun Electric in New Roads, La. Gifford Hill (Boyce Ash) from Rodemacher power plant in Boyce and Ash Management from Nelson power plant in Westlake, La. These producers were approved using specifications developed by the department for source approval for the Qualified Product List (QPL). Type F fly ash was also evaluated in this project. The specifications and procedures developed for fly ash concrete are provided in Appendix A.

MIXING PROGRAM

All of the mixes were prepared in the laboratory using a 3.5-cubic foot mixer. The variables were cement content, air content (air-entrained and non-air-entrained), and the quantities of fly ash added to mix as a replacement for cement. Mixes containing 0%, 10%, 20%, 30%, 40%, and 60% fly ash replacement by weight of cement were made for each source of fly ash. Mixes containing 0% fly ash were the control mixes. The cement factors selected were 4 bags, 6 bags, and 7 bags per cubic yard of concrete. The cement factor referred to throughout this report denotes the total cementitious content (i.e., a 6-bag mix with 10% fly ash indicated a mix design containing 508 lbs of cement and 56 lbs of fly ash per cubic yard of concrete). Only one source of cement was used in this project. Air-entraining agents were the only admixtures that were utilized in this study.

The same source of fine and coarse aggregate (Class A gravel) was used in all mixes.

TESTING PROGRAM

For each mix, the following properties were determined according to the appropriate ASTM procedures.

a. Compressive strength at 7, 28, 45, 200 days; ASTM C-39, Standard Test method for Compressive Strength of Cylindrical Concrete Specimens.

b. Flexural strength at 7, 28, 45, 200 days; ASTM C-78, Standard Test Method for Flexural Strength of Concrete (using Simple Beam with Third-Point Loading).

c. Abrasion resistance 28 days and 200 days; ASTM C-944, Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by Rotating Cutter Method.

d. Length change of hardened concrete; ASTM C-157 Length Change of Hardened Hydraulic-Cement Mortar and Concrete.

e. Test for resistance to rapid freezing and thawing to 300 cycles. ASTM C-666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing.

f. Absorption test; 7 and 28 days, ASTM C-642, Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete.

g. Slump, air content, unit weight, temperature and setting times. ASTM C-142, Standard Test Method for Slump of Portland Cement Concrete; ASTM C-231, Standard Test Method for Air content of Freshly Mixed Concrete by the Pressure Method; ASTM C-138, Standard Test Method for Air Content, Unit Weight and Yield of Concrete; ASTM C-403, Standard Test Method for Time of Setting of concrete Mixtures by Penetration Resistance.

DISCUSSION OF RESULTS

PROPERTIES OF PLASTIC FLY ASH CONCRETE

Slump, Air Content, Unit Weight, and Workability

The slump designated for these mixes was 2 to 4 inches and the target air content for the air-entraining mixes was 5 $\pm$ 1%. The water/cement + fly ash ratio was designed about 0.4 for mixes containing fly ash (10% less water in mixes containing air-entraining agents). However, since fly ash acts as a lubricant, it increases the slump at a given water/cement ratio. So for each rate of fly ash addition, the amount of water was reduced to maintain the same slump range. This practice was observed in both air-entrained and non-air-entrained mixes. This was done to evaluate the properties of fly ash concrete within the target slump and air content range acceptable for most classes of concrete. It was found that the amount of water should be reduced by approximately 7%, for mixes containing up to 20% fly ash, to maintain the same workability as the control mixes. This study showed that as much as 14% to 20% water reduction is possible when a high fly ash content (greater than 30% replacement) is used.

The air content of the fly ash concrete was stable and there was no problem achieving the designed air. The majority of the air-entrained fly ash mixes had air contents within the range of 4 to 5.8% with the normal dosages of air-entraining agents. Variation in slump and air content within the acceptable range were not considered in the evaluation of physical properties of fly ash.

It has been reported by other researchers that the use of fly ash can significantly alter the air-entraining agent demand of a mix. Apparently, the high surface area associated with carbon absorbs part of the air entraining agent, thereby reducing the amount of available air. The amount of carbon in the fly ash is generally measured as the loss on the ignition. The types of fly ash selected for this study all had low carbon content (loss on ignition less than 2.7%); therefore, the air content was achieved using normal dosages of air-entraining agent.

There was no effect on the unit weight of fly ash concrete as compared to the non-fly ash concrete. On the average, the unit weight of non-air-entrained fly ash concrete was approximately 141 lbs/cubic foot. Ambient lab temperatures during mixing averaged 66^0F for all mixes while the mix temperature of the plastic concrete averaged 69^0F.

Setting Time

Perhaps one of the most noticeable effects on the properties of plastic fly ash concrete is the setting time. There was an increase in the time of both initial set and final set of fly ash concrete with the increasing substitution rates of fly ash mixes. This was true for most of the mixes that were evaluated. The initial and final setting times are shown in Figure 1 through Figure 7 for the three sources of fly ash used in this study (Nelson, Bayou, Rodemacher) and concrete mixes containing 6, 7, and 4 bags of cement and fly ash per cubic yard (for both air-entrained and non-air-entrained mixes).

