NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 127

USE OF FLY ASH IN CONCRETE

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transporation Research Board

This synthesis will be of interest to materials engineers, bridge designers, pavement designers, and others concerned with mixture proportioning, structural design, and construction of concrete bridges, pavements, and appurtenances. Information is presented on the advantages and disadvantages of using fly ash in the portland cement concrete used in highway construction.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

The use of fly ash in concrete can, under the proper circumstances, improve the performance of the concrete and can lower costs while recycling what has often been a waste product of the electric power generating industry. This report of the Transportation Research Board describes the circumstances under which use of fly ash in concrete has been shown to be beneficial as well as other circumstances under which it may be less useful or not cost-effective. The synthesis also gives some guidance on the procedures necessary to ensure a quality product.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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William G. Gunderman, Engineer of Materials and Construction, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

USE OF FLY ASH IN CONCRETE

SUMMARY

This synthesis discusses the use of fly ash in concrete from the standpoint of its use in the construction of transportation facilities. Early developments relating to the use of fly ash from bituminous coal (Class F) are reviewed and the advantages and disadvantages as they apply to use by transportation agencies are discussed. The use of fly ash can improve workability of the fresh concrete and result in concrete of higher strength and lower permeability with consequent improved resistance to sulfate attack and ingress of corrosive liquids that might lead to corrosion of reinforcing steel. Unit costs per cubic yard of such concrete will usually be less than similar concrete without fly ash. However, from the overall viewpoint of a state highway agency, restraints may exist that eliminate the cost advantage of fly ash concrete (FAC) since greater testing and inspection cost will be encountered and fly ash is not always conveniently available near a construction site.

A brief overview of the fly-ash marketing procedures is provided and a summary of the amount of fly ash now being used is included. The significance of the specific requirements now included in national ASTM and AASHTO specifications is also summarized.

The synthesis reports the replies to a questionnaire concerning the status of the use of FAC in each state of the United States and the provinces in Canada. Transportation agencies in Canada are not yet making appreciable use of FAC. In the United States, because of federal requirements, all states previously not using FAC are reviewing their specifications to permit its use in some, if not all, applications. In a few cases substantial use of FAC has occurred over a number of years but a majority of state highway agencies have made little or no use of FAC. A substantial increase in use of FAC has occurred in some states since 1982 and indications are that such use will increase as more experience is gained. This trend is aided significantly by the development of a fly-ash industry that is conscious of the need for good quality control over its product. Present trends also indicate a developing technology that will be oriented around performance of the hydraulic cement concrete. Future specifications may involve performance requirements without specifying the types and amounts of mineral admixtures. However, development and implementation of such specifications within the next few years is unlikely. For the time being most states view the proportioning of FAC from the standpoint of the amount of portland cement to be replaced by the fly ash and have maximum replacement limits. Generally, a greater amount of fly ash will be added than the weight or volume of cement removed to bring 28-day strengths within specification requirements for the concrete without fly ash. There is a growing awareness that the same fly ash with different cements may react differently and develop different early and ultimate strengths. The need is emphasized for preliminary tests to establish optimum proportioning of ingredients in the concrete using materials from the sources to be supplied to the job.

CHAPTER ONE

INTRODUCTION

Renewed interest in the use of fly ash as an ingredient in hydraulic cement concrete was generated by the passage by Congress of the Resource Conservation and Recovery Act (RCRA) in 1976 and the subsequent decision by the Environmental Protection Agency (EPA) to establish a guideline for federal procurement of cement and concrete containing fly ash. This guideline was the first of a number of similar actions to implement the requirements established in the RCRA. The guideline was first published in the Federal Register on November 20, 1980 for review and comment and was published in its final form in the Federal Register of January 28, 1983 (*1*). It constitutes 32 pages of relatively fine print and covers general aspects of the RCRA including its purpose and scope. The criteria for selection of product areas are discussed and the potential applications and advantages and disadvantages of fly ash concrete (FAC) are summarized. The applicability of provisions of the guideline relating to size and cost of projects is also given.

The initial reaction of the Federal Highway Administration (FHWA) was that this guideline did not apply to the procurement of concrete for federal-aid highway projects; however, after discussions between FHWA and EPA led to a request for clarification of Congressional intent with respect to the RCRA, it was determined that the guideline did apply to federal-aid projects. In a memorandum dated January 4, 1985 from the FHWA deputy administrator to all FHWA Regional Administrators and the Administrator for the Direct Federal Construction Program (Appendix A), it is stated in part that:

> In the recently passed reauthorization of RCRA, Congress unequivocally states that Section 6002 applies to direct procurement and indirect Federal-aid programs of the FHWA. . . .

On this basis, FHWA advises that

> the guideline requires that all affected agencies revise their specifications, standards, and procedures to remove any discrimination against the use of fly ash in cement and concrete unless such use is found to be technically inappropriate in a particular application. A finding of technical inappropriateness should be documented, open for public scrutiny and a review process established to settle any disagreements.

The Deputy Administrator calls attention to EPA's expectation of a "high level of compliance to the guideline" and the permissibility for any person to commence civil action against the United States or any other governmental instrumentability that is alleged to be in violation of the guideline.

It is also pointed out that aggrieved bidders willing and able to supply a designated recovered material who are precluded from bidding by a failure of a procuring agency to comply with Section 6002 may be able to obtain satisfaction through this process (i.e., lawsuits).

FHWA has requested that all state highway agencies submit their revised specifications concerning the use of fly ash in concrete to its Washington headquarters to assist in establishing uniformity of interpretation and adequate documentation of technically inappropriate applications, if any.

The net effect of these developments is that all state highway agencies must review their specifications for hydraulic cement concrete and, unless technical inappropriateness is shown, they must remove restrictions to the use of fly ash as an ingredient in the concrete if the use of such specifications for procurement for federal-aid projects is to continue. Because of the long history of use of fly ash in concrete for numerous purposes, it is doubtful that blanket restrictions on the basis of technical inappropriateness for all applications can be supported. However, it has also been established through prior use and research that not all fly ashes and all fly ash-cement combinations provide adequate performance. Thus, conditions under which fly ash is used in concrete, specifications for the materials used, concrete mixture proportioning, quality control procedures, and construction techniques must all be established and adhered to for successful applications.

SCOPE OF SYNTHESIS

It is the intent of this synthesis to summarize information available concerning the use of fly ash in hydraulic-cement concrete and, where possible, to establish consensus concerning a number of applications relating to highway construction.

As stated, the use of fly ash in concrete is well established for some applications and, when properly applied, its use offers significant advantages and provides effective solutions to certain problems that may arise for highway applications. Proper consideration of potential benefits and careful establishment of suitable quality assurance measures should result in cost-effective use of FAC that will not only be of national benefit from the environment and energy saving viewpoint but also from an engineering consideration providing more economical and long lasting high levels of performance. However, it is also true that inherent changes in procedures are needed when fly ash is used and, if not properly addressed, problems can result. Thus, as conditions now exist the use of fly ash may be counterproductive for transportation agencies under some circumstances.

In the long term, given proper opportunity for FAC technology to develop to its full potential, many of the present restraints that result primarily from lack of full knowledge concerning fly ash-cement interactions can be removed. With better recognition of its limitations as well as of its potential for providing improved performance, it is likely that FAC will eventually gain general acceptance by transportation agencies in those situations that are cost-effective. However, there is a need for close cooperation between fly ash marketers, transportation agencies, and interested materials scientists to develop better knowledge of the complex interactions that exist and to translate those into more meaningful specifications and test methods.

DEFINITIONS OF COAL COMBUSTION BY-PRODUCTS

Although most people in the engineering field understand that fly ash is a by-product from the burning of pulverized coal in electric generating power plants, it is important to recognize that all combustion by-products are not fly ashes and that not all fly ashes are suitable pozzolans for use in concrete. A number of things enter into establishing suitability. Among these are the type of coal burned, the type of furnace in which it is burned, the burning efficiency, and the manner in which the fly ash is collected and stored before use.

The major residues from burning coal at a power plant are classified as bottom ash, boiler slag, and fly ash. The term economizer ash is also applied to the ash collected below the economizer unit in electrostatic precipitators. Another by-product is the residue resulting from flue gas desulfurization, sometimes designated as sulfate sludge.

To provide a general perspective of the total by-products resulting from the combustion of coal in power plants the following definitions are provided. More detailed information concerning the collection, properties, and quantities of these materials is included in Section 3 of the Coal Combustion By-Products Utilization Manual Vol. 1 (*2*).

Dry Bottom Ash

Dry bottom ash is the residue from coal burned in dry-bottom boilers and is the product that falls through open grates. It generally is a well-graded aggregate ranging in size between the U.S. Standard 19-mm (¾ in.) and 75-mm (No. 200) sieve. It is characterized as being porous and susceptible to degradation under compaction and loading. Although it may contain some dense fused particles, its specific gravity ranges between 2.08 and 2.73. The major components are silica (SiO_2), ferric oxide (Fe_2O_3), and alumina (Al_2O_3). The percentage of each in a given ash will depend on the source of the coal burned.

Wet Bottom Boiler Slag

Wet bottom slag is produced when the molten residue in a wet-bottom boiler is discharged into a water-filled hopper. It is smaller in maximum size than dry bottom ash and the particles are glassy and very hard and brittle. It is uniformly black in color. The specific gravity is usually around 2.7, but can range from 2.60 to 3.85 depending on the iron oxide (Fe_2O_3) content. The components are generally the same as those in dry bottom ash, but the amount of each will vary depending on the source of the coal.

Economizer Ash

Economizer ash consists of coarse particles of ash collected in hoppers below the economizer unit in electrostatic precipitators. If the fly ash is not being marketed, economizer ash will normally be disposed of with the fly ash. When fly ash is being marketed, economizer ash will be disposed of separately. Economizer ash is generally not suitable for use as a pozzolan.

