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16. Abstract <p>The need for more cost efficient construction materials for use in highway construction and the problem of waste disposal of fly ash have prompted the study reported herein. This study addresses the major concerns of resident highway engineers about concrete containing fly ash for highway applications, which include: curing conditions, strength development, durability, materials selection and mix proportioning. This report summarizes the proposed trial mix design procedure for concrete containing fly ash developed by the Texas State Department of Highways and Public Transportation. Contrary to the current practice in most states, the trial mix design procedure developed by the TSDHPT has as its main objective the development of a set of mixture proportions containing fly ash that would produce a concrete mix meeting the job specifications without reference to a control mix containing no fly ash. In other words, the procedure described herein is not intended to produce a concrete mix containing fly ash with strength equal to that of a concrete mix without fly ash, but to produce the most efficient concrete mix containing fly ash that will meet the job specifications for a given class of concrete.</p> <p>The mix design procedure described herein recognizes the fact that it is impossible if not unrealistic to efficiently design a concrete mix containing fly ash based on a predetermined cement replacement ratio either by weight or volume due to the different performance of different combinations of materials. Mix proportioning of concrete containing fly ash based on a predetermined cement replacement ratio often results in concrete mixes of questionable performance, having too high a fines content and being "too sticky." As a result, the procedure adopted makes no assumptions as to the interaction among a given set of materials but allows for the selection of their optimum mix proportions. In summary, this report describes a mix proportioning procedure that ensures the resident engineer the production of good quality concrete containing fly ash for highway applications.</p>			
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MIX PROPORTIONING OF CONCRETE CONTAINING FLY ASH  
FOR HIGHWAY APPLICATIONS

by

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and  
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Research Report No. 364-4F

Production of Concrete Containing Fly Ash

Research Project 3-9-84-364

Conducted for

Texas

State Department of Highways and Public Transportation  
In cooperation with the  
U.S. Department of Transportation  
Federal Highway Administration

by

CENTER FOR TRANSPORTATION RESEARCH  
BUREAU OF ENGINEERING RESEARCH  
THE UNIVERSITY OF TEXAS AT AUSTIN

May 1986

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

## P R E F A C E

This is the fourth and final report in a series of reports which summarizes the effect of fly ash on the production of concrete containing fly ash for use in Texas highways. The first report in the series summarized the effect of fly ash on the production of structural concrete. The second report summarized the effect of fly ash on concrete used for highway pavement applications. The third report of the series summarized the effects of fly ash on the durability of concrete containing fly ash. The fourth and final report of the series outlines a mix proportioning procedure for concrete containing fly ash. The last report uses the results of the previous three reports to develop a mix design procedure which results in a concrete mix that meets all applicable Texas State Department of Highways and Public Transportation specifications for a given class of concrete.

This work is part of Research Project 3-9-84-364, entitled "Production of Concrete Containing Fly Ash." The studies described were conducted jointly between the Center for Transportation Research, Bureau of Engineering Research, and the Phil M. Ferguson Structural Engineering Laboratory at The University of Texas at Austin. The work was co-sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration. The studies were performed in cooperation with the Texas State Department of Highways and Public Transportation Materials and Testing Division through contact with Mr. Fred Schindler.

The overall study was directed and supervised by Dr. Ramon L. Carrasquillo.

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## S U M M A R Y

The need for more cost efficient construction materials for use in highway construction and the problem of waste disposal of fly ash have prompted the study reported herein. This study addresses the major concerns of resident highway engineers about concrete containing fly ash for highway applications, which include: curing conditions, strength development, durability, materials selection and mix proportioning.

This report summarizes the proposed trial mix design procedure for concrete containing fly ash developed by the Texas State Department of Highways and Public Transportation. Contrary to the current practice in most states, the trial mix design procedure developed by the TSDHPT has as its main objective the development of a set of mixture proportions containing fly ash that would produce a concrete mix meeting the job specifications without reference to a control mix containing no fly ash. In other words, the procedure described herein is not intended to produce a concrete mix containing fly ash with strength equal to that of a concrete mix without fly ash, but to produce the most efficient concrete mix containing fly ash that will meet the job specifications for a given class of concrete.

The mix design procedure described herein recognizes the fact that it is impossible if not unrealistic to efficiently design a concrete mix containing fly ash based on a predetermined cement replacement ratio either by weight or volume due to the different performance of different combinations of materials. Mix proportioning of concrete containing fly ash based on a predetermined cement replacement ratio often results in concrete mixes of questionable performance, having too high a fines content and being "too sticky." As a result, the procedure adopted makes no assumptions as to the interaction among a given set of materials but allows for the selection of their optimum mix proportions.

In summary, this report describes a mix proportioning procedure that ensures the resident engineer the production of good quality concrete containing fly ash for highway applications.

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## I M P L E M E N T A T I O N

The information presented in this report constitutes the first step in the development of the needed information in a form useful to resident engineers for safe, economical, and efficient use of concrete containing fly ash in highway structures and pavements in the State of Texas.

The results from this study provide definite guidelines in the selection and proportioning of materials for producing concrete containing fly ash.



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## CHAPTER 1

### INTRODUCTION

#### 1.1 General

Our current knowledge of materials properties and mix design procedures is dangerously deficient with regard to producing concrete containing fly ash. There is no doubt that fly ash could be used successfully in concrete for highway applications. However, necessary modifications should be incorporated into currently used specifications, concrete practice, and quality control procedures to account for the effect of fly ash on the properties of fresh and hardened concrete.

Many problems occur today when concrete suppliers use fly ash in their concrete without performing the necessary preliminary trial mixes required to ensure against adverse effects on the properties of fresh concrete from using fly ash. One clear example of this is the increased placement problems and plastic shrinkage cracking resulting from using fly ash at a predetermined cement replacement ratio by weight without due regard to cement-fly ash interaction. This problem becomes critical in pavement concrete cast during hot and windy days typical in Texas and the southwest region of the United States.

However, if proper guidelines are established and followed for trial batch design, good quality concrete containing fly ash can be produced without any complication. The trial mix design procedure should be such that it (1) allows for optimization of the amount of fly ash to be added to the concrete, (2) considers available information on materials properties and on previous performance of concrete containing the same or similar fly ash, (3) ensures satisfactory performance of the concrete, both fresh and hardened, (4) uses the same materials as those proposed to be used in construction, and (5) minimizes the cost of the concrete.

In conclusion, fly ash will be used in concrete in highway applications in Texas in the near future, mainly due to both the abundance of fly ash and the reduced cost per cubic yard of concrete. It is urgent that the necessary guidelines are established for selection of materials and mix design procedures to ensure good quality concrete.

## 1.2 Problem Statement

Roads, large consumers of materials of all kinds, are among those civil engineering projects with which the builder can take the most technical risks; innovation in road building is therefore constant and progresses from the laboratory to practical use very rapidly.

Increased highway construction costs, coupled with decreasing revenues, are spurring the continuing development of more cost effective construction methods and materials. One set of materials being given serious consideration in Texas is locally available fly ash.

It is estimated that the current annual production of fly ash in Texas exceeds five million tons, making fly ash readily available within the state as a potential highway material.

The beneficial effects of fly ash in concrete are well known [1,2,3]; however, at present, although fly ash consumption has increased steadily throughout the world, with several countries producing standard specifications for its use in concrete [4,5], its consumption in concrete is still very small. There are a number of reasons for the resistance to more widespread use of fly ash, one of which is the inadequacy of the methods of proportioning concrete incorporating fly ash.

The mix proportioning procedure of concrete can significantly affect its properties and cost effectiveness and consequently, in the case of fly ash, the attitude towards its incorporation in concrete as a cementitious material. Unless an adequate mix design procedure is developed which considers the different interaction among sources of cement, fly ash, and their proportions, the full benefit of using fly ash in concrete will not be realized.

## 1.3 Scope and Objective

The main objective of this report is to describe and discuss the trial mix design procedure developed by the Texas State Department of Highways and Public Transportation for incorporating fly ash in concrete. This report is not intended to present a detailed review of existing literature on this topic. The guidelines for material selection and mix proportioning procedures are based on test results presented in previous reports from this study.

The proposed procedure developed by the Texas SDHPT has as its main objective the development of a set of materials proportions containing fly ash that would result in a concrete mix meeting the job specifications for a given class of concrete without reference to a control mix containing no fly ash. In other words, contrary to the current practice by most state agencies, the procedure described herein is not intended to produce a concrete mix containing fly ash of equal

strength to that of a concrete mix without fly ash, but to produce the most efficient concrete mix containing fly ash that will meet the job specifications. As a result, this procedure makes no assumption as to the interaction among a given set of materials but allows for the selection of their optimum proportions.

In summary, the proposed procedure provides the resident engineer with the means of optimizing the mix proportions, including fly ash content, so as to realize both the technical and economic advantages of concrete containing fly ash. In this report, each step and guideline of the proposed mix design procedure are explained in detail in order to facilitate understanding of the overall mix design approach.

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## C H A P T E R 2

### REVIEW OF FLY ASH CONCRETE MIX PROPORTIONING METHODS

A review of the literature reveals the controversy which exists today among engineers concerning the role of fly ash in concrete. Fly ash has been viewed as an admixture, as a partial replacement for portland cement, and as a partial replacement for sand. These different viewpoints have resulted in different mix design methods.