There are other variables such as water/cement plus fly ash ratios that affect the set time in addition to fly ash. Since fly ash has a plasticizing effect, the water content of the mix was decreased up to 20% for mixes containing up to 60% fly ash. Retardation of 5 to 6 hours was observed for mixes containing higher amounts of fly ash as compared to the control (no fly ash concrete). It is also interesting to note that in a few of the mixes that contained up to 20% fly ash (3 out of 70) there was some slight acceleration of the time of set. These mixes had a low fly ash content (up to 20%). However, based on the variation of set times in the control sample, there was probably no real acceleration. No other significant variation in setting times among the sources evaluated in this project was observed. It is generally evident from Figures 1 through 7 that increasing the dosages of fly ash at the rates investigated in this study increases the retardation; however, a mix containing 100% fly ash will stiffen up rapidly (final setting time in less than 1/2 hour), which is a characteristic of a Type C fly ash. Due to these rapid setting properties, this type of fly ash (at 100% replacement) is being used for minor patching in some areas as reported in TR News [9].

PROPERTIES OF HARDENED FLY ASH CONCRETE

Compressive Strength

Mixes containing 10%, 20%, 30%, 40% and 60% fly ash were made for each of the three sources and the cement contents selected for this project. Cylindrical specimens of 4" by 8" were tested for determining compressive strength after 7, 28, 45 and 200 days of the moist curing.

The compressive strength is discussed individually for each source of fly ash evaluated in this project.

Nelson Ash

The results of the 6-bag (564 lbs of cement and fly ash per cubic yard) concrete with no air-entraining agents generally showed a decrease of strength with the increasing dosage of fly ash. However, it is shown in Figure 8, the decrease of compressive strength is more evident at 7 and 28 days. For example, at 7 days, the strength of the 60% fly ash is 45% less than the 0% fly ash (control). However, the same concrete when cured for 200 days showed only 15% less compressive strength as control concrete. It can be concluded that the mixes with high fly ash content will take longer time to develop the strength as compared to mixes with low fly ash content.

The same pattern of strength development is also evident for the 6 bag air-entrained mixes, as shown in Figure 9. Generally, mixes with air-entraining show less strength gain than the non-air-entrained as shown in Figures 8 and 9.

The increase of the cement content from 6 to 7 bags per cubic yard of concrete had almost compensated for an early-age strength loss due to the use of the fly ash (prior to 28 days) for non-air-entrained concrete. The slope of the curve as seen in Figure 10 shows negligible losses in compressive strength beyond 45 days of curing even when high amounts of fly ash are used in concrete. However, when high cement contents and air-entraining agents are used, the loss of strength was greater with the increasing amount of fly ash, as seen in Figure 11. In this case, the introduction of 60% fly ash resulted in a strength loss of 55% less than the 7-bag control mix at 7 days and 42% less than the same control mix at 200 days.

<u>Bayou Ash</u>

This source of fly ash improved the strength development of fly ash concrete. In the 6 bag non-air-entrained concrete, there was a compressive strength loss of 23% when concrete containing 60% fly ash was used in 7 day testing as shown in Figure 12. However, addition rates of 10%, 20% and 30% showed higher strength than the control beyond 7 days. At 200 days, the strength of concrete containing 60% fly ash was approximately 13% higher than the same mix with 100% portland cement. This may be an exception; normally, higher fly ash contents decreased the strength at a given time, as seen in other sources.

The addition of air-entraining did not change this pattern, as seen in Figure 13. The increasing dosage of fly ash did not reduce the strength gain of concrete at 7, 28, and 45 days. At 200 days strength gain was achieved with increasing the dosage of fly ash.

Increasing the cement content from 6 to 7 bags basically showed loss of strength at 7 days, no change in strength at 45 days, and strength gain at 200 days in the non-air-entrained mixes, with the increasing dosage rates of fly ash as seen in Figure 14. However, when air-entraining agents were used, there was an average drop of 6.5% in strength for each 10% replacement of fly ash prior to 45 days of curing. When curing was continued for 200 days, the rate of the strength loss as compared to control mix was slowed and was limited to only 16% loss in compressive strength, as shown in Figure 15.

In order to evaluate the use of fly ash for minor concrete construction as specified in the 1982 edition of Louisiana Standard Specifications for Roads and Bridges, fly ash was also added in 4 bag mixes both with and without air-entraining agents. The pattern of strength development is similar to higher cement content concrete mixes. The strength loss is 60% at 7 days for mixes containing 60% fly ash. However, at 200-day testing there is no appreciable difference in strength between fly ash and non-fly ash concrete, as depicted in Figure 16. For the same group of mixes with air agents, the mixes show a uniform loss of strength with increasing dosage of fly ash as shown in Figure 17. The water used for these low-cement content mixes varied from 6.8 gallons/sack for 0% fly ash to 5.3 gallons/sack for a mix containing 60% fly ash. Slump varied from 2" to 4" from the same group of mixes.