Fly Ash

Fly ash is the material collected in the dust-collection systems that remove particles from the exhaust gases of power plants that burn pulverized coal. It is generally finer than portland cement and consists mostly of small spheres of glass of complex composition involving silica, ferric oxide, and alumina.

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

Class F is defined in ASTM specification C 618 as the fly ash normally produced from burning anthracite or bituminous coal. Under current conditions no appreciable amount of anthracite coal is used for power generation. Thus essentially all Class F fly ash now available is derived from bituminous coal. Class F fly ashes are not self-hardening but generally have 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 so formed are chemically very similar to those present in hydrated portland cement. The pozzolanic reactions occur slowly at normal atmospheric temperatures. Essentially all fly ashes in the United States before about 1975 were of this type.

Class C fly ashes normally result from the burning of subbituminous coal and lignite such as are found in some of the western states of the United States. They have pozzolanic properties but may also be self-hardening. That is, when mixed with water they harden by hydration much the same way portland cement hardens. In most cases this initial hardening occurs relatively fast. These materials are referred to as being cementitious and the degree of cementitiousness generally varies with the calcium oxide (CaO) content of the fly ash. Higher values of CaO denote higher cementitiousness. This type of fly ash has become available in large quantities in the United States only in the last few years as the western coal fields have been opened.

The general classification of fly ashes by the type of coal burned does not adequately define the type of behavior to be expected when the materials are used in concrete. There are wide differences in characteristics within each class. Despite the reference in ASTM C 618 to the classes of coal from which Class F and Class C fly ashes are derived, there is no requirement that a given class of fly ash must come from a specific type of coal. For example, Class F ash can be produced from coals that are not bituminous and bituminous coal can produce ash that is not Class F. Moreover, Class C fly ash is not required to have any CaO. Consideration is now being given in ASTM and other organizations to reclassify fly ash in a manner more closely related to the characteristics of the ash itself and its effect on the properties of concrete, but as yet no agreement has been reached as to the basis of such classification.

BACKGROUND OF FLY ASH USE

The suitability of fly ash as a pozzolanic ingredient for use in concrete was recognized as early in 1914. However, the annotated bibliography prepared by Abdun-Nur (*3*) and published by the Highway Research Board (HRB) cites the work by Davis and his associates reported to the American Concrete Institute in 1937 as the earliest substantial study in the United States. Considerable pioneering and development work in this field was conducted throughout the 1940s and 1950s. Although not identified as such, since only one type was available at that time, all this work applies to Class F material. During this early period, usefulness of Class F fly ash in concrete was established for a number of applications and the advantages as well as the disadvantages were identified. The Bureau of Public Roads [BPR (now FHWA)] conducted studies in the early 1950s, and concluded that a substantial amount of the portland cement in concrete could be replaced with fly ash without adversely affecting the long-term strength of the concrete (*4*). One of the BPR studies was directed toward evaluating various test methods for fly ash and showing the relationship of the characteristics of the fly ash to its effects on the characteristics of mortar and concrete (*5*). Cooperative tests were conducted by ASTM Committee C-9 (*6*) and studies on the fundamental characteristics of Class F fly ashes were reported by Minnick (*7*) during this period.

HRB Bulletin 284 (*3*) provides a comprehensive evaluation of the literature relating to Class F fly ashes from 1934 to 1959 including an annotated bibliography of important published reports to that date. Another comprehensive summary pertaining to Class F fly ash is the report published by the Tennessee Valley Authority in 1979 (*8*). Subsequent reports provide similar reviews and also incorporate references to Class C materials. One such report is that of the American Concrete Institute Committee 226 (*9*). This report includes a list of references covering almost all aspects of the use of fly ash in concrete and generally represents the state of the art as of 1985. It covers effects on properties of both fresh and hardened concrete and on mixture proportioning. It deals with aspects of fly ash in ready-mixed concrete, concrete pavements, concrete for pumping, and its use in mass concrete. Use of fly ash in concrete masonry units, grouts, mortars, and special applications is also covered.

Another document providing good general reviews of the literature and state-of-the-art reports is the technical paper by Berry and Malhotra published in the ACI Journal in 1980 (*10*). These authors have also published a compilation of abstracts of papers from recent international conferences and symposia on fly ash in concrete (*11*) and a comprehensive state-of-the-art report incorporating most of the advances in fly-ash technology made between 1976 and 1983 (*12*). This last document provides an excellent assessment of current knowledge and identifies major areas of needed research and development. Lane and Best also published a summary report in 1982 (*13*). The published proceedings of the workshop on research and development needs for use of fly ash in cement and concrete held in March 1981 and sponsored by the Electric Power Research Institute is also a good source of recent information (*14*). This report covers fly ash use generally from the viewpoint of the power companies or ash marketers in addition to research needs. The discussions concerning long-range research envision a fly-ash technology that goes well beyond the present state of the art.

Another general summary report that should be particularly useful for establishing a general perspective of the total problem is the National Bureau of Standards Report by Frohnsdorff and Clifton (*15*). This report presents an overview of the potential for use of fly ash in both cement and concrete from the standpoint of the objectives of the Resources Conservation and Recovery Act. It summarizes the significant benefits that can accrue from fly ash use. It also points out factors that account for the present low-level use of fly ash in cement and concrete. Major research needs to reduce or eliminate present barriers are discussed.

The proceedings of the first international symposium on the use of fly ash, silica fume, and other mineral by-products in concrete published by the American Concrete Institute as SP-79 (*16*) also contains a number of papers that are applicable to problems associated with the use of fly ash in concrete for construction of transportation facilities.

The Annotated Bibliography, which follows the References, provides a brief description of the contents of each of these reports as a guide to those seeking information on the broad aspects of fly-ash utilization in cement and concrete. This synthesis will review those aspects of interest to transportation agencies but will not cover all details included in the reports cited in the Bibliography.

This synthesis is concerned primarily with the use of fly ash in hydraulic cement concrete such as that used for pavements and transportation structures. Although related and of considerable interest to transportation agencies, the use of fly ash-cement combinations in base courses, embankments, and so forth is not covered.

METHODS OF FLY ASH USE

Fly ash is used in concrete either as an admixture at the concrete mixer or as an ingredient in blended cement. In the latter case, the ratio of fly ash to portland cement becomes fixed and generally no adjustment in amounts of cementitious material is made when blended cement is substituted for regular portland cement. Addition of fly ash at the mixer affords opportunities for adjustment of the ratio of fly ash to cement. At times the fly ash is added to improve workability and replaces fine aggregate in the concrete, but generally fly ash is considered as added cementitious material that replaces a portion of the portland cement that would normally be used. Whether added as a portion of the blended cement or at the mixer, the effect of a particular fly ash with the same cement should be essentially the same for the same ratios and amounts of cementitious materials. Thus, for the purposes of this synthesis the manner of addition is not considered important from the viewpoint of the characteristics of the FAC. In keeping with present trends, the discussions generally are from the viewpoint of addition as an admixture.

CHAPTER TWO

POTENTIAL ADVANTAGES AND DISADVANTAGES FROM USE OF FLY ASH IN CONCRETE

The emphasis on using fly ash in concrete as a means for eliminating problems associated with disposal of large amounts of by-products often tends to create a negative perception concerning its value. Many administrators and engineers unfamiliar with the properties of fly ash when used as a pozzolan are likely to think in terms of how much fly ash can be tolerated without harming the concrete rather than optimizing the potential benefits from its use. However, the proper quality and amount of fly ash in a properly proportioned mixture can provide concrete with superior qualities and usually at a lower cost.

BASIC CONCEPTS OF POZZOLANIC ACTIVITY IN CONCRETE

Although most Type C fly ashes react not only as pozzolans, it is the pozzolanic activity of fly ash that improves the ultimate strength of concrete. A pozzolan is defined as a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans may be natural materials, such as certain types of finely divided calcined clays or volcanic ashes, or they may be by-products, such as fly ash.

When fresh concrete sets it does so because of a reaction between water and the cementitious compounds in cement to form several types of calcium silicate and calcium aluminate hydrates. These products form a structure around the aggregate particles leading to the setting or hardening of the concrete. A by-product of the initial reactions is calcium hydroxide. The calcium hydroxide in solution reacts slowly with pozzolanic materials such as fly ash. The product of this reaction is basically of the same type and characteristics as the product of the initial cementitious reaction. Thus additional bonding product becomes available and additional strength will be developed. Because the pozzolanic reaction is much slower than the initial cementitious reactions, when the fly ash has replaced a portion of the cement it is likely that the strength at early ages will be lower, but ultimately equal or greater strength should develop. How quickly this occurs will depend on characteristics of the fly ash and cements used, as well as the proportioning of the ingredients of the fly ash concrete.

Another aspect is that in hydraulic cement concrete where the water-cement ratio exceeds 0.38 by mass, there is more water than needed for hydration of the cement. Such water is added to obtain proper workability. This excess water is present in capillary channels. If the concrete is properly cured, the calcium hydroxide dissolved in this water reacts with the fly ash and the solid reaction product fills (or partially fills) the channels, resulting in lower permeability of the concrete to aggressive fluids such as chloride or sulfate solutions.

Hydration reactions are exothermic—that is, a portion of the latent energy required to combine the elements is released by the hydration reaction and this raises the temperature of the concrete. If the reactions occur rapidly within a large mass of concrete and the heat is not dissipated quickly enough to prevent significantly increased temperatures, stresses in the concrete as it cools may be of sufficient magnitude to cause cracking. In FAC, because of the slower pozzolanic reactions, heat is released over a longer period of time and the concrete temperatures remain lower because heat is dissipated as it develops.