#### 2.1 Simple Replacement Methods

The principal method used by most mix designers for proportioning fly ash concrete is to substitute fly ash for cement. This substitution is generally made on a one-for-one basis either by weight or by volume in order to make sense out of the existing water-cement requirements of specifications. Fly ash concrete mixes proportioned by this method will usually have lower strengths than their control mixes at ages up to 28 days, but frequently equal or higher after 28 days.

The equal replacement approach to mix proportioning is suitable for most concrete applications, where early strength is not a prime requirement. The main drawback of this method is that the pattern of strength development and workability will fluctuate considerably, depending on the nature of the cement and fly ash, the water demand and pozzolanic activity of the fly ash, as well as the percentage cement replacement [6].

#### 2.2 Modified Replacement Methods

All these methods have one common feature. The amount of fly ash put into the mix is greater than the amount of cement removed, the difference being accommodated by a change in the aggregate proportions.

Lovewell and Washa [7] showed that the actual quantity of fly ash in excess is dependent on the cement content of the original mix, with the extra amount of fly ash required increasing as the cement content decreased.

Modified replacement methods permit a fixed amount of cement reduction within a certain range, irrespective of the original cement content in the corresponding plain concrete mix. However, the use of fly ash in mixes of certain strength ranges may not be economical due to the cement/fly ash cost ratio [6].

### 2.3 Rational Methods

Smith [8] was probably the first to develop a rational approach to fly ash concrete mix proportioning. This method is based on the assumption that every fly ash possesses a unique cementing efficiency ( $k$ ) such that a mass ( $F$ ) of fly ash would be equivalent to a mass ( $kF$ ) of cement. The required strength and workability of fly ash concrete comparable to plain concrete are obtained by applying Abrams' relationship between strength and water/cement ( $W/(c+kF)$ ) ratio and by controlling the volume ratios of cementitious particles to water and aggregate.

ACI 211.1-81, Standard Practice for Proportioning Normal, Heavyweight and Mass Concrete, gives proportioning procedures in mass concrete containing pozzolans. Significant cement reductions can be achieved by adding fly ash to mass concrete in quantities greater than the amount replaced. In addition, fly ash will reduce the heat of hydration in mass concrete. The ratio of fly ash to cement will vary depending on the pozzolanic activity and job specifications.

The method applied by the Tennessee Valley Authority (TVA) [9] for proportioning fly ash concrete is essentially based on ACI 211.1-81. Modifications to this standard serve to adjust mixture performance due to the addition of fly ash. The increased workability obtained with fly ash allows for lower water contents than those proposed in ACI 211.1-81. As the cement content is reduced by using fly ash, the water-cement ratio by weight is no longer valid. Consequently, a water-cement plus pozzolan ratio was adopted by TVA several years ago and proposed by ACI Committee 211 [10].

### 2.4 Summary

It is clear that research is needed to develop better proportioning procedures to optimize the properties and cost of concrete containing fly ash. However, due to the impossibility of making predictions based on the chemical and physical properties of the materials available and the interaction among these materials in concrete, the only rational mix design approach is one based on trial batches conducted under the expected job conditions.

## CHAPTER 3

### PROPOSED MIX DESIGN PROCEDURE

#### 3.1 General

Mix design procedures for conventional portland cement concrete are based on general knowledge of the relationship between the mix proportions and the expected characteristics of both the plastic and hardened concrete. Laboratory testing is usually required to verify the expected performance. The extent of physical tests necessary for confidence depends on the information available on the past performance of each of the particular constituents used in the mix.

The above considerations apply to the design of concretes containing fly ash, as well, because in general the fly ash mix design procedure has as its objective a particular concrete strength at a desired consistency.

The mix design procedure may be in terms of weights or volumes, but must ultimately yield 27 cubic feet of materials per cubic yard of concrete for the specified cement plus fly ash content, coarse aggregate factor, air content, and water factor. The procedure described herein consists of a rational approach to proportioning the constituents in concrete containing fly ash to produce good quality concrete that meets the concrete specifications for a given job. This procedure is intended to optimize the mix proportions of concrete containing fly ash in order to take full advantage, both technical and economical, of using fly ash in concrete.

In general, the recommended procedure consists of conducting a series of trial batches at varying cement factors and fly ash contents on an equal volume replacement basis. Analysis of the test results from strength specimens cast from each trial batch allows the resident engineer to select the most efficient mix design for a given job. The main concern of the mix design procedure developed by the Texas SDHPT is to determine the mix proportions for producing concrete containing fly ash that meets the concrete specifications for a given class of concrete. A copy of Supplement No. 2 to Construction Bulletin C-11 of the Texas SDHPT, which contains the trial mix design procedure for concrete containing fly ash, is included in Appendix A.

#### 3.2 TSDHPT Concrete Specifications

Before discussing the mix design procedure, a review of the TSDHPT concrete specifications is needed in order to better understand the mix

proportioning procedure. Concrete specifications are mostly governed by the use and expected performance of the concrete in service and not by the materials to be used in making the concrete. Furthermore, it is not the intent of this report to question the validity of each item in the current concrete specifications of the TSDHPT. As a result, concrete containing fly ash must meet, with no exceptions, the same concrete specifications as concrete containing no fly ash, including strength requirements at a specified test age, maximum water content, minimum cement content, and workability requirements.

**3.2.1 Strength Requirements.** The strength of concrete, either flexural or compressive, is an indication not only of the load-carrying capacity of the concrete but of the durability, abrasion resistance, and resistance of the concrete to construction loads at a specified age. Therefore, if the TSDHPT is to follow current construction practices while using concrete containing fly ash, the concrete containing fly ash must meet the same strength requirements at all specified test ages as concrete containing no fly ash.

**3.2.2 Minimum Cement Content.** The minimum cement content requirement in the specifications is not intended to ensure a given concrete strength. The cement content of the concrete is an indirect indication of the minimum paste requirement, consistency, and bleeding characteristics of the concrete. In order to ensure that concrete containing fly ash has similar rheological characteristics, such as consistency, to concrete containing no fly ash, it must have the same volume of cement plus fly ash per cubic yard as the volume of cement per cubic yard in concrete containing no fly ash. In other words, for concrete containing fly ash, the minimum cement content requirement for a given class of concrete refers to a minimum cement plus fly ash content requirement on an equal volume basis. For example, the minimum cement content for Class C concrete is 6 sks per cubic yard or 2.92 cubic feet of cement per cubic yard of concrete. Class C concrete containing fly ash must have a minimum combined volume of cement plus fly ash per cubic yard of concrete of 2.92 cubic feet. In other words, as shown in Fig. 1, the term cement content refers to cement plus fly ash content on an equal volume basis when designing a concrete mix containing fly ash.

**3.2.3 Maximum Water Content.** Current specifications contain a maximum limit on the amount of water per sack of portland cement in the concrete. This limit ensures adequate impermeability of the hardened concrete and prevents excessive bleeding and segregation. For Class C concrete, the maximum water content limit is 6.0 gallons per sack of cement or 6.0 gallons per 0.485 cubic feet of cement. Due to its pozzolanic properties, concrete containing fly ash would be less permeable than concrete containing no fly ash for similar mix proportions. If concrete containing fly ash is not to be more permeable than a similar concrete containing no fly ash, it must not have a higher water content. In the TSDHPT mix design procedure, this is accomplished

by defining the existing maximum water content for a class of concrete in terms of a maximum allowable water content per volume of cement plus fly ash equal to the volume of 1 sack of cement, as shown in Fig. 2. In other words, the maximum allowable water content for Class C concrete containing fly ash is 6.0 gallons per 0.485 cubic feet of cement plus fly ash.

**3.2.4 Workability Requirement.** Concrete containing fly ash must meet the same slump requirements as concrete containing no fly ash under the current mix design procedure. However, for similar proportions and equal slump, concrete containing fly ash will have a better workability than concrete containing no fly ash due to the particle shape and size of the fly ash.

### **3.3 Mix Design Procedure**

**3.3.1 Approach.** The approach of the proposed mix design procedure for concrete containing fly ash is to design the most efficient and cost effective concrete mix meeting all applicable TSDHPT specifications for a given class of concrete. It must be clear that contrary to the current practice in many states, the TSDHPT procedure is not designed to produce the mix proportions of a concrete mix containing fly ash of equal strength to that of a concrete mix containing no fly ash. However, it is designed to ensure that the quality and fresh and hardened properties of the concrete containing fly ash meet the TSDHPT concrete specification for a given class of concrete. These include consistency, bleeding, segregation, durability, workability, and strength.

**3.3.2 Materials Selection.** The proposed procedure applies for use with normal weight aggregates consisting of gravel, crushed stone or combinations thereof, and either natural or manufactured sand or combinations thereof. The materials used for determining a mix design should be the same materials as those approved for use in the actual construction. Only materials meeting TSDHPT specifications for use of that material in concrete should be used. A copy of the fly ash specifications adopted by the TSDHPT, Departmental Materials Specification: D-9-8900, "Fly Ash," is included in Appendix B.

**3.3.3 Cement Replacement.** The proposed procedure adopted by TSDHPT introduces fly ash into the concrete mix as a replacement of a portion of the portland cement on an equal volume basis. As a result of substituting the cement with fly ash on an equal volume basis, mixes containing a given cement or cement plus fly ash content would have similar rheological properties. Cement replacement with fly ash ranging from 20 to 35% is recommended depending on type of fly ash and class of concrete.