<u>Rodemacher (Boyce) Ash</u>

Using this type of fly ash basically provided results similar to the other types of fly ash. There was a uniform decrease in strength with increasing dosage of fly ash at ages prior to 45 days. However, at later ages (200 days), there was almost no difference in the compressive strength of the different fly ash contents used for the 6 bag concrete with no air-entraining, as seen in the Figure 18. The addition of air-entraining seemed to slow the strength gain of concrete even at the 200-day testing, as seen in Figure 19. However, it is probable that at the later ages

(1 year and beyond), fly ash concrete will have a compressive strength not less than the comparable 100% portland cement concrete.

With the increase of the cement content from 6 to 7 bags, the same pattern of strength development was noticed, as seen in Figures 20 and 21. There was very little change in the 200-day breaks at varying fly ash contents. The addition of air-entraining agent produced the same pattern but at lower strength levels as seen in Figure 21.

Overall, increasing the amount of fly ash generally causes a reduction of compressive strength as illustrated in Figures 22 through 25. In these figures, the compressive strength of the similar fly ash mixes from the three sources were averaged and were compared to control mix (0% fly ash). The plots show the percent gain or loss of compressive strength for each amount of added fly ash (10%, 20%, 30%, 40%, 60%) for each age (7, 28, 45, and 200 days) for 6 and 7-bag cement content with and without air-entraining agents.

The compressive strengths used for tabulation of the comparison charts are shown in Tables 2, 3, and 4 for all mixes made in this study. The maximum strength gain (up to 200 days of curing) is less than 10% for all ages and all fly ash contents tested in this study. The addition of air-entraining agents and fly ash also causes lower strength development as compared with non-air-entrained mixes. Also, a higher amount of fly ash (greater than 40 percent) results in strength loss of up to 40% at 7 days of curing. Overall averages of the strengths indicated that in no instance could the 60% fly ash content reach the strength of the normal concrete even after 200 days of curing. It can be concluded from this data that for general fly ash usage in concrete, the fly ash content should not exceed a maximum of 40% replacement. In situation where the possible strength losses could not exceed 10%

of the control, a maximum of 25% fly ash content can be used. Each job mix is different and a trial mix has to be made. The information contained herein can be used as a guide to achieve the proper mix design. This limit has to be reduced if there is a need for obtaining required strength, especially at early ages. Since this study did not consider the effect of fly ash in early ages (prior to 7 days), no comment is made in regard to early age strength of fly ash concrete. However, since the result of 7-day breaks for fly ash concrete is less than the reference concrete for the average of all the fly ash mixes, it can be concluded that it would be lower in the earlier ages. In other words, fly ash normally reduces the early strength of concrete in mixes that contain a certain percentage of fly ash.

Fly ash has been used in the production of high-strength concrete in combination with other admixtures elsewhere. However, according to the data obtained in this study, the maximum strength gain was less than 10% as compared to normal (100% portland cement concrete). Therefore, one cannot rely only on fly ash to achieve high-strength concrete, and other admixtures have to be utilized. In general, there is a decrease in strength of the concrete with the addition of fly ash. The difference in strength is more evident when an air-entraining agent is used and/or when the concrete is less than 28 days old.

In order to estimate the maximum quantity of fly ash that can be safely used in concrete mixes, the compressive strength from the mixes with the same amount of cement, fly ash content, and admixture was averaged. The linear relationship between the average compressive values and percent fly ash content is shown in Figures 26 through 29 for 6 and 7-bag (air and non-air) groups. From these figures, one can estimate the total fly ash that can be added to a concrete mix (by replacing the portland cement), depending on the required design strength and the minimum time of curing necessary to achieve the design strength. For example, referring to Figure 26 and assuming a 28-day design strength of 5000 psi for a 6-bag air-entrained concrete, the maximum fly ash that can be added should not exceed 24% by weight of cement. For concrete with a higher cement content such as a 7-bag/cubic yard of concrete and air-entrainment, the maximum fly ash content is less than 20% percent for the same design strength requirement. Based on these results, it is not necessary to change the current specifications for the maximum fly ash content for use in concrete mixes. In order to evaluate the effect of different sources of fly ash on the compressive strength of concrete, an analysis of variance (ANOVA) was conducted. This was done through the T Tests on the compressive strengths of fly ash concrete with the same total cementitious content on all mixes that were made in this study. A value level of 0.05 was selected for the level of significance. The results indicated that the variation from one source of fly ash to another is not significant.

It is felt that as long as the fly ash meets the requirement of current source approval specification, it should be suitable for use in concrete mixes.

Flexural Strength of Fly Ash Concrete

The flexural strengths for each group of mixes containing the same fly ash dosage rates were averaged for 6 and 7-bag cement concrete groups with and without air-entraining agents. The results are shown in Figures 30 through 33 for mixes containing 6 bags with air-entraining, 6 bags with no air, 7 bags with air, and 7 bags with no air-entraining agent, respectively. Assuming a 28-day design flexural strength of 700 psi, for a 7- bag non-air entrained mix, concrete mixes containing up to 40% fly ash were able to achieve this strength. However, with the addition of air-entraining agents, the strength levels decreased and, as can be seen from Figure 32, it can be concluded the maximum fly ash content should not be more than 20%.