The above is a simplified picture of what occurs with pozzolans. Some of the specific reactions and the sequence of those reactions have been questioned, but they provide a general explanation of the reasons why fly ash, acting as a pozzolan, can enhance desirable properties and a recognition that it is not an inactive ingredient or adulterant in the concrete. When the pozzolan also has hydraulic properties, as is the case with Class C fly ashes, additional strength-producing reactions also occur. These are generally considered to be similar to normal hydration actions that occur with compounds in the cement.

SUMMARY OF EFFECTS OF FLY ASH ON CONCRETE PROPERTIES

Several of the comprehensive reviews (Annotated Bibliography) as well as other publications summarize the accepted views concerning the advantages and disadvantages of using fly ash in concrete. The following summary is based on the information contained in these and other referenced reports.

Effects on Fresh Concrete

Workability

The spherical shape of most fly ash particles permits greater workability for equal water-cement ratios, or the water-cement ratio can be reduced for equal workability. In addition, because the absolute volume of cement plus fly ash (especially Class F) normally exceeds that of cement in similar concrete mixtures without fly ash, the increased ratio of the solids volume to the water volume produces a paste with improved plasticity and better cohesiveness. The stability of the dispersion of the cement and fly ash particles in the fresh paste is improved.

Bleeding

Bleeding is reduced by the greater volume of fines and lower water content for a given workability.

Pumpability

Pumpability is increased by the same characteristics affecting workability; that is, the lubricating effect of the spherical fly-ash particles and the increased ratio of solids to liquid that makes the concrete less prone to segregation.

Time of Setting

The effects of fly ash on the time of setting depends on the characteristics and amounts of fly ash used. All Class F fly ashes generally increase the time of setting as do most Class C materials. However, some Class C materials are reported to reduce the time of setting and others have no effect. For highway construction, changes in time of setting of fly ash-concrete from concrete without fly ash using similar materials usually will not introduce a need for changes in construction techniques and the delays that occur may be considered advantageous. However, delays up to four hours have been observed with some mixtures; thus trial tests should be made with the actual mixture proportions and materials for the job.

Effects on Hardened Concrete

Temperature Rise

The initial impetus for using fly ash in concrete stemmed from the fact that at early ages FAC develops less heat per unit of time than does similar concrete without fly ash. Thus the temperature rise in large masses of concrete is significantly reduced since more of the heat can be dispersed as it develops. This characteristic is of considerable importance for highway-related construction involving large foundations or piers for bridges, etc. where thickness is greater than about 10 in. (250 mm). Not only is the risk of thermal cracking reduced, the pozzolanic reactions that occur at a slower rate provide for equal or greater ultimate strength for such concrete with fly ash than is attained by regular concrete.

Strength and Rate of Strength Gain

FAC in which a portion of the cement normally used has been replaced with a fly ash having proper pozzolanic properties (as defined by ASTM C 618) will ultimately develop greater strength than the similar concrete without fly ash. However, the rate at which such strength is developed and the level of such strength depends on the characteristics of the fly ash, the cement used, the proportions of fly ash to cement, and the curing regimen. A slow rate of strength development is of concern to highway engineers under some circumstances. For example, in continuously reinforced concrete pavements, the development of proper cracking patterns is important and inadequate early strengths resulting from using fly ash may change the desired pattern.

The general perception that fly ash concrete has low early strength results from research findings involving Class F fly ash that show comparisons of strength gains of two concretes containing the same aggregate. In one case portland cement is the only binding constituent and in the other a portion of the cement is replaced by Class F fly ash on a volume-for-volume or weight-for-weight basis. In such cases the FAC will have lower strengths at early ages, but usually will develop strengths higher than those of similar concrete without fly ash at later ages.

This characteristic of FAC is of concern when it is placed in cold weather. Some state highway agencies do not permit placement after a specific date in the fall and not before a specific date in the spring. Similar restrictions are placed on the use of blended cements in cold weather. To counteract potentially low strengths, an amount of fly ash in excess of the amount of cement removed is added. When necessary, adjustment in the amounts of fine aggregate is also made. When so proportioned, FAC should have adequate strengths at early ages to meet the usual requirements for strengths of highway concrete. If the specification for FAC is based on the needed characteristics of the concrete for the conditions to be encountered, it should not matter if the concrete develops strength at a faster or slower rate than does some other combination of ingredients, as long as the desired strength levels are attained at the specified ages.

Problems could be encountered if normal procedures for removing forms for structures or opening pavements to the use of construction traffic are such that dependence is placed on strength development at a greater rate than that actually required by specifications. To avoid this possibility, some states require a greater delay in removing forms from concrete structures with FAC or concrete made with blended cement over that normally used for concrete with Type I or Type II cement.

A recent study reported by the West Virginia Department of Highways in which fly ash concretes at very early ages were exposed to freezing and thawing cycles revealed that these fly ash concretes did not have any serious loss of durability compared to control concretes (*17*). This indicates that with proper mixture proportioning and with the same cold-weather restrictions applied to non-fly ash concrete, the FAC can be placed under the same ambient conditions as other concrete and thus earlier "cut-off" dates for FAC may not be needed. However, until more general information is available, the possibility that some FAC may be affected by cold weather in a manner different from regular concrete must be considered.

When Class C fly ash is used, the strength development with time is likely to be different from that encountered for Class F fly ash. The self-hardening reactions with Class C fly ash are likely to occur within the same time frame as the usual hydraulic cement hydration reactions, giving equal or greater strengths at early ages. The pozzolanic activity of such materials further increases strength at later ages. The ultimate strength developed in concretes using Class C fly ash will vary greatly depending on the properties of the fly ash, the cement used, and the proportioning of the concrete mixture. It has been demonstrated that very-high-strength concretes can be attained with some Class C fly ashes with high lime contents.

Resistance to Damage from Freezing and Thawing

As with all concretes, the resistance of FAC to damage from freezing and thawing depends on the adequacy of the air-void system; the soundness of the aggregates; age, degree of hydration (maturity), and strength of water cement paste; and moisture condition of the concrete. Special attention must be given to attaining the proper amount of entrained air when fly ash is being used in concrete. The problems associated with air entrainment are discussed in Chapter 4.

Some reports have indicated that even with adequate entrained air, FAC has a lower resistance to freezing and thawing when compared with concrete without fly ash at equal ages. However, when comparisons are made under conditions that ensure that the FAC has developed adequate strength, no significant differences in durability have been observed.

When comparative laboratory tests are made with similar specimens with and without fly ash, it is likely that FAC will show greater surface scaling. However, it is recognized that the test conditions are generally more severe than the environmental conditions to which the concrete is exposed. A number of fly ash concretes have performed satisfactorily for a number of years with no evidence of scaling. Greater surface scaling has been reported for some experimental installations but when such scaling occurs it does not affect the internal structure and integrity of the concrete (*18, 19*).

Resistance to Ingress of Agressive Liquids and Reinforcing Bar Corrosion

In ordinary concretes water-soluble calcium hydroxide formed during hydration of portland cement can be leached out over a period of time; this will make channels available for the ingress of water and corrosive solutions. However, when fly ash is present it reacts with the calcium hydroxide to produce insoluble calcium silicate hydrates of the same or similar types that occur in the normal hydration products of cement. This reduces the risk of leaching calcium hydroxide. The reaction products also tend to fill capillaries, thereby reducing permeability to agressive salt solutions that might initiate corrosion of embedded steel. Even though the pozzolanic reaction reduces the amount of calcium hydroxide present, adequate alkalinity remains to preserve the passivity of the steel necessary to prevent corrosion. Tests indicate that corrosion resistance is improved when fly ash is used at rates up to 50 percent of the total cementitious material. It is reported that sufficient calcium hydroxide remains to preserve passivity at as high as 75 percent replacement of the cement.

Alkali-Silica Reaction

One of the earliest applications of Class F fly ash in highway concrete was its use as a means of inhibiting or reducing expansion resulting from the alkali-silica reaction. In theory, the reaction between the very small particles of amorphous silica glass in the fly ash and the alkalies in the portland cement and the fly ash ties up the alkalies in a nonexpansive calcium-alkali-silica gel. Thus hydroxyl ions remaining in solution are insufficient to react with the material in the interior of the larger reactive aggregate particles and disruptive osmotic forces are not generated. However, because a number of fly ashes have appreciable amounts of soluble alkalies, there is a danger of increased reaction under some circumstances. It is therefore necessary to make tests on the ingredients to be used in the field proportions to ensure that expansion will be reduced to safe levels in the long term. The choice of low-alkali cement has traditionally served to avoid disruptive expansions with aggregates susceptible to this reaction. However, current environmental and energy concerns make recycling of particulates removed from the flue gases during cement manufacture an economically attractive procedure. This in turn tends to result in higher alkali cements than have normally been produced from the same raw materials. Thus, the use of Class F fly ash in concrete may provide a means by which greater alkalies in the cement can be tolerated for equal or lower unit cost of the cement as well as with a reduction in the amount of cement used. However, a study conducted in Canada showed that the use of Class F fly ash in concrete had no effect in reducing expansions resulting from the alkali-carbonate reaction (*20*). Current knowledge concerning the role of Class C fly ashes for reducing expansion is not sufficient to draw specific conclusions concerning their overall effectiveness.

In some wetting and drying tests made by the Kansas Department of Transportation, two Class C fly ashes failed to reduce expansions in the tests with reactive sands and, in fact, increased expansions in some cases with 15 percent replacement of cement with fly ash (*21*). Although it was determined during the course of the investigation that the fly ash used was much coarser than fly ash normally supplied from that source and did not comply with the requirements of ASTM specification C 618, results such as those obtained in the Kansas tests emphasize the need for careful evaluation of all the ingredients to be used when a potential for alkali-aggregate reactions exists. The relative percentages of fly ash, cement, and fine aggregate may be as important as the alkali contents of the fly ash and the cement.