A minimum cement replacement of 20% was selected in order to ensure adequate resistance of the concrete to damage due to alkali-aggregate

reaction. Test results from an ongoing research study, TSDHPT Study No. 450, on the alkali-aggregate reactions in concrete containing fly ash using Texas fly ashes indicate that for certain material properties, if fly ash is used at less than 20% cement replacement, the risk of alkali-aggregate reaction damage to concrete increases. This is shown in Fig. 3. The maximum limit of 35% was established because not much information is available on the performance of concrete having more than 35% fly ash made using Texas fly ashes in highway applications.

Additional guidelines are provided regarding the recommended cement replacement based on the typical range of optimum fly ash content for each type of fly ash. Type A fly ash is recommended to replace 20 to 30% of the absolute volume of the portland cement and a Type B fly ash is recommended to replace 25 to 35%. However, either type of fly ash could be used in concrete within the allowable range of 20 to 35% as long as the concrete produced meets all concrete specifications for the job. A further limit has been established on the maximum allowable cement replacement in concrete mixes having less than 5 sacks or 2.425 cubic feet of cement per cubic yard. In these concrete mixes, a maximum cement replacement of 25% is allowed because of lack of available information on the durability and performance of these concretes. Note in Fig. 4, that when fly ash is added to concrete as a cement replacement on an equal volume basis, the total combined weight of cement plus fly ash is less than the weight of the concrete mix containing no fly ash. The reason for this is that fly ash has a lower specific gravity than portland cement.

Several factors influenced the decision to introduce fly ash into the concrete on an equal volume basis rather than on an equal weight basis in the trial mix design procedure. These factors were:

1. The current mix design procedure used by the TSDHPT is based on absolute volume
2. When fly ash is added to concrete as a cement replacement on an equal volume basis, the rheological properties of the concrete for a given slump and cement or cement plus fly ash content are similar regardless of the fly ash content
3. Cement replacement with fly ash on an equal volume basis represents the most fundamental cement replacement scheme allowing for optimum use of the materials and most economical design of the concrete mix
4. It is not possible and not a good engineering practice to predict the interaction among fly ash and cement in concrete on the basis of the chemical and physical properties of these materials without conducting trial batches under the expected job conditions

5. It is not the intention of the mix design procedure to produce concrete mixes with and without fly ash of equal strength but to produce a set of mixture proportions with and without fly ash of similar rheological properties for a given cement or cement plus fly ash content. Then, final selection of the mix proportions for use in a job should be made based on the strength test results from specimens cast from each batch.

Comparing the test results from some field trial batches conducted using Texas fly ashes shown in Figs. 5 through 8, it is clear that the interaction among cements and fly ashes commercially available for use in concrete in Texas is impossible to predict without conducting trial batches.

Figure 7 shows that the use of different brands of Type I cement could have a significant effect on the flexural strength of concrete mixes having similar proportions and rheological properties. Figures 5 through 8 also show that the addition of fly ash to concrete as a cement replacement on an equal volume basis may result in higher, lower or similar concrete strength to that of the concrete mix containing no fly ash. In addition, Figs. 5, 6, and 8a also indicate that the use of minimum cement content for a given class of concrete may result in concrete strengths much higher than that specified for the job. For these cases, even if the addition of fly ash to the concrete resulted in lower concrete strengths, the concrete with fly ash may still meet the strength requirements for that class of concrete.

In summary, due to the high variability in interaction among cements and fly ashes, the only rational approach allowing for optimum use and performance of the materials to proportion concrete containing fly ash is by adding fly ash on an equal volume basis and selecting the mix proportions for a job based on strength test results.

#### 3.3.4 Mix Design Procedure

Step 1: The first step in designing concrete mixes with fly ash is to design a mix which meets water:cement ratio, workability and air content requirements without any fly ash. This will be considered the control design. An existing mix design which is satisfactory in every respect may be used; however, a trial mix should be made from this design. The main purpose for designing a control mix is to establish guidelines on the mixing water requirement, workability, setting times, and required admixture dosages for a given cement content. In addition, the control mix allows the resident engineer to verify the adequacy of the coarse aggregate factor selected for that concrete. At least three test specimens for strength, either flexural or compressive, should be cast and tested according to TSDHPT Test Procedures.

Step 2: The second step is to replace a portion of the absolute volume of portland cement with fly ash. In this case the absolute volume of portland cement, for the control design, is known. The amount of fly ash replacement should be the minimum recommended for the type of fly ash to be used--20% for Type A fly ash or 25% for Type B. Make small trial mixes until a design is produced which meets all workability and air content requirements. The mixes containing fly ash will generally require less water than the control design and most likely would require an adjustment in the admixture dosages needed to achieve the desired air content. Concrete containing fly ash must meet air content requirements for the class of concrete specified. Adjustments in the dosage of Type A and D admixtures may be required in order to prevent excessive set retardation of the concrete. Cast and test at least 3 specimens for strength, either flexural or compressive, according to TSDHPT Test Procedures.

Step 3: Repeat Step 2 for other fly ash contents within the allowable cement replacement range of 20 to 35%. It is recommended that at least one more trial mix be made at the highest allowable fly ash content for the type of fly ash being used.

Step 4: The final step is to plot the strength test results from the trial mixes including flexural strength, water content, air content, concrete temperature, and slump as shown in Fig. 8. Final selection of the mix proportions to be used for concrete must be made based on the strength test results. If the strength of the mixes is not sufficient, a new set of trial mixes should be made starting at a higher cement content and following the procedure outlined in Steps 1 through 4.

An adequate overdesign factor for strength should be considered when selecting a concrete mix based on the strength test results in order to compensate for fluctuations in strength caused by variations in materials, equipment, job conditions, and job procedures. An overdesign factor of at least 10% of the specified flexural strength or 20% of the specified compressive strength is recommended.

Adjustment for Yield: The water demand for the mixes containing fly ash may vary from the control design and should be adjusted as necessary, on an absolute volume basis, to produce the desired workability. Based on the trial batches conducted to date by the TSDHPT, water reductions on the order of 10-12% are possible for a constant slump when replacing 35% of the volume of cement with fly ash.

In general, concrete mixes containing fly ash will require less mixing water than the control mix for the same workability. As a result, an adjustment in mix proportions is needed to ensure proper yield. For mixes containing fly ash, any decrease in volume of mixing water should be compensated for by an equal increase in volume of coarse



aggregate. The volume of fine aggregate in mixes containing fly ash should be kept the same as in the control mix in order to avoid any significant changes in consistency of the concrete mix.

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## CHAPTER 4

### SUMMARY AND CONCLUSIONS

The need for more cost efficient construction materials for use in highway construction and the problem of waste disposal of fly ash have prompted the study reported herein. This study addresses the major concerns of resident highway engineers about concrete containing fly ash for highway applications, which include: curing conditions, strength development, durability, materials selection and mix proportioning.

This report summarizes the proposed trial mix design procedure for concrete containing fly ash developed by the Texas State Department of Highways and Public Transportation. Contrary to the current practice in most states, the trial mix design procedure developed by the TSDHPT has as its main objective the development of a set of mixture proportions containing fly ash that would produce a concrete mix meeting the job specifications without reference to a control mix containing no fly ash. In other words, the procedure described herein is not intended to produce a concrete mix containing fly ash with strength equal to that of a concrete mix without fly ash, but to produce the most efficient concrete mix containing fly ash that will meet the job specifications for a given class of concrete.

The mix design procedure described herein recognizes the fact that it is impossible if not unrealistic to efficiently design a concrete mix containing fly ash based on a predetermined cement replacement ratio either by weight or volume due to the different performance of different combinations of materials. Mix proportioning of concrete containing fly ash based on a predetermined cement replacement ratio often results in concrete mixes of questionable performance, having too high a fines content and being "too sticky." As a result, the procedure adopted makes no assumptions as to the interaction among a given set of materials but allows for the selection of their optimum mix proportions.

In conclusion, the mix design procedure adopted by the Texas State Department of Highways and Public Transportation has proven to be a valuable tool in designing the most efficient and cost effective concrete mix containing fly ash. Furthermore, as part of the mix design procedure, the resident engineer develops the fundamental information that will be needed during actual construction if adjustments in proportions are needed due to cold weather or hot weather concreting conditions.

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F I G U R E S

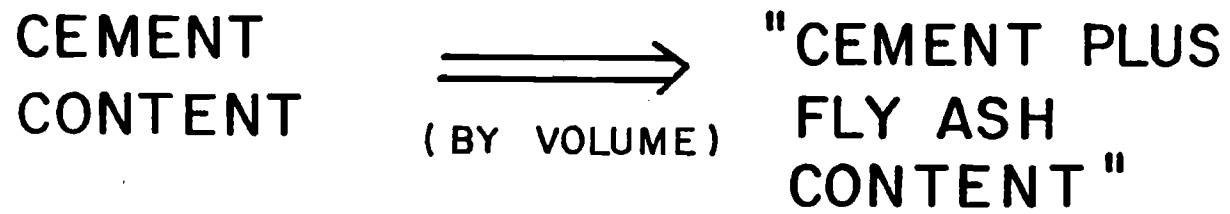


Fig. 1 For concrete containing fly ash, the term cement content refers to the combined volume of cement plus fly ash on an equal volume basis



# MAXIMUM WATER CONTENT

NO FLY ASH

"CEMENT PLUS FLY ASH"

6.25 Gallons/sk

$1 \text{ sk} = 0.485 \text{ Ft.}^3$

6.25 Gallons Per  
0.485 Ft<sup>3</sup> Of  
"Cement Plus  
Fly Ash"

Fig. 2 Definition of maximum water content specification for concrete containing fly ash