Comparisons of flexural strength of the fly ash mixes to mixes containing 0% fly ash similar to those discussed in the compressive strength section were made. The results of these comparisons are graphically presented in Figures 34 through 37 for the 6 and 7-bag groups (no-air and air-entrained mixes). For the non-air entraining mixes, fly ash content of up to 20% replacement in 7-bag mixes resulted in an increase of a maximum of 15% from the reference mix (Figure 37). With the addition of air-entraining agents, no increase of flexural strength was noticed as shown in Figure 36. Again, we can conclude that fly ash up to 20% can be used in all types of concrete with some increases in flexural strength. Higher amounts of fly ash up to 40% can also be used if certain restrictions can be applied, such as requiring a longer curing period. Based on the results of this study, fly ash content of more than 40% results in low flexural strength and is not recommended for use. Tables 5 through Table 7 in Appendix C show the actual data that were used for this discussion.

Modulus of Elasticity

The modulus of elasticity of concrete is not affected by the fly ash as seen in Figure 38. In this figure, the average modulus for the three sources of fly ash are depicted for 6 and 7-bag groups with and without air-entraining agents. The modulus of elasticity, like compressive strength, is dependent on the total cement (cement and fly ash) content of the concrete and is also influenced by the addition of air-entraining agents. As can be seen from Figure 38, the 7-bag total cementitious concrete produced higher modulus values than the to 6-bag concrete. Also, mixes containing air-entraining agents produced lower modulus values than comparable mixes without air agents. Overall the addition of fly ash did not affect the modulus. A value of 6×10^6 psi can be used for fly ash concrete for structural and paving concrete application (based on 28 day testing).

Freeze and Thaw Durability Discussion of Fly Ash Concrete

The durability factors for the three sources of fly ash selected in this study were determined for non-air and air-entrained mixes according to ASTM C-666 Procedure B with modified curing period (14 days of moist curing followed by 14 days of drying before the start of the test). The results of these tests are depicted in Figures 39 through 44 for 6 and 7-bag cement content for Nelson, Bayou, and Rodemacher fly ash sources respectively.

As can be seen from these figures, in general the durability is improved significantly when air-entraining agents are added to fly ash concrete as it is for normal, 100% portland cement concrete. However, from our previous experience, chert gravel aggregate, which was used in this project has shown poor durability performance as measured by ASTM C-666 Procedure B modified. This poor durability was often observed even in the mixes that had air-entraining agents.

The addition of fly ash (even in high dosages) did not produce any adverse effect on the F & T durability of concrete. In the 6-bag group mixes from the Bayou fly ash source, the cement that was used may have been partially mixed with Type A cement (air-entrained cement) which probably happened during the manufacturing of the cement. This caused higher air contents in some of the mixes using this cement. As soon as the problem was identified, the cement source was changed. Subsequently, some of the results were also affected, causing some of the mixes of the non-air group to show better durability as compared to others (Figure 40). The results of mixes containing the air- entraining cement were excluded from overall averaging.

In Figures 45 and 46 the results of the durability factors from similar mixes were averaged and are shown for comparison. It is clear that fly ash does not adversly affect the durability of concrete. More so, the percent increase or decrease in the durability factors as compared to normal, 100% cement are shown in

Figure 47. The majority of the mixes containing fly ash retain the same effectiveness in durability factors. The durability was improved in high fly ash content mixes (60%), particulary in the non-air-entrained mixes.

Length Change of Hardened Fly Ash Concrete

The effect of fly ash on the drying shrinkage of fly ash concrete was evaluated using the ASTM Procedure 157 entitled "Length Change of Hardened Cement Mortar and Concrete."

The results are plotted in Figures 48 and 49, showing the percent length change for each fly ash content and cement content evaluated (6 and 7-bag) and also percent difference from the control (100% cement). The results indicated that the fly ash does not significantly influence the dry shrinkage of concrete. Furthermore, less drying shrinkage is experienced with the high dosages of fly ash. This could be due to the lower amount of water that was used in those mixes with high fly ash content. The majority of the reduction noticed fell between .025% and .035% length change after curing for 28 days. The shrinkage of the mixes with low cement content (4-bag total cement and fly ash per cubic yard) was between .035% and .04% with little variation for various fly ash contents, as shown in Figure 50. It is important to note that this test does not measure the shrinkage or shrinkage cracking of concrete during the first few hours after placement and further testing needs to be developed to study the rate of shrinkage immediately after placement for fly ash concrete.

Abrasion Resistance of Fly Ash Concrete

The abrasion resistance of the fly ash concrete in this study was determined using the ASTM Procedure C-944 entitled "Abrasion Resistance of Concrete or Mortar Surfaces by Rotating-Cutter Method." In this procedure, using a drill press or a similar device, concrete specimens are subjected to the abrasive action of a set of dressing wheels for a certain time period. At the end of the test period, the loss of mortar due to abrasion is measured and the results are reported in gram loss per square centimeter of abraded areas.