Resistance to Chlorides and Sulfates

Class F fly ash has been used in highway concrete in Alabama since about 1953 and its use has been required there since 1960. One of the primary benefits attained by such use is the increased resistance of the FAC to attack from sulfates and potentially corrosive salts that penetrate into the concrete and cause steel corrosion with accompanying cracking and spalling of the concrete. Similar results have been reported in Florida by Larsen (*22*). As previously stated, the reaction of the fly ash with lime from cement hydration results in additional calcium silicate hydrates and accompanying reduction in permeability of the concrete. Larsen also suggests that the fly ash may combine with some of the alumina phases in the cement, thus reducing the potential for expansive sulfate-alumina reactions responsible for sulfate attack (*22*).

Dikeou studied the resistance to sulfate attack of a number of cement types with and without fly ash (*23*). He reported the following order of resistance from the most resistant to the least resistant for the fly ashes and cements used in his studies:

(a) type V plus fly ash
(b) type II plus fly ash
(c) type V
(d) type II
(e) type I plus fly ash
(f) type I

Class F fly ash was used in this investigation. Generally this type of fly ash will improve the sulfate resistance of any mixture in which it is included, although the quantitative amount of improvement may vary with either the cement used or the fly ash. However, the situation with Class C fly ash is different. There is evidence that some Class C fly ashes may reduce sulfate resistance when used in normal proportions. The effects noted will also vary with the characteristics of the cement as well as the fly ash.

Dunstan has proposed an indicator of the relative sulfate resistance of a fly ash termed the "R" value (*24*). The "R" value is a ratio of calcium to iron oxide expressed as:

$$\text{"R"} = \frac{\%\ CaO - 5}{\%\ Fe_2O_3} \qquad (1)$$

For the fly ashes used by Dunstan in his test program, those having "R" values of 1.5 or less generally improved sulfate resistance while those with higher values did not. Further studies are now being made to determine if Dunstan's factor is applicable to all fly ashes.

It is generally accepted that the maximum sulfate resistance for the concrete will be achieved by employing the most sulfate-resistant portland cement available along with fly ash. In selecting the fly ash one should look for an ash with the lowest "R" value and a proven history of satisfactory performance either by laboratory or field tests.

Other Characteristics

A number of other characteristics are discussed in the ACI summary listed in the Bibliography (*9*). Very briefly the effect of fly ash is summarized as follows:

a. Bond of Concrete to Steel—May be improved with proper consolidation and equivalent strength; anchorage of reinforcement in concretes with fly ash should be equal to that in concrete without fly ash.

b. Bond of New Concrete to Old—Concrete can be bonded equally well to old concrete with or without fly ash.

c. Impact Resistance—Use of fly ash affects impact resistance only to the extent that it usually improves compressive strength with time.

d. Abrasion Resistance—At equal compressive strengths, properly cured and finished concrete with and without fly ash will exhibit essentially equal resistance to abrasion.

e. Drying Shrinkage—Increase in drying shrinkage may occur from increases in the paste volume if water content is the same. If water content is reduced, shrinkage is minimal. No differences were reported for replacements of up to 20 percent of cement with fly ash.

f. Creep—The effects of fly ash are limited primarily to the extent to which fly ash influences the ultimate strength and rate of strength gain. Concrete with fly ash proportioned to have the same strength at the age of loading as concrete without fly ash produced less creep strain at all subsequent ages.

RESTRAINTS ON THE USE OF FAC IN HIGHWAY CONSTRUCTION

As is evident from the preceding discussions, almost all of the recognized effects of fly ash on concrete properties tend to improve its characteristics so that, considered from the viewpoint of the concrete alone, its use is advantageous. However, whether or not there is an overall advantage to the use of FAC by a highway agency depends on a number of additional factors. With the present state of the art, these additional factors often override the indicated advantages in using FAC for highway construction.

A report by the Virginia Highway and Transportation Research Council (VHTRC) summarized a number of the restraints relating to the use of fly ash in concrete for construction of highway or other transportation facilities (*25*). This report, which was based on information available and the conditions existing in 1980, cited quality assurance and logistic or procedural problems that constitute deterrents to greater use by state transportation agencies. The major restraints discussed are:

1. Not all fly ashes have sufficient pozzolanic activity to provide good results in concrete. There is also potential variability of quality of fly ash from the same source.
2. Special precautions may be necessary to ensure that the proper amount of entrained air is present.
3. Suitable fly ashes are not always available near the construction site and fly ash transportation costs may nullify any cost advantage.
4. Additional personnel, time, and money may be required for adequate quality assurance.
5. New concrete mixture proportions may be needed with each change in ingredients.

Another factor not considered in the Virginia report is the uncertainty as to the relative performance characteristics of Class F and Class C materials and the differences in behavior of fly ashes containing low, moderate, or high contents of lime. Finally, the cement-fly ash reaction is very dependent on the properties of the cement. Thus, it is necessary for a transportation agency not only to test and approve each fly-ash source but also to investigate the properties of the specific fly ash-cement combination to be used for each project. This further adds to the cost of quality assurance and creates a need for additional personnel that may be difficult to fill because of administrative restrictions on the number of employees.

Most of these factors relate to quality control and acceptance procedures and will be discussed in Chapter 4.

CHAPTER THREE

FLY ASH MARKETING AND UTILIZATION

INCENTIVES FOR BY-PRODUCT UTILIZATION

The use of fly ash in concrete is only one part of the total effort for use of the residue from burning pulverized coal for electric power generation. The American Coal Ash Association, first organized as the National Ash Association in 1968, has promoted the by-product use for a number of applications. However, the enactment of the Resource Conservation and Recovery Act (RCRA) (which is intended to promote resource conservation and safe disposal of solid wastes) and the current emphasis to burn more coal and less petroleum fuel for power generation have created increased interest on the part of all power-generating companies to market their ash as a by-product rather than simply disposing of it in an acceptable manner.

As set forth in the introduction to Volume 1 of the Coal Combustion By-Products Manual (*2*), long-term increases in volumes of by-product are expected and there is a scarcity of available disposal sites. The manual states:

> Utilization of coal combustion products is therefore becoming an increasingly attractive alternative to disposal. Use is attractive for many reasons, among them the following:
> - Disposal costs are minimized or eliminated.
> - Less area is reserved for disposal, thus enabling other uses of the land and decreased permit requirements.
> - There may be financial returns from by-product sales, or at least offset of processing costs.
> - The by-products can replace some scarce or expensive natural resources.

OVERALL VOLUME OF FLY ASH PRODUCED

Estimates are that as of 1984 coal ash is being generated at a rate of 69.15 million tons per year (*26*). At present only about 16.04 million tons are being used per year for all purposes. It is thus obvious that finding storage or disposal sites could become a serious problem unless the use can be increased significantly. It is likely that much of the increased use will be in fills and embankments. Problems associated with such use are different from the problems associated with marketing a fly ash suitable for use as an admixture in concrete. Discussions of the overall aspects of coal ash use are included in the Utilization Manual, Vol. I (*2*) and an annotated bibliography of much of the applicable literature is presented in Volume 2 of the Manual (*27*).

When fly ash is to be used as a pozzolan in concrete it must perform as an active ingredient of the concrete. Therefore, considerably more testing and monitoring of its characteristics is required as compared to other uses such as for fills and embankments or as a filler in asphaltic pavements.

MARKETING AND PRODUCTION OF FLY ASH AS A POZZOLAN

Summaries of power plant operation presented at several seminars on the use of fly ash in highway construction provide some insight into the problems and considerations that are encountered by power generating companies marketing fly ash suitable for use as a pozzolan in concrete.

Tackett (*28*) discusses the effects of coal characteristics on fly ash quality. He points out that not only do the characteristics of the inorganic constituents vary from coal to coal, there is also variation in the quantitative amount of ash and its characteristics in the same coal. Such variations can affect burning conditions, which in turn relate to the slagging that occurs in the furnaces, all of which affect the operating efficiency with respect to power generation. One important observation of Tackett's is that "more excess air results in more thorough combustion, a reduction in slag, a reduction of carbon in fly ash, but also in less furnace efficiency. Less excess air results in higher efficiency, but more carbon in the fly ash." Thus, it becomes a matter of trade-off between higher efficiency and lower carbon content of the fly ash. He adds that most often a furnace in reasonably good balance will produce a good quality ash. He also discusses the difficulty of achieving a new balance when the source of the coal is changed.

The fineness of the pulverized coal is also known to relate to the efficiency of burning and thus the carbon content of the fly ash. At times in some plants fuel oil is added to the pulverized coal to achieve furnace balance. When this happens a residue from unburned oil is likely and this will greatly decrease the quality of the fly ash as a pozzolan and could intensify problems of air entrainment if such ash is used in concrete. Color of the concrete might also be affected. Thus Tackett recommended that all such fly ash be discarded and not placed in the silos to be used for storing and shipping fly ash that meets ASTM specification C 618 (*28*). In a similar presentation, Cooksey (*29*) described his company's experience in installing facilities for providing high quality fly ash for sale as a pozzolan meeting ASTM specification C 618. His company's fly ash is marketed by a separate company. He pointed out the necessity for the power plant to recognize that without special effort and facilities the normal product of a power plant was not uniform and that factors such as carbon content and fineness are of concern to the ultimate user of the fly ash. Because the sale of high quality fly ash can be a significant positive economic factor to a power company, it is as much to its advantage as it is to the ash marketer to maintain the ash quality as much as practical. Cooksey describes special equipment and procedures necessary for good ash production.

Amount of Fly Ash Used in Concrete

The present and potential availability of fly ash suitable for use in concrete can greatly affect the economic impact of its use by a transportation agency. The 1984 summary of ash use provided by the American Coal Ash Association shows that of the 69.15 million tons of ash produced, 51.32 million tons were fly ash (*26*). An earlier summary (*2*) based on 1980 data showed that 70 percent of the fly ash produced in that year was Class F and 30 percent was Class C. About 10.1 percent of the Class F material and 23.1 percent of the Class C material was used in 1980. Of this amount 3.39 million tons of the Class F material and 3.33 million tons of the Class C material were used as admixtures in concrete and about 0.5 million tons and 0.8 million tons respectively for Class F and Class C were used in the manufacture of blended cements.