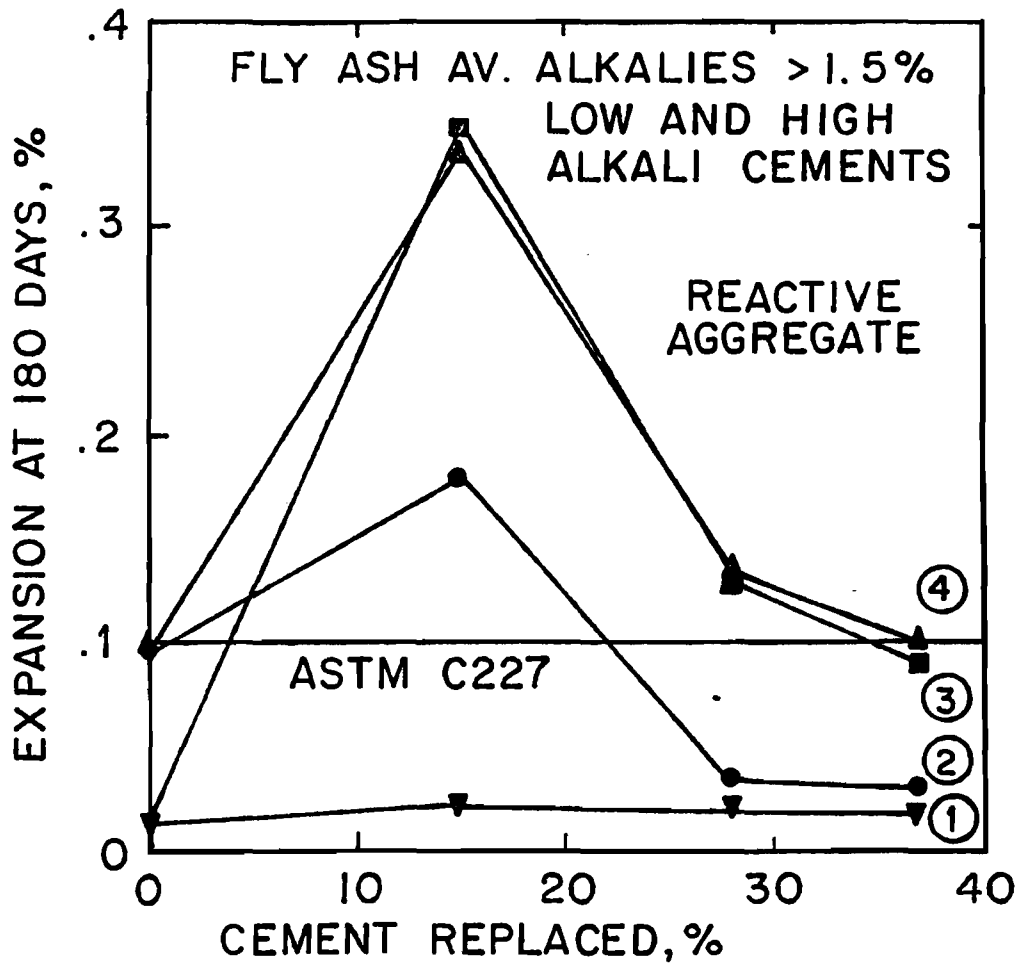


Fig. 3 Mortar bar expansion versus fly ash content for Type B fly ash in concrete mixes containing reactive aggregates

## EXAMPLE :

CLASS C CONCRETE = 6 sks/yd<sup>3</sup> MINIMUM ( 2.92 Ft<sup>3</sup> )

FLY ASH CONTENT, by Volume	MINIMUM "CEMENT PLUS FLY ASH" ALLOWED			
	by Volume, Ft.		by Weight, * lbs.	
	CEMENT	FLY ASH	CEMENT	FLY ASH
0 %	2.92	0	564	0
20 %	2.34	0.58	453	92
35 %	1.90	1.02	368	162

\* ASSUME A FLY ASH SPECIFIC GRAVITY OF 2.55

Fig. 4 Weight of cement and fly ash per cubic yard of concrete for different fly ash contents by volume

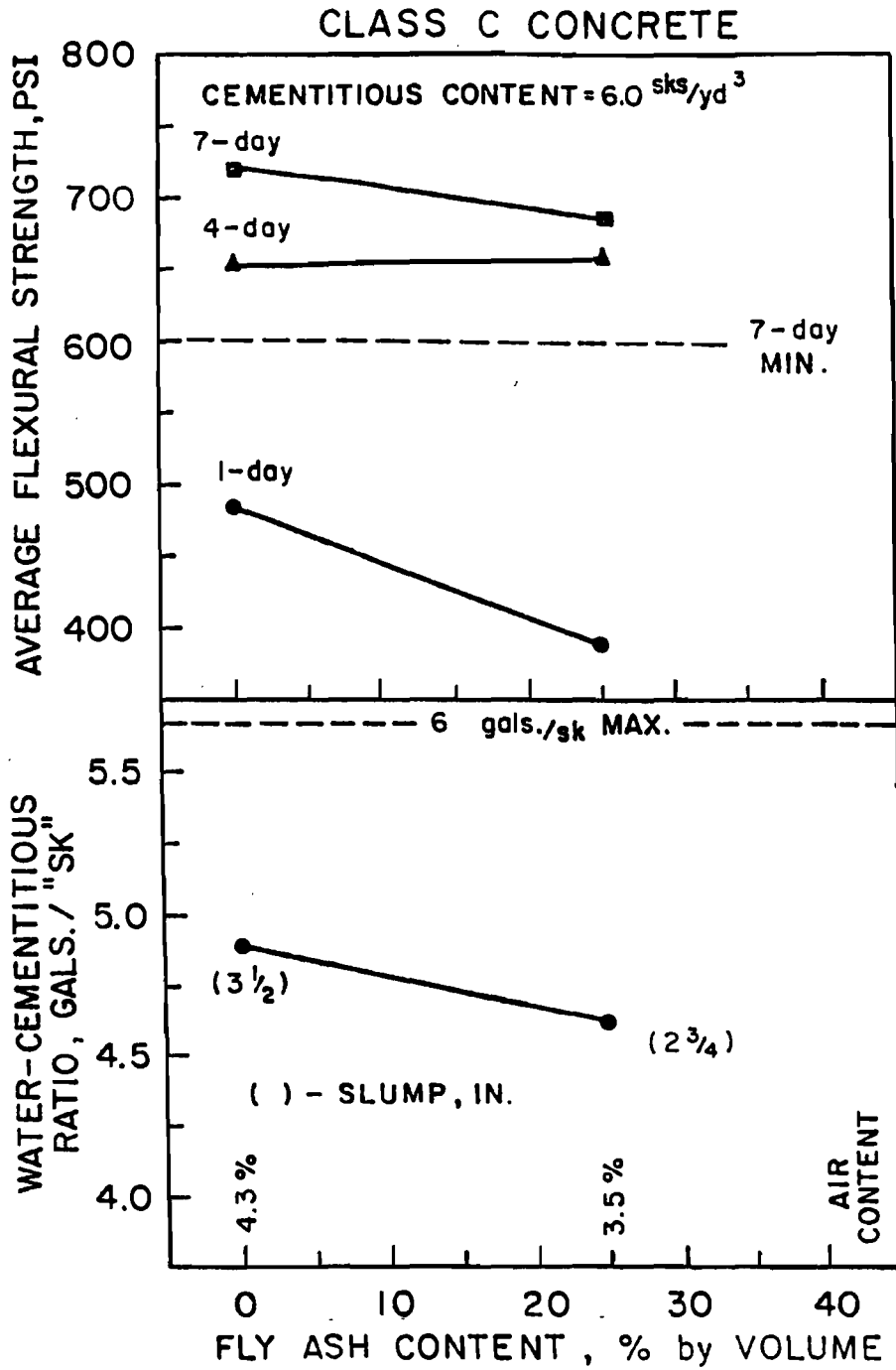


Fig. 5 Field trial batch test results for Class C concrete made using Type B fly ash in Carthage, Texas