The abrasion test was conducted on the 6 and 7-bag concrete mixes (both air- entrained and non-air) and fly ash contents of 10%, 20%, 30%, 40% and 60% after 28 and 200 days of curing. The abrasion resistance of concrete increases with time; however, the increasing amount of fly ash had greater loss of mortar, as shown in Figure 51. Also, air-entraining agents seem to decrease the abrasion resistance of hardened concrete during the early ages. After 200 days of curing, the amount of fly ash in the mix does not make a significant difference in abrasion resistance of concrete as shown in Figure 52.

Absorption Characteristics of Fly Ash Concrete

The absorption characteristics of the fly ash concrete were determined using the ASTM procedure 642 entitled "Specific Gravity, Absorption, and Voids in Hardened Concrete." The results indicated insignificant differences among the various percentages of fly ash content, the cement content, or the presence of air-entraining admixture. The overall results are shown in Figure 53. Test periods of 28 and 200 days of submersion were used in this study for various fly ash contents. All of the absorption rates fall between 4% and 5%, which is considered normal for concrete.

EVALUATION OF TYPE F FLY ASH

Type F fly ash is not normally available in Louisiana and therefore is not used locally. For this reason, it was not originally included in this evaluation. However, in order to see if there are any differences in terms of its influence in normal concrete, Type F fly ash was obtained from Trinity Materials at Purvis, Mississippi. Two groups of mixes containing 6 bags of cement per cubic yard with 10% and 20% fly ash were evaluated in the laboratory.

According to ASTM 618, Class F fly ash is normally produced from burning anthracite or bituminous coal. Class F fly ash is not self hardening but generally has pozzolanic properties. This means that in the presence of water, the fly ash particles react with calcium hydroxide (lime) to form cementitious products.

The results of our strength evaluation are shown in Figure 54 for the compressive strength and Figure 55 for the flexural strength. The strength gain of the Type F fly ash seems to be somewhat slower than the comparable mixes with Type C fly ash. However, after 45 days of curing the difference is minimized. Other properties of of Type F fly ash concrete were similar to the Type C fly ash concrete evaluated in this project.

FIELD USE OF FLY ASH CONCRETE

In order to evaluate the properties of fly ash concrete under field conditions, special provisions were written to allow the use of fly ash in a concrete paving job. For this purpose, State Project 77-05-29 was selected. This project included the reconstruction and widening of Jefferson Highway in Baton Rouge, La. from two lanes to four lanes between Brentwood Drive and Drusilla (total length of a project was 3611 feet). The existing asphaltic pavement was removed and replaced by an 8 inch portland cement concrete pavement (20 ft. joint spacing) with a 3 inch hot mix base course over a 6-inch lime-treated subbase. The 66-ft wide road was constructed with two 4-ft. sidewalks and also included a center turn lane for better traffic flow. The construction was completed in the fall of 1986. The contractor was Barber Brothers Contracting Co., Inc., Baton Rouge, Louisiana. The concrete specifications (see Appendix A) called for the substitution of 20% fly ash which was supplied by

Bayou Ash, a source that was evaluated in the laboratory phase of this project. The concrete mix design was according to the standard Type B concrete pavement specifications (5.8 bags of cement/cubic yard, maximum water cement ratio of 6 gallons/sack). This was the first DOTD concrete paving project in Louisiana in which fly ash was used. Currently, standard specifications permit the use of up to 15% and 20% (by weight) replacement of portland cement with Type C fly ash in structural concrete and paving concrete, respectively.

THE CONCRETE PAVEMENT

The properties of fresh and hardened concrete were determined through tests on random samples. The molded cylinders cast from the paving concrete at the job site, and moist cured in the laboratory produced an average compressive strength of 3657, 4984, 5554 psi after 7, 28, and 45 days of curing, respectively. The results of the flexural strength testing obtained from job site cast concrete were 584, 655 and 721 psi for the same curing period as the cylinders. There were no unusual problems associated with the use of fly ash concrete during the paving construction according to the contractor personnel or inspectors. Other properties of concrete were similar to those obtained from laboratory experimentation. Since this project, several other paving projects were constructed using fly ash concrete.

There were some problems reported with concrete that contained fly ash based on local construction as well as information received from other states. In a rehabilitation and widening project of I-12, State Project 454-01-40, excessive full depth transverse cracking was experienced at several locations throughout the project. This caused removal and replacement of an approximately one mile long (27 feet wide) portion of the highway. Although the cause of the cracking could not be accurately determined, several factors such as the thickness of the pavement (14"), shallow depth of the saw cut, improper timing of the saw cut due to set retardation of concrete which may have been caused by the fly ash, and bonding of the pavement to the asphaltic concrete base course were identified as possible causes. In other projects, there were some transverse cracks developed which were repaired by removing and replacing a 6 foot long section of the highway at the crack site. Other problems reported by other states when fly ash was used in concrete include the following:

Rapid drying:
Bridge deck concrete containing Class C fly ash has exhibited rapid surface drying. This causes finishing problems such as tearing and holes in the surface. It can also result in shrinkage cracks.