Technical Information Letter No. 426 of the National Ready Mixed Concrete Association (*30*) reports the results of a 1984 survey of its member companies to determine the extent of fly ash use in that industry. This letter estimates that in 1983 fly ash use by the ready-mix concrete industry exceeded 2.5 million tons and that ash appears to have replaced from 1.2 to 2.1 million tons of portland cement. The concrete containing fly ash represents 24 to 31 percent of the concrete and the average amount of fly ash per cubic yard of concrete was estimated to be 108 lb. The survey showed that 39 percent of all ready-mixed concrete producers use fly ash and, for those companies using the material, 42 percent of the concrete produced contains fly ash. Generally, large concrete producers make more use of fly ash than do small producers. Most producers believe that the use of fly ash in concrete will remain constant or increase. Very few indicated that they thought fly ash use would decrease in the near future.

PROPERTIES OF FLY ASH CURRENTLY PRODUCED

Much of the literature concerning use of fly ash in concrete before 1980 dealt with fly ashes resulting from the burning of bituminous coal, designated as Class F in ASTM specifications. However, since 1980 a number of studies have been reported dealing with the characteristics of the fly ashes from subbituminous or "western" coals in the United States (*31, 32*). These fly ashes generally can only meet the requirements for Class C of ASTM C 618 but some can meet all the physical and chemical requirements of Class F. Other studies have sought to characterize products from modern plants that are representative of the types of fly ash being marketed.

These reports have increasingly demonstrated that modification of the present classification system is desirable and various authors have suggested systems but none have as yet been adopted (*33, 34*). The report by McKerall et al. (*31*) on the analysis of Class C fly ashes produced in Texas shows those products to be useful in both soil stabilization and in hydraulic cement concrete. The CaO content of these Texas fly ashes varied from about 10 to 29 percent. One innovation developed in this study was a rapid heat evolution test that related to the CaO content of the fly ash. The authors believe that such a test would be useful as a quick measure of the uniformity of different shipments of fly ash from the same source.

Electric Power Research Institute Study

A more extensive study on fly ashes was reported by Mehta in 1984 (*35*). This study included tests on 11 fly ashes of diverse properties. Seven were derived from eastern and western bituminous coals, three from Wyoming subbituminous coal, and one from Texas lignite.

The calcium oxide content of the fly ashes from bituminous coal was less than 7 percent; that of the other fly ashes varied from 15 to 27 percent. Mehta reported that the furnaces producing the fly ashes represented three major U.S. suppliers and that all but one of the furnaces were relatively modern, having been installed between 1967 and 1981. He thus concluded that the materials tested are representative of those that will probably continue to be produced for some time in the United States.

Mehta concluded from his study that, except for the calcium content, variation in the chemical constituents of fly ash appeared to have little effect on its pozzolanic and cementitious properties. Fly ashes containing less than 7 percent CaO, produced by the combustion of bituminous coals, showed lower reactivity than the high-calcium fly ashes produced by the combustion of subbituminous and lignite coals. On the other hand, even large variations in SiO_2 (36.0 to 57.6 percent), Al_2O_3 (13.0 to 29.0 percent), and Fe_2O_3 (5.0 to 20.6 percent) did not significantly affect the strength-contributing potential of the fly ashes used in this investigation. In his view, the higher reactivity of the high-calcium fly ashes was most likely related to the presence of calcium in the aluminosilicate glass. The high-calcium fly ashes also contained reactive crystalline phases such as $3CaO \cdot Al_2O_3$ and $CaSO_4$.

Particle size distribution was indicated to be the most important parameter determining the relative reactivity of different fly ashes. A large percentage of fly ash particles greater than 45 μm (No. 325) had a negative effect on the 28- and 90-day strengths of normally cured portland cement-fly ash mortars; a large percentage of particles less than 10 μm had a positive influence on mortar strengths. It was also shown that the pozzolanic activity index as required in ASTM C 311 did not provide a useful measure for relative reactivity of fly ashes from different sources. More useful information was obtained from test mortars containing a fixed proportion of fly ash by weight of the total cementitious material and a constant ratio of water to cementitious materials (portland cement plus fly ash). Another general conclusion drawn by Mehta was that under normal operating conditions modern furnaces are capable of producing fly ash that is generally low in carbon and high in glass content, and thus well suited for use as a pozzolan in the cement and concrete industry.

Iowa Study

A study of fly ashes produced in Iowa was conducted by Iowa State University for the Iowa Department of Transportation and the results published in September 1983 (*32*). Seven fly ashes from different coal sources were tested in this study. All the fly ashes were from power plants located in Iowa but with one exception the fuels used were Wyoming coals classed as lignite or subbituminous. In some cases the fuel came from a blend from two to more mines. The other fuel was a blend of Illinois and Montana coals. Three of the seven fly ashes in this series had $SiO_2 + Al_2O_3 + Fe_2O_3$ contents greater than 70.0 percent and thus would be classed as Class F although the coal was not classed as bituminous. Two of these three materials had low CaO contents (4.3 and 1.5 percent) and the third had a relatively high CaO content of 13.6 percent. The Class C materials had CaO contents ranging from 29.5 to 31.5 percent. A significant contribution of this study is the X-ray fluorescence and X-ray diffraction techniques developed to permit rapid determination of elemental composition (X-ray fluorescence) at a low cost per sample and determination of compound composition (X-ray diffraction). Aluminum-bearing cementitious compounds were identified in the crystalline phase. Other compounds, such as quartz, mullite, and magnetite were identified as well as significant amounts of magnesium and calcium oxide. The differentiating factor noted in the amorphous composition of the seven fly ashes was the amount of calcium in the glass. The authors of the report believe that the calcium in the glass has an influence on the pozzolanic activity of the fly ash.

Significant findings counter to usually assumed relationships are also reported in this study (*32*). For example, the high heat of hydration was shown not to necessarily relate to the free lime content. One fly ash with total calcium expressed as CaO on the order of 30 percent had only about 2.1 percent free calcium oxide. Heat of hydration was related more to the hydration of cementitious compounds than to the free lime reaction. A range of inert compounds from 5.5 to 23.5 percent was also indicated. Autoclave expansion for these fly ashes were found to be related to the free lime (CaO) present rather than the magnesium oxide (MgO). It was also found in these tests that high-lime fly ashes that produced superior results with portland cement consistently failed the ASTM lime-pozzolan test while low-lime fly ashes passes the ASTM standard. However, it is reported that these results were not consistent with findings by another laboratory, which showed that the ASTM standard was met. Tests then were made that showed that when commercial lime was used in the test, satisfactory results were obtained but when reagent grade lime was used, results were low. This study also identified a fly ash-coarse aggregate interaction that influenced resistance of concrete to freeze-thaw damage. This phenomenon was reported as a clustering of air bubbles around coarse aggregate particles. The possibility that a foam flotation test could be used to identify the problem and possibly determine air-entraining agents not sensitive to the mechanism was discussed but further research is needed. It is noted that this phenomenon has not been reported by other researchers. Generally, distribution factors are reported to be satisfactory (*18*). Tests on the sample-to-sample variability of fly ashes from the same source were also conducted and the authors concluded that, for the plants included in their study, the variability was less than that encountered with portland cement from a single source.

Indiana Study

Results of an extensive study of fly ashes produced in Indiana were reported in October, 1985 by Diamond (*36*). Tests made in this study included complete chemical analysis and determination of soluble alkalies and sulfate; particle size distribution; surface area and specific gravity measurements; determination of magnetic (nonreactive) particles; X-ray diffraction; scanning electron microscope study; and determinations of pozzolanic activity index. It was reported that most Indiana fly ashes were Class F materials. Only two Class C materials were among those sampled. The Class F materials in this study were all obtained from plants burning coal from local Illinois Basin coals and consequently were almost identical in chemical analysis parameters. There were major differences among the fly ashes in calcium contents, particle size distribution and other properties of importance with respect to use of the fly ash in highway concrete.

Several significant contributions result from this work. One is the procedure for determining the quantitative amount of magnetic particles that is shown to relate to the percentage of components in the fly ash that do not react with cement or act as a pozzolan. Thus such components should be classed as additions to the fine aggregate in concrete rather than as replacements to the cement. The percentage of such particles for the Indiana fly ashes varied from about 4 to 43 percent, the average being about 25 percent. This finding generally supports the general practice of adding more fly ash than the amount of cement to be left out when proportioning FAC. It is of interest to note that the amount of magnetic particles was close to the iron oxide content of fly ash in some instances, but in others the content of magnetic particles was significantly greater than the iron oxide content.

Significant differences in the particle sizes and shapes were revealed by studies with the scanning electron microscope. Particle size distributions were also shown to vary significantly among the fly ash tested in this study. Greater fineness appears to be related to greater pozzolanic activity as might be expected.

This study also demonstrates significant variation in responses of the fly ash-cement combinations to pozzolanic activity tests. The standard test described in ASTM C 311 compares the strength of mortars in which 30 percent of the weight of the cement used for the reference mortar has been replaced with an equal volume of fly ash and the amount of water has been adjusted to give essentially equal flows for the two mortars. Thus this test combines the effects of water reduction with the effects of pozzolanic activity in the final result. In addition to the standard test, the Purdue study included tests on mortars in which 30 percent of the weight of the cement was replaced with 30 percent by weight of the fly ash. The water content of the fly ash mixtures was not adjusted for changes in water demand but were left the same as that of the reference cement mortars. Diamond states that by comparing results obtained in both tests a much more reliable interpretation of the properties of the fly ash as they affect the concrete is attained than if either test method were used alone.