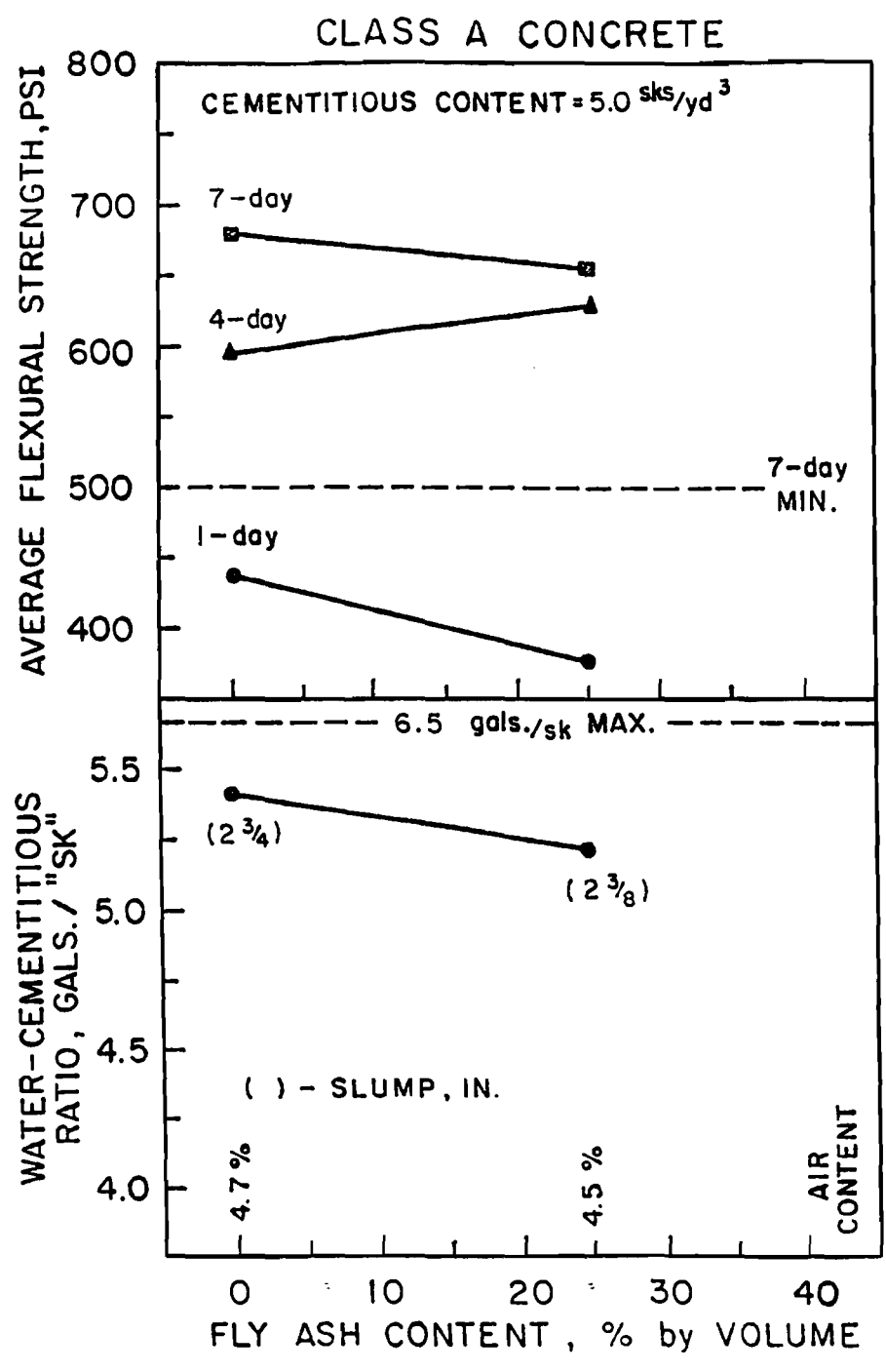


Fig. 6 Field trial batch test results for Class A concrete made using Type B fly ash in Carthage, Texas

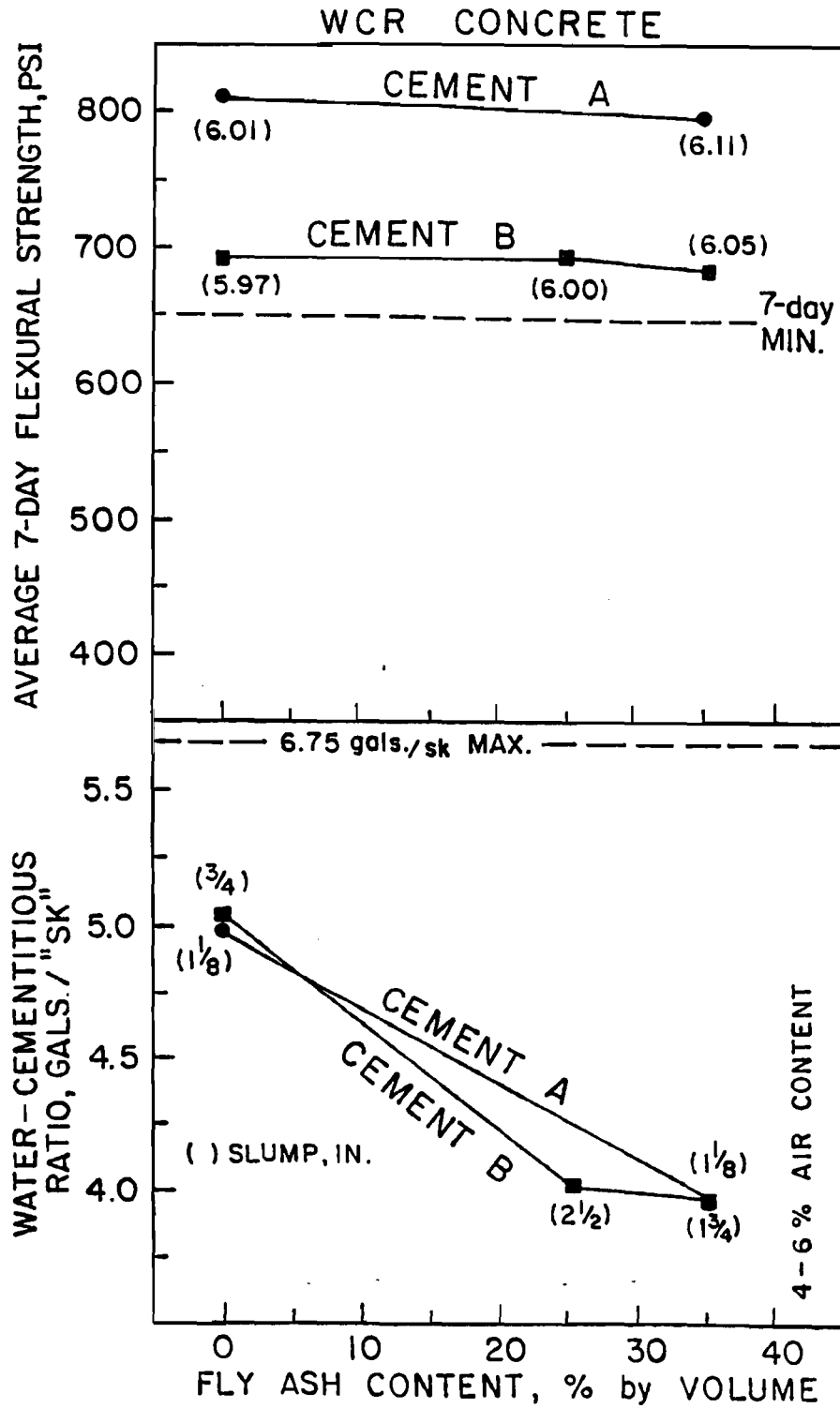


Fig. 7 Field trial batch test results for WCR pavement concrete using Type B fly ash made in Texarkana, Texas, using two different brands of Type I portland cement

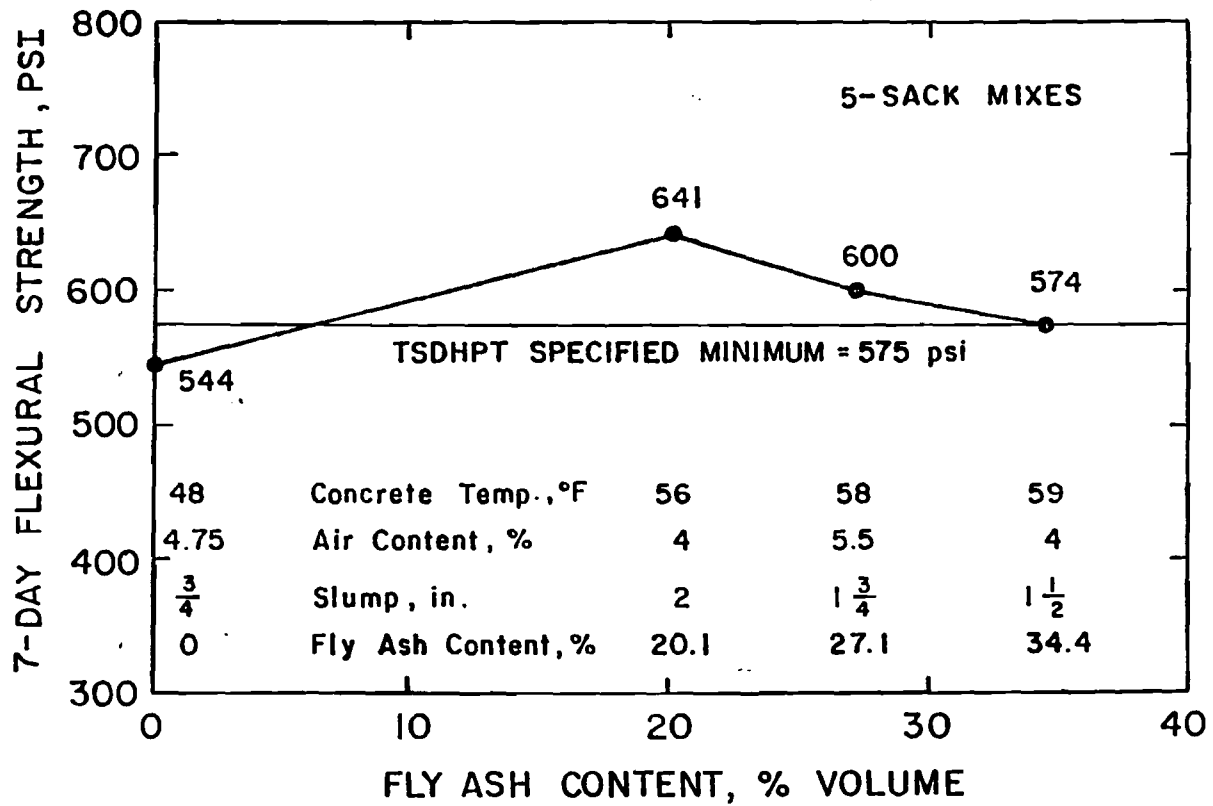


Fig. 8a Field trial batch test results for CRCP pavement concrete made using local Type B fly ash and Brand C portland cement in Amarillo, Texas