Set retardation:
Deck concrete containing fly ash (usually Class F) has exhibited severe set retardation. In some cases it has taken 12 hours or more to set. This makes it very difficult to cover the deck for protection against cold or precipitation without damaging the surface.

Variation of Consistency:
In many cases fly ash causes an excessive variation of air content in concrete. This results in a variation of consistency (slump). In decks, this variable consistency produces an uneven surface.

COST AND AVAILABILITY OF FLY ASH

Currently, in the Baton Rouge area, fly ash costs about $15 per ton and portland cement costs approximately $47 per ton for concrete usage. Savings obtained in a cubic yard of concrete containing 6 bags of cement and fly ash (20% replacement by weight of cement) is 14% lower as compared to a 100% cement mix. Actual savings may be less since the contractor has to provide additional storage and handling facilities for fly ash. Availability of locally produced fly ash is shown in Table 8, Appendix C.

CONCLUSIONS AND RECOMMENDATIONS

Based on the overall laboratory findings of this study, it is concluded that:

1. Increasing the amount of fly ash generally slows the strength development. Also, the maximum strength gain was not greater than 10% of the comparable mix of 100% portland cement. Fly ash contents of greater than 40% significantly delay the strength development of fly ash concrete.

2. The qualified procedures currently in use by the department in approving fly ash source for concrete use are adequate.

3. Fly ash delays the setting time of concrete. Increasing the amount of fly ash in concrete mix will result in higher retardation.

4. Fly ash when added to concrete can act as a water reducer while maintaining the same workability.

5. Fly ash sources evaluated in this study did not affect the air-entraining ability of air-entraining agents when mixed in concrete.

6. There is no influence on modulus of elasticity, dry shrinkage properties and water absorption characteristics of concrete by the substitution of fly ash at the rates evaluated in this study.

It is recommended that the current specifications and procedures for approving and using of fly ash in concrete be followed. No changes are recommended at this time. Also, in order to obtain field data on placement and long term performance of fly ash concrete, structures built with fly ash concrete should be monitored closely to provide the needed information.

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1983.

APPENDIX A

QUALIFICATION PROCEDURES

TABLE 1

FLY ASH UTILIZED BY HIGHWAY AGENCIES

State	1980 Survey	1986 NCHRP Survey
Alabama	----	Pioneer in use of fly ash among all state agencies, Class F fly ash in use since 1953, specification required Type 1P in pavement concrete since 1960. No problem with durability and air-entrainment if loss of ignition is less than 4%.
Alaska	----	No fly ash available.
Arizona	----	Substantial use of Class F in the pavement.
Arkansas	----	Laboratory experimentation concluded satisfactory replacement of fly ash (type C) up to 65% in non-air-entrained concrete and 25% replacement in air-entrained concrete.
California	----	Uses 95% Class F and 5% Class C.
Colorado	----	Fly ash allowed under special circumstances in all applications.
Connecticut	----	----

Delaware	----		Specification change, no use to date.

TABLE 1 (Continued)

FLY ASH UTILIZED BY HIGHWAY AGENCIES

State	1980 Survey	1986 NCHRP Survey
District of Columbia	----	Specification change.
Florida	----	Research has shown Type F fly ash improved sulfate resistance, reduced maximum temperature. Class F fly ash may be used in Type 1, Type II, Type III, or Type V with certain restrictions.
Georgia	----	Permitted at option of contractor, Type F.
Hawaii	----	Permitted at option of contractor but none has been used to date.
Idaho	----	Permitted use of fly ash but no competitive bids have been received.
Illinois	----	Fly ash permitted and used in paving project, no performance data.
Indiana	----	Fly ash as admixture not permitted.
Iowa	Permitted in paving concrete, 5% maximum loss of ignition.	Permitted with quality aggregate.

TABLE 1 (Continued)

FLY ASH UTILIZED BY HIGHWAY AGENCIES

State	1980 Survey	1986 NCHRP Survey
Kansas	Use not permitted.	Will change specification to comply with FHWA and EPA.
Kentucky	Use not permitted, blended cement in few paving projects.	Permitted at option of contractor.
Louisiana	Fly ash not permitted Type 1P allowed.	15% in structural and 21% in paving projects.
Main	No fly ash available.	Specifications are being re-evaluated.
Maryland	Class F Allowed, limited limited use, 15% substitution.	Permitted at option of contractor.
Massachusetts	Not permitted.	Will revised specification to comply with FHWA.
Michigan	Permitted fly ash and Type IP except during the cold season.	Permitted at option of contractor, very limited use except in pavements.
Minnesota	Largest user of fly ash northern states.	Extensive use, among greatest use of Class F.
Missouri	----	Planning to use in the few selected projects.
Montana	----	Fly ash not permitted.