In addition to the thorough determination of the characteristics of the fly ashes now being produced in Indiana, this study makes significant contributions toward the methodology of studying all fly ashes. The unique procedures that will be of assistance in studying all sources of fly ash are:

1. The method for accurately and reproducibly determining the content of magnetic particles in fly ash.
2. The method for specimen mounting of fly ash for scanning electron microscopy.
3. The method for analyzing and displaying the results of particle size distribution determinations to bring out meaningful differences among different fly ashes.

Generalizations from Recent Studies

Although most tests with present-day fly ashes provide the generally expected trends established over a number of years, it is evident that the introduction of fly ashes from western coals has complicated the technology to a considerable extent. Some fly ashes from western coals can meet the chemical and physical requirements of Class F material as well as the requirements of Class C but the reactions and performance of such materials may depart from established trends for Class F fly ashes. Most Class C materials, while providing good concretes, introduce interactions in the concrete that as yet are not completely understood. It has also been demonstrated that the specific fly ash-cement interactions will vary with the cement characteristics as well as with the characteristics of the fly ash.

Additional evaluations of the characteristics of fly ashes available in specific areas have been made or are under way. One of these, for which no results have been as yet reported, is an extensive study being sponsored by the Electric Power Research Institute. This project has as its objective the development of a system for determining the usefulness of fly ash for a number of applications; in addition, models for different classifications and fly ash types are being sought. The materials being tested include samples from all areas of the country and the results will form a data base for evaluating the applicability and limitations of the models developed in the study.

The differences in characteristics of fly ashes from different areas of the country, and the differences of products from different power plants using essentially the same coal source, emphasize the necessity for all users of FAC to make trial mixtures for the ingredients to be used in any project to ensure that the desired characteristics of the FAC are attained. Such trial mixtures should include the admixtures to be used as well as the cement, fly ash, and aggregate. Such tests should preferably include variations of proportions of fly ash to cement and possibly variations in water contents to establish optimum mixtures. In particular, all new sources of fly ash must be carefully evaluated. Should any change in source of materials be necessary during the course of a project, the effects of that change should be evaluated before continued use.

CHAPTER FOUR

QUALITY ASSURANCE PROCEDURES FOR FAC IN TRANSPORTATION FACILITIES

Because of the requirements under the RCRA and the EPA guideline for concrete procurement, restrictions against the use of FAC in the construction of transportation facilities are being removed rapidly. There is also a growing fly-ash marketing industry and developing technology that will almost certainly lead to substantial increases in the amount of FAC used by transportation agencies, especially in pavements. However, as stated earlier, whether or not the use of FAC is cost-effective for a transportation agency may depend on factors other than the properties of the FAC itself.

The primary concerns are of initial selection of proper materials and of quality assurance. Quality assurance in this context is defined as both the quality control of the fly ash, which is the responsibility of the fly ash marketer, and the acceptance procedures and tests that are the responsibility of the purchasing agency. Quality assurance also applies to the mixture proportioning and placement of the FAC. Of equal importance is economics. The distance that materials must be moved to reach the point of use has a significant effect on whether or not FAC is more or less costly than portland cement concrete without fly ash. The potential volume of FAC that can be used also affects cost-effectiveness since capital investment in silos and fly-ash handling equipment is necessary. Various aspects of these responsibilities are discussed in the following sections.

FLY ASH SPECIFICATIONS

The basic concepts of present specifications for use of fly ash as a pozzolan in concrete were developed in the United States by cooperative efforts among users, producers, and general interest participants sponsored by ASTM Committee C-9 on concrete. Thus, the viewpoint has been from that of concrete technology.

An ASTM specification for fly ash, C 350 was first adopted in 1954. In 1968 this was combined with C 402 to form the present C 618, which has been modified a number of times to keep it current with newer developments and improved test methods. The latest published version is C 618-85. The AASHTO subcommittee on materials has adopted its specifications M 295, which is very similar but not identical to C 618. Important differences are a limit of 5.0 percent for loss on ignition in M 295 instead of 6.0 percent in C 618-85 and M 295 cites only the pozzolanic reactivity test with cement and tests at an age of 7 days while C 618 still contains both a 28-day test with cement and a 7-day test with lime. Requirements for a maximum content of MgO are still retained by M 295 but have been dropped in C 618. Each of these specifications are for pozzolans rather than for fly ash per se and each defines three classes of pozzolans—Class N for natural pozzolans, Class F fly ash, and Class C fly ash (previously defined in Chapter 1).

Even though it is now apparent that C 618 and M 295 are inadequate in several aspects, they constitute the best available guidelines for immediate use in specifying the characteristics of fly ash for use in concrete to be used in constructing transportation facilities. In particular, ASTM provides opportunity for input by all groups. These include fly ash producers and marketers, concrete producers, transportation agencies, other concrete users, and academic interests. Thus, through cooperative efforts, a national consensus best representing the needs of everyone is being developed and if transportation agencies make use of the national specification they will have access to the latest accepted test procedures and specification requirements as they are developed.

The general background and consensus for the various requirements for Class F materials present in specification C 618 were presented by Mielenz in three papers at the International Symposia on the Use of Ash from Burning Coal (1967, 1973, and 1979) concerning the development of specifications for fly ash as a pozzolan (*37–39*). The ACI report on the use of fly ash in concrete also contains a general discussion of the significance of the various requirements (*9*). The elements of the specification for fly ash, with special emphasis on their significance with respect to highway construction, are discussed in the following sections.

Chemical Requirements

Total Oxides

For Class F fly ashes the sum of silica, alumina, and iron oxide must be at least 70.0 percent. For Class C the required minimum is 50.0 percent. The 1980 survey by the Virginia Highway and Transportation Research Council (*40*) showed that some states still retain separate limitations for silica and alumina as well as the total oxides, but it is likely that materials meeting the requirements of C 618 will also meet such specifications. Early studies sought to establish a relationship between the result of various pozzolanic activity tests and various percentages of individual oxides (*5,7*). However, definitive relationships could not be established. The recent study by Mehta confirms this finding (*35*). Consequently, because by definition the pozzolan must have components capable of reacting with lime in the presence of water, a minimum on total silica, alumina, and iron oxide to ensure that sufficient reactive constituents are present is all that is required. The lower requirements for Class C materials recognize that considerable CaO will be present in self-hardening cemetitious materials and thus the percentages of the pozzolanic components must necessarily be lower.

Sulfur Trioxide (SO_3)

The maximum SO_3 content permitted in the fly ash by ASTM C 618 is 5.0 percent. The cooperative tests reported by Committee C-9 in 1962 (*6*) showed that the SO_3 content of fly ash influenced to some degree the early compressive strengths of mortar and concrete specimens, with higher SO_3 contents resulting in higher strengths. This finding is consistent with recognition that different cements require different amounts of SO_3 for the development of maximum strength and that the limits in effect for cements at that time generally were set below the optimum amount. Thus, the added SO_3 from fly ash was an advantage. However, a maximum limit on SO_3 is considered necessary to avoid an excess in the hardened concrete that could contribute to a disruptive sulfate reaction. Some states concerned with this problem place a lower maximum limit on SO_3 content than that required by C 618 and M 295.

Moisture

A 3.0 percent limit is placed on moisture content to minimize caking and packing of the fly ash in shipping and storage, to control uniformity of fly ash shipments, and to avoid sale and handling of significant amounts of water as a part of the admixture. Some states have reduced this limit to 1.0 percent. A low moisture content for Class C fly ash is needed also to prevent caking from hydration of its cementitious compounds.

Loss on Ignition (Carbon)

The maximum permissible loss on ignition is related to the amount of carbon or unburned coal constituents in the fly ash, although for some fly ashes there is a significant difference in carbon content and loss on ignition. Loss on ignition is limited to 6.0 percent or less by all the state transportation departments using the material. Earlier versions of ASTM Specification C 618 permitted a loss on ignition up to 12.0 percent but changes made in 1980 reduced this maximum to 6.0 percent when the ash is to be used in air-entrained concrete. The AASHTO specification M 295 places the limit at 5.0 percent.

The need for a low carbon content in fly ash is related to requirements for proper air entrainment. More air-entraining agent is required to entrain a given amount of air in FAC than is required for a similar concrete not containing fly ash. This increase is needed because of the greater surface area within the concrete mixture. Fly ash is normally finer than cement and the volume added is usually greater than the volume of the cement replaced. Because of this, a greater volume of air-entraining agent is needed to provide the same surface concentrations of the active air-entraining ingredient. The second phenomenon leading to a requirement for more air-entraining agent is related to the carbon content of fly ash. The carbon adsorbs a portion of the air-entraining agent, which makes it unavailable for creating the needed conditions for stable air bubbles. The amount of adsorption varies with the amount of carbon present and, possibly, with the form of such carbon. Thus, variations in the loss on ignition (carbon content) result in a need to vary the amount of air-entraining agent. Meininger (*41*) has also shown that there can be a significant loss of air with time and possibly erratic behavior for some combinations of ingredients, and has suggested that the presence of organic constituents other than carbon may interact with the air-entraining agent to reduce its effectiveness. It is noted that the presence of adsorptive carbon may also alter the effectiveness of other admixtures.

These problems are not completely eliminated by either the 6.0 percent or 5.0 percent maximum limit for loss on ignition. A number of states indicated that problems with erratic entrainment of air are not encountered with fly ashes having carbon contents less than 3.0 percent, and some have adopted a limit for loss on ignition or for carbon in this range (*40*).