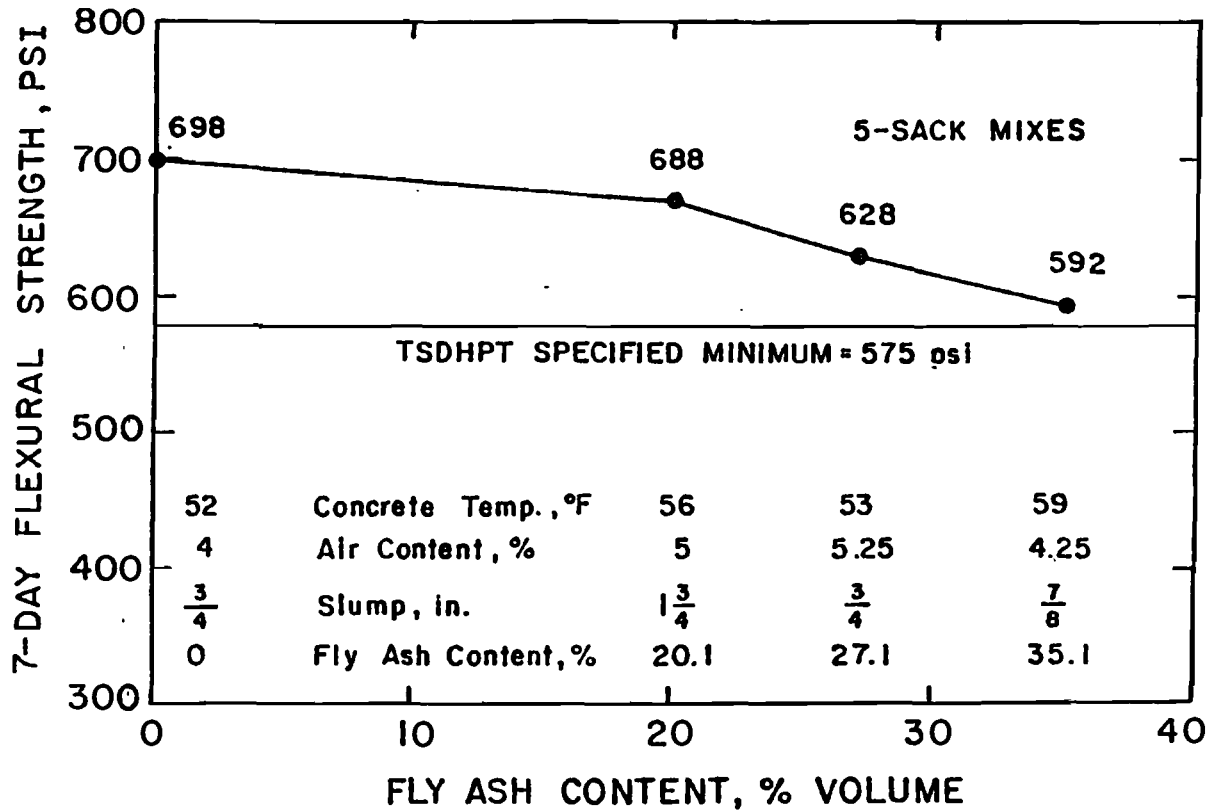


Fig. 8b Field trial batch test results for CRCP pavement concrete made using local Type B fly ash and Brand D portland cement in Amarillo, Texas



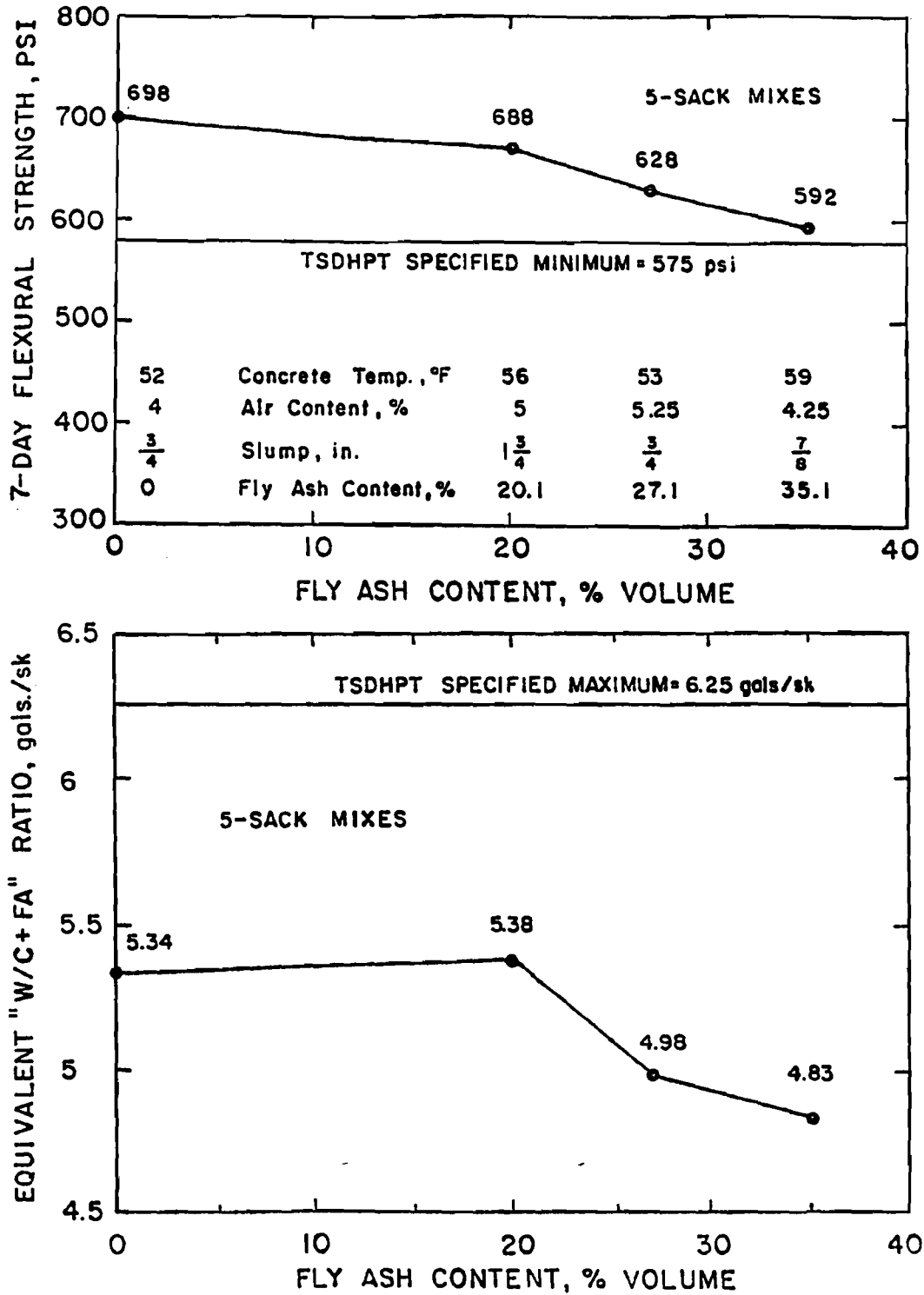


Fig. 9 Typical plot of test results from trial mixes

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A P P E N D I X A

SUPPLEMENT NO. 2

TO

CONSTRUCTION BULLETIN C-11

TEXAS STATE DEPARTMENT OF HIGHWAYS AND

PUBLIC TRANSPORTATION



**SUPPLEMENT NO. 2  
TO  
CONSTRUCTION BULLETIN  
C-11**

**JANUARY, 1986**

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State Engineer-Director.**

**FOREWORD**

This Supplement is intended as a guide only for use in design of concrete containing fly ash and for high strength structural concrete.

The guidelines and procedures for mix design and job control given in Construction Bulletin C-11 and Supplement thereto remain applicable except as modified herein.

Specifications shall take precedence when a conflict occurs with this Supplement.

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## **DESIGN OF CONCRETE CONTAINING FLY ASH AND HIGH STRENGTH STRUCTURAL CONCRETE**

### **1. General**

This Supplement is a guideline for the design of portland cement concrete containing fly ash. Guidelines for high strength concrete are also included. Where conflict exists between these guidelines and the specifications, the Specifications shall govern.

Fly ash is used to replace a portion of the portland cement in a concrete mix. The amount it replaces may vary between 20 and 35 percent of the absolute volume of the required amount of portland cement depending on the type of fly ash and specification requirements for the concrete.

Fly ash should not be used as a cement replacement in concrete containing less than five sacks of portland cement per cubic yard prior to such replacement. For mixes containing less than five sacks of cement, per cubic yard, replacement of cement with fly ash may adversely affect the strength gain characteristics of fresh concrete properties significantly.

This guideline is proposed for use with normal weight aggregates consisting of gravel, crushed stone or combinations thereof and either natural or manufactured sand or combinations thereof.

The materials or ingredients used for determining a mix design should be the same materials or ingredients as those which will be used in actual construction.

The term "cement plus fly ash", (C+F), refers to the total combined weight or volume of portland cement and fly ash in a concrete mix.

Only fly ash meeting the requirement of Departmental Material Specification D-9-8900, "Fly Ash" should be used.

### **2. Mix Design (with Fly Ash)**

For designing concrete mixes with fly ash, a trial mix procedure, based on absolute volume, similar to that described in Construction Bulletin C-11 and Supplement thereto, is used.