Nebraska	Class F fly ash permitted in paving concrete.	----

TABLE 1 (Continued)

FLY ASH UTILIZED BY HIGHWAY AGENCIES

State	1980 Survey	1986 NCHRP Survey
Nevada	Not permitted.	----
New Hampshire	Not permitted, no good	Specifications are being re-evaluated.
New Jersey	Not permitted.	Special provisions, experimental use.
New Mexico	Fly ash permitted.	Fly ash permitted with some aggregates.
New York	Not permitted in highways or structures.	Experimental project underway, will revise specification.
North Carolina	Not permitted.	Not permitted, experimental use under evaluation.
North Dakota	Fly ash permitted in pavement.	Permitted at option of contractor.
Ohio	Permitted fly ash only in base concrete, Class F.	Recent specification change.
Oklahoma	Not permitted.	Permitted the use of fly ash.
Oregon	Permitted in structures only if 28-day strength is greater than 4000 psi. Not used in concrete deck wearing surfaces.	Permitted in construction of curbs, gutters, foundations, etc. Not in pavement and bridge decks.
Pennsylvania	Permitted in pavement but not in structures, Class F.	Permitted at option contractor, no reduction in cement for pumping applications.

Rhode Island	Not permitted.	Use to date, may change.

TABLE 1 (Continued)

FLY ASH UTILIZED BY HIGHWAY AGENCIES

State	1980 Survey	1986 NCHRP Survey
South Carolina	Type IP only.	Not permitted, very little experience.
South Dakota	Permitted in pavement	Specifications are being only prepared.
Tennessee	Not permitted.	Not permitted, experimental usage.
Texas	Use not permitted.	Permitted at option of contractor, special provision.
Utah	Used in one project only, limiting the use of fly ash in projects with re-active aggregate.	Experimental use of fly in concrete mix with reactive aggregate.
Vermont	Use not permitted.	Will revise specifications to comply with FHWA-EPA.
Virginia	Not permitted, used ex-perimentally in curbs, gutters, etc.	Recent specification change.
Washington	Use not permitted.	Recent specification change.
West Virginia	----	Considerable use in pavement.
Wisconsin	----	Pavement use only.
Wyoming	----	Specific projects only.

TABLE 8

LOCAL AVAILABILITY OF FLY ASH

PLANT	LOCATION	STORAGE	POWER OUTPUT	PRODUCTION/DAY	SUPPLIER
Nelson	Westlake	1 silo 756 tons	550 MW	250-325 tons	Ash Management
Cajun	New Roads	2 silos 5160 tons (total)	3 units at 540 MW each	1125 tons	Bayou Ash
Rodemacher	Boyce	1 silo 4517 tons	542 MW	300 tons	Gifford Hill
Cason	Cason, TX	3 silos	3 units @ 428 MW each	300 tons	Gifford Hill

TABLE 2

COMPRESSIVE STRENGTH OF FAC, NELSON ASH

TABLE 3

COMPRESSIVE STRENGTH OF FAC, BAYOU ASH

TABLE 4

COMPRESSIVE STRENGTH OF FAC, RODEMACHER BAYOU ASH (BOYCE)

TABLE 5

FLEXURAL STRENGTH OF FAC, NELSON ASH

TABLE 6

FLEXURAL STRENGTH OF FAC, BAYOU ASH

TABLE 7

FLEXURAL STRENGTH OF FAC, RODMACHER (BOYLE) ASH

State of Louisiana
Department of Transportation and Development (DOTD)
Materials and Testing Section Qualification Procedure
for
Qualified Products List 50

FLY ASH

MATERIAL SPECIFICATION REFERENCE:

DOTD Standard Specifications, Subsection 901.02, 03, 08, 1018.25 and MS-166-001 (copies attached).

PRELIMINARY REQUIREMENTS:

Qualified Product Evaluation Form

The manufacturer shall submit a standard "Qualified Product Evaluation Form" (copy attached) to the DOTD Materials and Testing Section coordinator listed below, along with a letter requesting evaluation for the Qualified Products List. The following information must be included in the request for evaluation.

1) Complete names and addresses of the fly Ash source and owner.
2) Complete name and address of the supplier.
3) Complete name and address of the coal mine.
4) Type of fly ash produced and type of coal used.
5) Description of fly ash storage facilities including capacities.
6) An outline of production procedures including pulverization techniques, description of additives mixed with coal during production, and ash collection methods.
7) An outline of the supplier's quality assurance sampling and testing program.
8) Name and address of laboratory performing quality control tests and a copy of their CCRL inspection reports.
9) Intended use of fly ash.

Product Data Sheets

Manufacturer is to include a Materials Safety Data Sheet (MSDS).

Certification and/or Test Reports

Submit a notarized Certificate of Analysis for the five preliminary samples and the ten weekly qualification samples. The Certificate of Analysis shall show test results applicable to the intended use of the material. All test results included on the certificate of analysis shall be performed by a laboratory which has been inspected by CCRL.

Sample (to be furnished at no cost to the Department)

Submit five daily samples, each consisting of approximately one gallon of fly ash, to the DOTD Materials and Testing Coordinator for evaluation. Each sample shall be randomly taken each day for five days from one identifiable storage unit.