Although there appears to be no evidence that high carbon contents in fly ash are detrimental to the proper strength development and durability of fly-ash concrete when the proper air entrainment is attained, the problems associated with attaining the proper air entrainment may override all potential advantages to a state highway agency for using FAC. The need for additional testing and inspection personnel eliminates any cost advantage for FAC. The risk that erratic behavior with some combinations of ingredients will permit inadequate or excess air in some portions of a structure to go undetected makes the use of FAC questionable in the absence of any other advantages derived from the properties of the FAC.

It is noted that problems related to the high carbon contents in fly ash are greatly diminished by present developments in power production. Under the general conditions existing before the oil embargo and adoption of the RCRA, power companies burning coal often had little interest in fly-ash quality. Except for a few companies, no attempt was made to carefully control the carbon content at a low level. Thus, a higher loss on ignition requirement was needed to avoid limitations on the available supply of fly ash when the special characteristics provided by FAC were needed. However, under the present situation many power companies are required to burn more coal and the need for maximum efficiency for burning and the trend for selective storage of high-quality fly ash provides the opportunity for lowering specification requirements for loss on ignition without adversely affecting marketing procedures for high-quality materials. The accompanying reduction in quality assurance problems and the reduction of risks from potentially damaging low percentages of entrained air greatly enhances the incentives for using FAC in pavements and other transportation facilities.

Although loss on ignition is still the test most often used to indicate the presence of carbon, equipment for a rapid direct determination of carbon is now used by a number of agencies. An example of such equipment is the LECO combustion furnace that automatically indicates the carbon content.

Magnesium Oxide

A requirement for magnesium oxide content was initially in C 618 as an optional requirement that applied only when specifically requested. This has now been dropped. The purpose was to avoid unsoundness of the concrete that might result if the magnesium oxide were present in a form capable of hydrating in the hardened concrete with accompanying expansion and disruption. Dependence is now placed on the results of the autoclave expansion test to ensure proper soundness. The optional requirement is still retained in AASHTO M 295.

Available Alkalies

In some areas where aggregates subject to alkali-aggregate reaction are present, it is desirable to limit the water-soluble alkalies in the concrete. For this purpose, available alkalies in the fly ash are determined after an intimate mixture of lime, fly ash, and water has been stored for 28 days at 100°F (37.8°C). The available alkalies are those soluble in hot water after the period of storage. A maximum of 1.5 percent is allowed in both C 618 and M 295.

The proportion of the total alkalies that become water soluble when the fly ash is mixed with lime and water is dependent on the temperature during storage and the length of time the material is stored. Thus "available alkalies" obtained by this test may not relate to the conditions actually existing in field concrete. However, the maximum limit provides protection against excessive amounts of sodium and potassium ions in the hardened concrete. This requirement is not needed where there is no danger of encountering reactive aggregates.

Physical Requirements

Particle Shape

In addition to its chemical composition, the physical state and the size and shape of the particles in fly ash are important performance parameters. This is illustrated by the photomicrograph of a fly ash shown in Figure 1. This picture shows the typically spherical shape of the fly ash particles, some of which are hollow. Material of this type normally complies with the requirement for pozzolanic activity index discussed in the following sections.

Both Mehta (*35*) and Diamond (*36*) discuss particle shape and surface characteristics of fly ash particles. Mehta shows scanning electron micrographs of particles of both high-lime and low-lime fly ashes. The particles may be hollow spheres (cenospheres) or at times spheres within a sphere (plerospheres). He states that spheres within a sphere may be found in both high-lime and low-lime fly ashes (Classes C and F, respectively by ASTM definition). The surfaces of the spherical particles in low-lime fly ashes are generally cleaner than those in high-lime fly ashes.

The scanning electron micrographs shown by Diamond (*36*) reveal the presence of significant particles that are not spherical in a number of fly ashes from different sources.

Fineness

Assuming the presence of sufficient silica and alumina and the typical particle shape illustrated in Figure 1, fineness is the

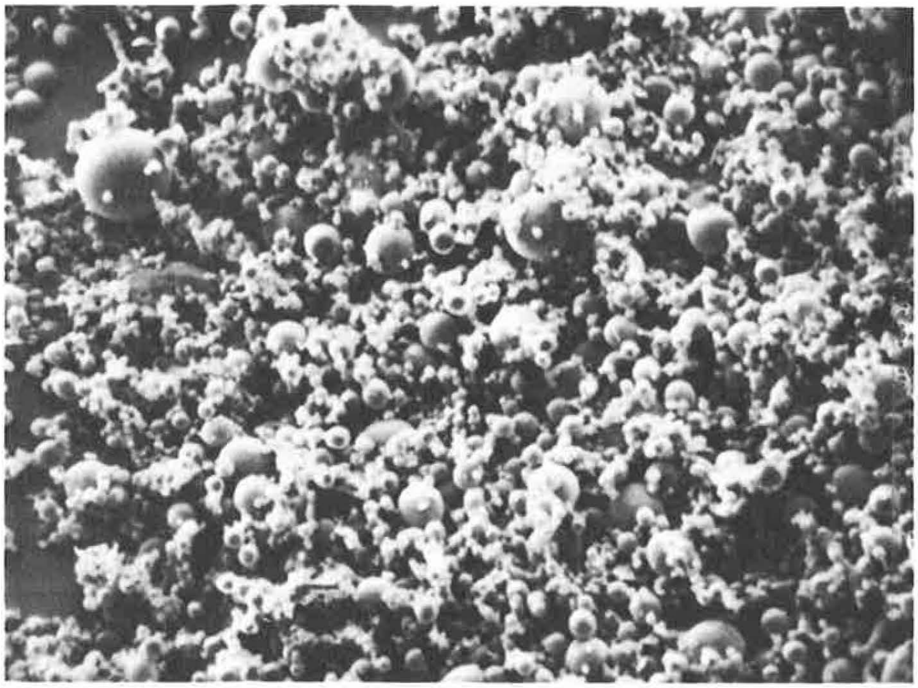

Figure 1 Photomicrograph of fly ash (X 1000).

primary physical characteristic of a fly ash that relates to its pozzolanic activity. Present specifications generally include a requirement for a maximum amount retained on the 45-μm (No. 325) sieve when wet sieved. The limit in C 618 is set at 34 percent.

Earlier versions of C 618 also included limits on surface area as determined by the Blaine air-permeability method, but these have been deleted because the ASTM subcommittee found no consistent relationship of this property to the performance characteristics of pozzolans in mortar or concrete. The subcommittee finding is generally supported by other early research.

However, there is a renewed interest in determining additional information concerning particle size distribution and its effects on pozzolanic activity. Mehta (*35*) shows the lack of agreement between several methods for particle size and particle-size distribution but concludes that particle-size distribution is the most important parameter determining the relative reactivity of different fly ashes. A large percentage of fly ash particles larger than the 45-μm (No. 325) sieve had a negative effect on the 28- and 90-day strengths of normally cured portland cement-fly ash mortars; a large percentage of particles less than 10 μm had a positive influence on mortar strengths. Diamond's work generally reaches the same conclusion (*36*).

The ACI summary report (*9*) states that the air-permeability test procedure provides a rapid method for detecting changes in fly ash. Increased surface area, as determined by air-permeability tests, in many cases correlates with higher reactivity especially when comparing ashes from a single source.

Pozzolanic Activity Index

The requirement for pozzolanic activity with cement is that the strength developed by the specimens of the test mixture, in which 35 percent of the volume of the cement is replaced with the same volume of the fly ash being tested, shall be a minimum of 75 percent of the strength of the control specimens after storage at 100° ± 3°F (38° ± 1.7°C) for 1 day and at 131° ± 3°F (55° ± 1.7°C) for 6 days. The AASHTO specification M 295 requires a 7-day activity test with portland cement and consideration has been given to including the same requirement in the ASTM specification. Under the proposed changes to C 618, the fly ash would be acceptable on the basis of the 7-day test, but would be rejected only if it failed the 28-day test. Most suitable fly ashes would meet the 7-day limits. Consequently, for such materials, the time for establishing suitability as a pozzolan would be greatly reduced.

All of the present specification tests for pozzolanic activity have been subject to criticism. Although initially intended to be a measure of the ability of the fly ash to develop strength from the pozzolanic reaction, it has been shown that the lime or cement used in the test significantly affects results. The same fly ash may pass the tests with one cement or lime and fail with others. In addition there appears to be no direct relation of results of the test to the performance of the fly ash in concrete. Alternatives to the present test have been proposed by several authors (*35, 36, 42*) and a measure of activity is being sought in the EPRI research currently being conducted, but no general consensus for a better evaluation of pozzolanic activity has as yet been attained.

Thus, with the present state of the art it is necessary to make trial tests with the same ingredients and proportions of materials to be used in FAC to obtain valid estimates of potential strength development.

Autoclave Soundness

The requirement for the autoclave soundness test is a maximum of 0.8 percent expansion or contraction. The soundness test is normally conducted with specimens containing 25 parts by weight of fly ash and 100 parts by weight of a portland cement conforming to C 150. However, if the fly ash is to be used in amounts greater than 20 percent of the cementitious material in the project mix design, the test specimens for autoclave expansion shall contain that anticipated percentage. The cement to be used in the project should be used. This test protects against the delayed expansion that could occur in concrete if sufficient amounts of MgO are present as periclase, which expands as it hydrates.

Uniformity Requirements

The uniformity of the fly ash is controlled in C 618 by limiting the variability of the specific gravity and fineness as measured by the amount retained on the 45-μm (No. 325) sieve. The requirement is that any sample tested shall not deviate from the average of the 10 previous tests, or the total of all tests if the number is less than 10, by more than 5 percentage points. In addition, C 618 contains an optional requirement applicable when air-entrained concrete is involved. The amount of air-entraining agent to give 18.0 percent air by volume in mortar shall not vary by more than 20 percent of the average of the preceding 10 tests, or the average of all tests where the number is less than 10.