The specific gravity of fly ash must be known to calculate absolute volume for mix proportioning. The Materials and Tests Division will furnish the specific gravity of fly ash from the approved sources to be used.

A Class A fly ash can replace 20 to 30 percent of the absolute volume of the portland cement and a Class B fly ash can replace 25 to 35 percent.

The first step in designing concrete mixes with fly ash is to design a mix which meets water:cement ratio and workability requirements without any fly ash. This will be considered the control design. An existing mix design which is satisfactory in every respect may be used; however, a trial mix should be made from this design. Make at least three test specimens for strength (flexural or compressive) and test them in accordance with Test Method Tex-418-A or 420-A.

The second step is to replace a portion of the absolute volume of portland cement with fly ash. In this case the absolute volume of portland cement, for the control design, is known. The amount of fly ash replacement should be the minimum recommended for the class of fly ash to be used - 20 percent for Class A fly ash or 25 percent for Class B. Make small trial mixes until a design is produced which meets all workability requirements. The mixes containing fly ash will generally require less water than the control design. Make at least three test specimens for strength (flexural or compressive) and test them in accordance with Test Method Tex-418-A or 420-A.

The third step is to make another mix design using the maximum amount of fly ash recommended - 30 percent for Class A fly ash and 35 percent for Class B. Trial mixes should be made as necessary until a mix is designed which meets workability requirements. Make at least three test specimens for strength (flexural or compressive) and test them in accordance with Test Method Tex-418-A or 420-A.

The water demand for the mixes containing fly ash may vary from the control design and should be adjusted as necessary, on an absolute volume basis, to produce the desired workability.

For each mix design, the water:(C+F) ratio should be determined on a weight basis - pounds of water per pound of (C+F) or on a volume basis - gallons of water per "sack" of (C+F) where "1 sk" (C+F) equals 0.485 cubic feet.

In general, concrete mixes containing fly ash will require less mixing water than the control mix for the same workability. As a result, an adjustment in mix proportions is needed to ensure proper yield. For mixes containing fly Ash, any decrease in volume of mixing water should be compensated for by an equal increase in volume of coarse aggregate. The volume of fine aggregate in mixes containing fly ash should be kept the same as in the control mix in order to avoid any significant changes in consistency of the concrete mix.



The dosage rate for Type A and D admixtures should be based on just the amount of Portland cement used in the mix design. These admixtures have little or no effect with fly ash and an overdose is possible if the dosage rate is based on cement plus fly ash.

Next, plot the values of strength and water:(C+F) ratios as illustrated in Figure 1. If the strength is insufficient, select a higher cement content (one sack higher) and repeat steps 1 through 3 and plot the resulting data as illustrated in Figure 1. From Figure 1 determine the optimum fly ash content, strength and W:(C+F) ratio. Make a trial batch for pilot test to prove all aspects of the design.

The selected design should have at least 110 percent of the minimum specified flexural strength (120 percent compressive strength). This overdesign is needed to compensate for variations in strength caused by variations in materials, equipment, job conditions and job procedures.

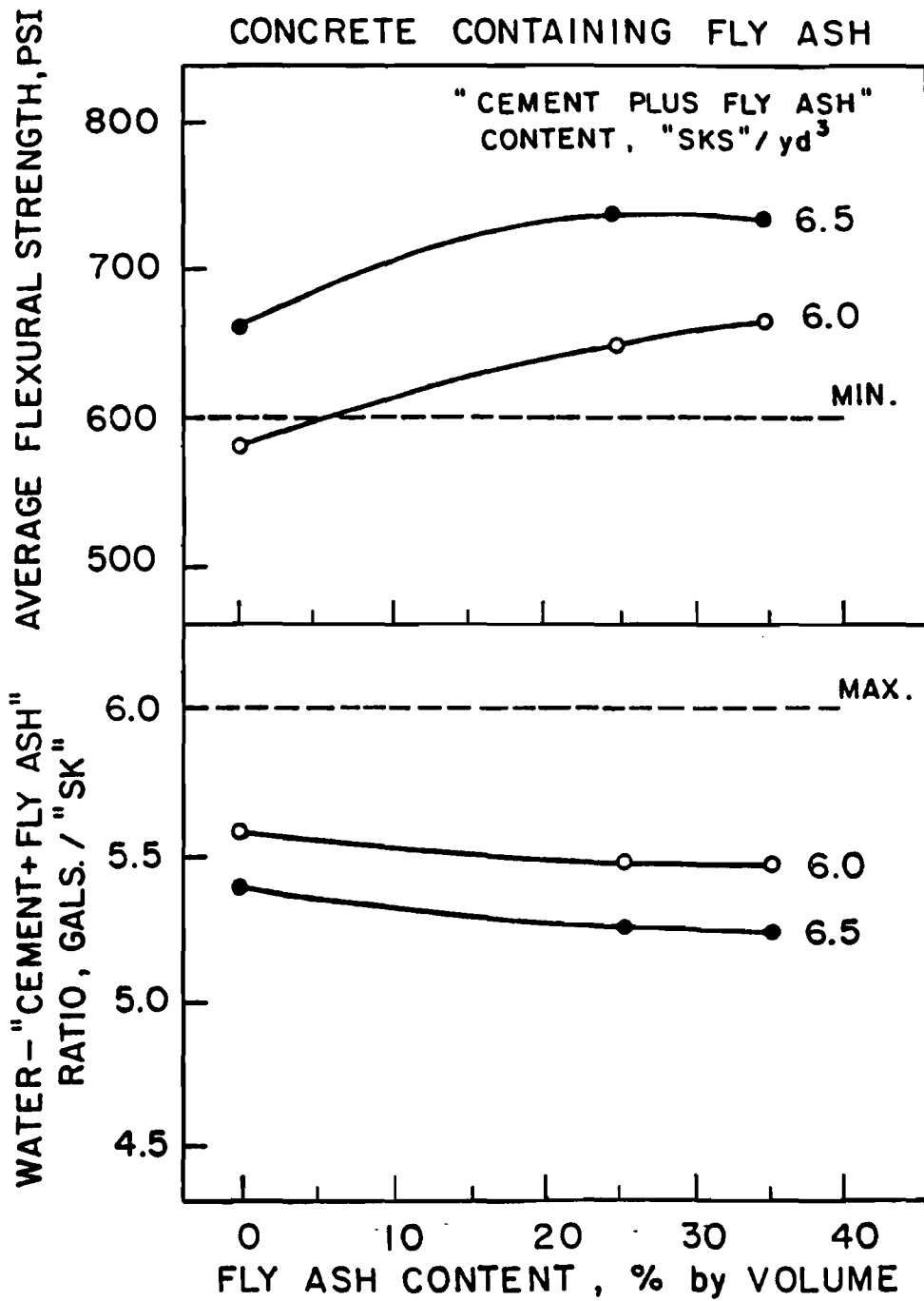


FIGURE 1. EXAMPLE OF SMALL TRIAL MIX DESIGN RESULTS

### 3. High Strength Concrete

The following items and Table I should be used as a guide for design of high strength concrete (higher than 9000 psi compressive strength) with or without fly ash. Table I gives reasonable values from which to start a mix design. Some variations will occur depending on materials and their sources. An increase in the amount of water shown in the Table will result in a drastic loss of strength.

a. The most important variable affecting the strength of high strength concrete is the water:C or (C+F) ratio. For a 28-day compressive strength of at least 9000 psi, the water:(C+F) ratio must be less than 0.35.

b. If no admixtures or fly ash are added to the mix, at least ten sacks of portland cement per cubic yard are needed to produce high strength concrete with a slump of three to four inches. A portland cement content of  $9\frac{1}{2}$  sacks per cubic yard is near optimum for strength and workability when high range water reducer (HRWR) is used to produce a water:C ratio of 0.30 and a slump of at least four to five inches.

c. When HRWR is used in producing high strength concrete, the slump of the concrete prior to the addition of the HRWR must be in the range of one to two inches. This will result in concrete having adequate consistency and workability after HRWR is added.

d. Compressive strength increases as HRWR dosage rate increases, up to a dosage rate which causes the mix to segregate and become unworkable. Significant retardation may result from the addition of too much HRWR. Strength, workability and dosage rates may vary with the brand of HRWR.

e. High strength concrete can be produced from either natural gravel or crushed stone; however, crushed stone produces higher strength.

f. High strength can be produced with aggregate ranging in size up to one inch maximum. However, with or without HRWR, the highest concrete compressive strength results from using smaller maximum size aggregate.

g. For mixes containing no admixture, high strength concrete can be best produced using a sand with a fineness modulus of from 2.7 to 3.1. Fineness modulus as low as 2.4 are satisfactory for producing high strength concrete when HRWRs are used.

h. More compressive strength has resulted by adding Class B fly ash than by adding an equal weight of portland cement, if the absolute volume of fly ash is in the range of 20 to 35 percent of the total absolute volume of portland cement and fly ash.

i. Generally, the one-day strength of high strength concrete is slightly reduced by the addition of fly ash, however, this loss of strength can be overcome by the reduction of the water content with the addition of HRWR.

j. The 28-day compressive strength of concrete ideally cured for seven days is not seriously affected by curing in hot dry conditions from 7 to 28 days after casting.