Each source must also provide 10 weekly qualification samples to the Department's Materials Section for source approval. At the end of each week, equal portions of daily samples shall be composited and blended to obtain the weekly sample. This composited sample shall be continually split until a 10-lb. sample is obtained. Half of the 10 lb. sample shall be sent to the Materials Section and the other half retained and tested by the supplier. The supplier shall forward applicable physical and chemical test results obtained on the retained sample to the DOTD Materials and Testing Coordinator upon completion of tests. The 28-day Pozzolanic Activity Index test will not be required on weekly composite tests. After completion of tests, the Department may grant source approval depending on the results of the weekly samples. When source approval is given, weekly samples will be discontinued and monthly samples begun.

TEST REQUIREMENTS:

Laboratory Testing

Each qualification sample will be tested by a Laboratory previously inspected by CCRL for compliance with the applicable Departmental Specification for its intended use. All tests will be conducted in accordance with ASTM Designation C 311. After the qualification samples have been tested, the average fineness and specific gravity will be determined and Initial Variability limits will be established for each source as follows:

Fineness, percentage points from average ±5/l
Specific Gravity, max. variation from average ±5%

Field Evaluation

the Department may require an Inspection of the plant to review methods of sampling, testing and handling of fly ash.

Total Evaluation Time

Laboratory Testing - 28 weeks
Field Evaluation - 2 weeks

GENERAL:

Upon completion of the evaluation, the distributor will be notified in writing concerning the results of the evaluation and whether the source will or will not be added to the Qualified Products Lists. Source approval may be granted based on the Department's satisfaction that consistent fly ash is being produced, and that it conforms with Departmental Specifications.

The source must have an effective quality control program to ensure that the fly ash possesses uniform characteristics within the Department's specifications. The variability limits as defined above will be recalculated after each monthly sample has been tested and will be based on the most current 10 test results.

If approved, the manufacturer is required to submit a list to the DOTD Materials and Testing Coordinator showing plant representatives authorized to:

1) Sample fly ash in accordance with this procedure.

2) Sign ""Fly Ash Certificate of Delivery" forms which must be completed for each shipment.

3) Submit monthly source samples an sign certificates of analysis for the monthly source samples.

The monthly sample will be representative sample of the production of fly ash for each month. The 20 lb. sample is to be split with half retained and tested by a CCRL inspected laboratory and half submitted to the DOTD Materials and Testing Coordinator. All results obtained on monthly samples must be submitted to the DOTD Material and Testing Coordinator with proper identification stating month represented an sample number.

When plants are periodically inspected by the National Bureau of Standards Cement and Concrete Reference Laboratory (CCRL), a copy of the latest CCRL report accompanied by documentation of resolutions of any discrepancies in lieu of the above mentioned inspection shall be submitted to the DOTD Materials Section. CCRL reports will be treated with strict confidentiality.

A completed ""Fly Ash Certificate of Delivery" form, supplied by the Department, shall accompany all shipments of fly ash intended for use on state projects. A copy of each form shall also be sent to the Materials Engineer Administrator. This form shall be signed by an authorized representative. The

distributor shall keep the certificate on file and issue a new certificate with each shipment to state projects with a copy of the new certificate mailed to the Materials Engineer.

The Department reserves the right to send a representative to make on-site inspections of facilities with emphasis on the method of sampling and testing.

PROJECT ACCEPTANCE REQUIREMENTS:

Verification

The Department's personnel will sample shipments to state projects in accordance with the Department's Materials Sampling Manual. These samples will be submitted to the Materials Section for testing in accordance with ASTM Designation: C 311 for compliance to the specifications governing the intended use.

Acceptance

Fly ash received on the jobsite from an approved source will be accepted by project personnel based on properly completed Certificate of Delivery forms. The Certificate of Delivery shall be signed by an authorized representative of the supplier and should accompany each shipment to state projects. The certificate should address specifically the specification governing each delivery's intended use. If it is established by the Materials Section that fly ash verification samples from an approved source does not conform with the variability limits as calculated under the heading "TEST REQUIREMENTS" or "GENERAL", then subsequent shipments from that source will be sampled prior to use and acceptance of each shipment will be based on conformance with specifications. Pretesting of shipments for acceptance will continue until such time that 1) variability limits are no longer exceeded or 2) the source is removed from the Qualified Products Lists (see "DISQUALIFICATION").

DISQUALIFICATION:

The Department reserves the right to remove any source from the Qualified Products Lists at any time confidence is lost in a manufacturer's ability or intent to produce material of uniform characteristics complying with Departmental specifications. Causes for removal from the list may include, but are not limited to the following:

1. Failure of the supplier to provide proper certifications as required by this procedure.

2. Failing test results obtained by the Materials Section on consecutive verification samples.

3. Continued violation of variability limits.

REQUALIFICATION:

Once removed from the Qualified Products List, a source may gain reinstatement by submitting a written request to the Materials Engineer Administrator for reinstatement indicating the causes and solutions to the problem areas which caused removal, an satisfying all of the preliminary requirements shown herein.

After examination of the information gained from the above, at the Materials Engineer Administrator's discretion, the source may be reinstated after a minimum period of 3 months from the date of request for reinstatement.