TABLE I. HIGH STRENGTH CONCRETE MIX DESIGN GUIDELINES

Min Comp. Strength 28 day, psi	9,000 (a)	10,000 (a)	9,500 (a)	10,500 (a)
Sacks Cement Per Cu Yd	10.0	8.5	7.0	6.0
Max Water-Cement Ratio (gal/sack)	3.9	3.4		
Max Water:(C+F) Ratio (#/#)			0.31	0.27
Crushed Coarse Aggr. Grade Number (b)	4,5 or 6	4,5 or 6	4,5 or 6	4,5 or 6
CA/FA Ratio (by weight)	2.0 (c)	2.0 (c)	2.0 (c)	2.0 (c)
Fly Ash (Class B) % of (C+F)	-	-	35(f)	35(f)
High Range Water Reducer	-	Yes (d)	-	Yes (d)
<u>General Usage</u>				
Prestressed Concrete	Yes	Yes	Yes	Yes
Cast in Place	Yes	Yes	Yes	Yes
<u>Other Notes</u>				
Good Formed Surfaces	Yes	Yes	Yes	Yes
Good Finished Surfaces	Yes	See Note (e)	Yes	See Note (e)

**Notes:**

- (a) Based on tests performed on 6 in. dia. x 12 in. cylinder of concrete made using a rigid steel mold.
- (b) Crushed stone should have saturated surface-dry unit weight of at least 90 lb/cu ft, and a saturated surface-dry specific gravity of at least 2.50.
- (c) Mixes containing no high-range water-reducer should be made using a coarse sand whose fineness modulus is at least 2.70.
- (d) Dosage of high-range water-reducer should be highest possible without causing segregation or excessive retardation of fresh concrete.
- (e) Smoothly finished surfaces possible with motor-driven finishing tools. Despite high fines content this mix is not easily finished by hand.
- (f) Use of Class B fly ash at a rate of 35 percent by absolute volume of the total cement plus fly ash content is recommended for these mix proportions.

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A P P E N D I X B

TSDHPT FLY ASH SPECIFICATIONS

STATE DEPARTMENT OF HIGHWAYS  
AND  
PUBLIC TRANSPORTATION

Departmental Materials Specification: D-9-8900  
Fly Ash

- I. Description: This specification shall govern for the composition, quality, sampling and testing of two types of fly ash. Fly ash is hereby defined as the finely divided residue or ash that remains after burning finely pulverized coal at high temperatures.
- II. Bidder's and/or Supplier's Requirements:
  - A. Procurement by the State: All prospective bidders are hereby notified that, before any bid is considered, the material proposed for submission shall be a material on the list of approved sources of material covered by this specification maintained by the Department.
  - B. Contracts: All contractors and/or suppliers on contracts are hereby notified that all fly ash, utilized in production of products for the Department shall be a fly ash from a source shown on the list of approved sources of fly ash maintained by the Department.
- III. Payment:
  - A. Procurement By the State: Payment for all materials under this specification shall be in accordance with the conditions prescribed in the contract awarded by the State.
  - B. Contracts: All materials under this specification utilized in the production of products for the Department will be paid for in accordance with the governing specifications for the items of construction in which fly ash is used.
- IV. Prequalification and Performance History:
  - A. Establishment of Prequalification as an Approved Source: Prospective Bidders and/or Suppliers who desire to establish prequalification for materials governed by this specification, should contact the Materials and Tests Engineer, State Department of Highways and Public Transportation, Austin, Texas 78703.



The following information must accompany the request for approval:

1. The name of the supplier or company
  2. Location of the power plant
  3. Coal origin
  4. Storage facilities and capacity
  5. Production procedures. Production procedures shall be one of the following:
    - a. Use coal from only one origin
    - b. Use coal from two or more origins blended uniformly at a constant ratio prior to burning.
    - c. Use coal from two or more origins with the fly ash from each stored in separate, identifiable units.
    - d. Use coal from two or more origins stored and burned separately, and the fly ash kept separately until blended uniformly at a constant ratio prior to placing in storage.
  6. Copies of test reports showing results obtained in their quality control program. (At least one test report per month for the previous six months shall be submitted.) The test reports shall include the coal origin, sampling and test date and all chemical requirements specified elsewhere in this specification.
  7. Details of Quality Control Program shall be submitted along with request for prequalification. Details shall include measures taken to ensure that fly ash not meeting the requirements of this specification produced during shut-down or start-up and other operations is kept separated from material meeting the requirements of this specification.
- B. Sampling for Prequalification: Sampling for establishment of prequalification as an approved source shall be in accordance with Test Method Tex-733-I Prospective Bidders and/or Suppliers will be notified, after their material has been evaluated, as to conformance with requirements of this specification.

- C. Quality Control of Approved Sources: Sources on the approved list must furnish the following items to the Materials and Tests Division on a monthly basis:
1. A copy of a test report showing results obtained in their routine quality control program. The test report shall include the coal origin, test date and results of all chemical requirements specified except available alkalies, as  $\text{Na}_2\text{O}$ .
  2. A sample from the same material represented by the test report in 1, above, shall be submitted along with test report. Minimum sample size shall be 1 pint.
- D. Sampling for Quality Control of Approved Sources: Sampling for quality control of sources on the approved source list shall be in accordance with Test Method Tex-733-I.
- E. Performance History: Some of the tests required by this specification extend over a prolonged period of time and some tests cannot be made after the material is used. Therefore, testing for acceptance of materials supplied on any contract or State purchase order will only be considered on those materials which are identifiable by the Materials and Tests Engineer as being a material having an established performance history of compliance with the criteria established by this specification and shown on the list of approved sources.
- F. Re-evaluation: When, it is determined that changes have been made in the composition, burning process, or quality of a prequalified material that may affect its performance, a re-evaluation of the performance may be required. The Department reserves the right to conduct whatever tests are deemed necessary to identify a prequalified material and to determine if a change has been made in composition, burning process, or quality that may affect its performance. Changes that are detected in composition, burning process, or quality that may affect performance and have not been reported by the source, may be cause for removal of that source from the list of approved sources of fly ash.
- G. Withdrawal, Approved Source: A source may be removed from the approved list for the following reasons:
1. Any change in the production procedures, including the use of precipitator performance additives, from those shown in the original request for approval.

2. Failure of any project or source sample to comply with specification requirements.
  3. A source becomes inactive and/or does not furnish fly ash to Department projects for a period of one year.
- H. Re-establishment as an Approved Source: Any source that has been removed from the list of approved sources for any reason and desires to be re-established as an approved source shall document, in writing, to the Materials & Tests Engineer that the cause for removal has been corrected and request prequalification in accordance with Article IV. Prequalification and Performance History of this specification. In addition, the supplier seeking re-establishment as an approved source shall stipulate that all costs associated with re-establishment will be borne by the supplier and shall be paid to the Department prior to replacement on the list of approved sources.
- V. Sampling and Testing: Sampling and testing shall be in accordance with the Department of Highways and Public Transportation, Materials and Tests Division Manual of Testing Procedures, Test Method Tex-733-I. Easy access shall be provided for sampling.
- VI. Packaging: When packaged in bags for shipment and/or delivery to a project, each bag shall contain approximately one cubic foot of fly ash, volume shall be based on bulk density. Each bag shall be labeled with the following:
- A. Supplier
  - B. Power Plant Location
  - C. Net Weight \*
  - D. Type of Fly Ash
- \* Weight from bag to bag shall not vary more than plus or minus 5% of the weight shown on bag.
- VII. Material Requirements: This specification covers the general and specific requirements for two types of fly ash. Both types of fly ash shall meet all requirements of this specification except when specific requirements are shown for a particular type of fly ash.
- A. Chemical Requirements: Fly ash shall conform to the chemical requirement for each type as shown in the following table.

	<u>Type A</u>	<u>Type B</u>
Silicon dioxide (SiO <sub>2</sub> ) plus aluminum oxide (Al <sub>2</sub> O <sub>3</sub> ) plus iron oxide (Fe <sub>2</sub> O <sub>3</sub> ), min, %	65.0	50.0
Sulfur trioxide (SO <sub>3</sub> ), max, %	5.0	5.0
Calcium Oxide (CaO), Variation in percentage points of CaO from the average of the last 10 samples (or less provided 10 have not been tested) shall not exceed plus or minus	4.0	4.0
Magnesium Oxide (MgO), max, %	5.0 *	5.0 *
Available alkalies, as Na <sub>2</sub> O, max, %	1.5	1.5
Moisture content, max, %	2.0	2.0
Loss on ignition, max, %	3.0	3.0

\* When the autoclave expansion or contraction limit is not exceeded, an MgO content above 5.0% may be acceptable.

- B. Physical Requirements: Fly ash shall conform to the physical requirements for each type as shown in the following table.

	<u>Type A</u>	<u>Type B</u>
Fineness ----- retained on 325 sieve (45 cm), max. %	30.0	30.0
Variation in percentage points retained on the 325 sieve from the average of the last 10 samples (or less provided 10 have not been tested) shall not exceed	5.0	5.0

Pozzolanic activity index with portland cement as a minimum percentage of the control at 28 days	75	75
Water requirement, maximum percentage of control	100	100
Soundness autoclave expansion or contraction, maximum %	0.8	0.8
Increase of drying shrinkage of mortar bars at 28 days, maximum percent	0.03	0.03
Reactivity with cement alkalis mortar expansion at 14 days, maximum percent	0.020	0.020
Specific gravity, maximum variation from average %	5.0	5.0

Drying shrinkage shall be tested in accordance with ASTM C 157.

Alkali reactivity shall be tested in accordance with ASTM C 441.

Specific gravity shall be tested in accordance with ASTM C 188.

All other physical requirements shall be tested in accordance with ASTM C 311.