Drying Shrinkage

The summary report by the Singleton Materials Engineering Laboratory for the Tennessee Valley Authority (TVA) points out that drying shrinkage is more a function of the volume of the paste, the water-cement ratio, and the type of aggregate than a function of the composition of cementitious material (*8*). Because the addition of fly ash usually increases paste volume, the drying shrinkage may also be increased by a small amount if the water content remains constant. A reduction in the water content will compensate for shrinkage because of increased paste volume. Results of tests by Davis at the University of California and by the TVA are cited that show the drying shrinkage of plain concrete and FAC to be essentially the same. Thus, potential differences in drying shrinkage between FAC and similar concrete without fly ash are not considered a significant problem for most applications. However, C 618 provides for an optional requirement, which can be requested by the purchaser, that limits the difference in drying shrinkage between test mortar bars containing fly ash and that of similar mortar bars without fly ash.

In this test, described in ASTM method C 311, the same amount of cement is used in the control mix and the test mix and a portion of the Ottawa sand is replaced with fly ash in the latter. The water content is adjusted to provide for the same flow. The maximum difference permitted is 0.03 percent at an age of 28 days. New sources of fly ash should be tested when drying shrinkage might be a problem.

Reactivity with Alkalies

An optional requirement of maximum mortar-bar expansion of 0.020 percent can be requested by the purchaser. Such test need not be requested unless the fly ash is to be used with aggregate that is regarded as deleteriously reactive with alkalies. Class F fly ash has been successfully used to reduce the danger from alkali-silica reaction in concrete, and this test would be needed in the highway field only as a means to ensure that the danger of expansion had been eliminated. The tests may be made with any high-alkali cement. However, if the cement or cements to be used are known and available, the test for mortar-bar expansion should be made with each of them.

QUALITY ASSURANCE PROCEDURES FOR FLY ASH

Test Frequency and Source Approval for Fly Ash

The standard procedures for sampling and testing fly ash are given in ASTM Method C 311. Some of the procedures are time-consuming, and if complete tests are attempted for all shipments of fly ash to a highway project, the extra cost of testing may become so high that any economic advantage from using fly ash is lost. Consequently, it is important to establish a frequency schedule for tests that provides adequate quality assurance at a reasonable cost and also permits decisions within a reasonable time. ASTM Method C 311 for sampling and testing fly ash provides for several methods of sampling and recommends that tests for fineness, moisture, specific gravity, loss on ignition, and soundness be made on each 400 tons (400 Mg) of material. Other tests, including chemical analysis, 7-day lime-pozzolanic activity, and 28-day cement-pozzolanic activity, are made for each 2,000 tons (2,000 Mg). The sample used for the 2,000-ton tests is made up of a composite of 5 previously tested samples representing 400 tons each.

In earlier limited applications of fly ash in many experimental installations, relatively little information was available as to the amount of variability of fly ash from the same source with time. However, more use of FAC and industry efforts to control uniformity now indicate that the chemical composition of the inorganic portion of the ash is not likely to vary significantly, as long as the same coal is burned in the same plant and no start-up fuel oil or extraneous matter, such as lime or sodium carbonate, is added. Problems could arise if different coals or varying blends of several coals are burned. Loss on ignition and fineness are somewhat dependent on the condition of burning and how well the collectors function. More variability in these characteristics is expected than in the inorganic chemical composition. Most sources processing fly ash for sale in compliance with ASTM Specification C 618 monitor these characteristics on a frequent basis, often daily.

The replies to the questionnaire discussed in Chapter 5 and a review of specifications used by the highway and transportation departments making the most use of fly ash shows that most have established a system for approving the source of fly ash. Initial approval may be on the basis of the state's tests or tests provided by the fly-ash producer through an independent testing laboratory. The product is then often accepted by certification of compliance with random or periodic check tests described in C 311 as the basis for checking sources. Some highway agencies require that tests such as fineness and loss on ignition be made on each sample. The experience of most states using the system of approved sources has been satisfactory.

CONTROL OF FLY ASH CONCRETE

Proportioning for Fly Ash Concrete

Highway engineers generally consider the use of fly ash as a pozzolan to be a replacement for part of the cement. Consequently, most highway and transportation department specifications are based on the maximum amount of cement that can be replaced.

Replies to the questionnaire discussed in Chapter 5 and summarized in Table B-3 of the appendix showed that the maximum replacement limits vary from 8 percent to 50 percent. Sixteen states set the limit at 15 percent replacement and another 10 establish the limit at 20 percent. Several states control the amount in terms of 1 bag or ½ bag of fly ash added for each bag or ½ bag of cement replaced, respectively, as the case may be. Six states limit the amount to 8 percent, one to 10 percent, and three to 25 percent. The 30 to 50 percent replacement limits indicated by two states apply to mass concrete only.

A number of states establish a specification requirement that the mass of fly ash used not be less than the mass of cement replaced. Often a minimum ratio of parts by weight of fly ash to cement replaced (varying from 1.1:1 to 1.6:1) is required. Values used by various states are given in Table B-3. As Lovewell and Hyland (*43*) have pointed out, some additional adjustment in water or fine aggregate may also be needed for optimum qualities in the concrete. Ideally, a performance specification based on the strength and durability of the concrete would be used. However, there are uncertainties about the ability of present tests, such as resistance to freezing and thawing and soundness, to predict the overall durability of concrete containing less than the usually specified amounts of cement.

The approach taken by ACI Committee 345 in guidelines for concrete for bridge decks offers a means of writing a specification for FAC (*44*). The ACI guideline states that for bridge deck concrete, a minimum of 564 pounds (6 sacks) of cement per cubic yard (33.5 kg/m^3) be used except when a pozzolan is present. In this case the cement plus fly ash must be equal to or greater than 564 lb/yd^3. There is also a requirement that the ratio of water to cementitious material (cement plus pozzolan) be no greater than 0.45. This same principle would apply to concretes used for other purposes, with proper designation of the minimum amount of cement or cement plus fly ash and a suitable limitation on the ratio of water to cementitious material.

Strength Requirements

Essentially all specifications for FAC in construction of transportation facilities establish 28-day strength requirements for concrete containing fly ash or blended cement the same as these for portland cement concrete. The extent to which tests at earlier ages can be relied on for acceptance must be determined by experience. Any concrete that meets present criteria for acceptable strength at early ages would be acceptable, but because of the potentially slower strength development many acceptable concretes may not reach the strength level established by experience for portland cement concrete not containing fly ash. Tests at later ages, for example 90 days, may be needed to establish the level of strength for fly ash concrete at maturity.

Some transportation agencies specify or permit the use of water reducers to lower the ratio of water to cementitious material and thereby attain strengths of the FAC concretes at early ages (7–14 days) essentially equal to the similar strengths of concretes without fly ash but with a higher water-cement ratio.

Control of Entrained Air in Fly Ash Concrete

The problem of ensuring that adequate entrained air is in the hardened fly-ash concrete is a major concern for all transportation agencies using the material for structures and pavements. In Virginia, poor performance of fly-ash concrete resulted from inadequate entrained air in some parts of a project on which fly ash concrete was used, even though satisfactory results were attained on other portions of the project with the same materials and with adequate entrained air (*25*). For unexplained reasons, the normal quality control procedures used for measuring air contents at the plant failed to detect the conditions leading to the very low air content in the hardened concrete.

In other instances in Virginia informal trial batches of concrete containing fly ash have been reported to yield erratic results with respect to air entrainment (*25*). This has led to a reluctance to use fly ash until more information is gained concerning the rate of loss of air content in the fly ash concrete and means are available to ensure adequate air content at the time of placement.

As previously mentioned, most states indicated that problems with erratic amounts of entrained air content for the same ingredients do not occur when the loss on ignition of the fly ash is about 3 percent or less. The work reported by Meininger (*41*) showed that the loss of air with time occurred with some combinations of fly ash, cement, and sand with one fly ash that had a loss on ignition as low as 2.9 percent. Consequently, on the basis of present knowledge, a completely safe limit cannot be established. However, problems are minimal at loss of ignition values of 3 percent or less.

Meininger (*41*) showed that different cements and different air-entraining agents could react differently with the same proportions of other ingredients in the fly ash concrete. Under the present state of knowledge, tests for air content should be made on each load of concrete immediately before its placement. In a study conducted by the Virginia Highway and Transportation Research Council (*45*), it was shown that the average of two determinations with a Chace air indicator should provide adequate control, provided the Chace indicator being used has been carefully calibrated against the air pressure meter. The report recognized that the average of two results by the Chace indicator could not be relied on to provide a precision equal to that obtained by the air-pressure meter but the use of two Chace tests eliminates much of the danger of gross errors and significant variations in air content can be detected quickly. This quick detection of change is of paramount importance when each load of concrete is being tested. For any load of concrete for which compliance to the specification for air content may be in doubt when determined by the Chace indicator, a determination must be made by the air-pressure meter and the decision to accept or reject made on the basis of that test. On any given project, until better knowledge is available concerning the load-to-load uniformity of air content in the fly ash concrete, it is extremely important that each load be tested. The durability of the product is at stake and costs of replacing failed concrete can be exceedingly high.

CHAPTER FIVE

EXPERIENCE AND STATUS OF USE OF FLY ASH CONCRETE BY HIGHWAY AGENCIES

A detailed summary of the replies provided by the highway agencies in the United States and Canada to a questionnaire submitted by the Transportation Research Board to the Materials Engineers or their equivalents in each agency is provided in Appendix B. Fifty-one agencies replied to the questionnaire. Generally it can be stated that in the United States, where the Federal Highway Administration has requested all states to comply with the objectives of the EPA guidelines, a number of states have recently changed their specifications to permit the use of fly ash concrete in pavements or are planning to do so. However, many still have reservations and concerns with respect to significant advantages or the cost-effectiveness of fly ash concrete under present conditions (1985). The nonavailability of good fly ash also affects potential use in a number of states.

It is also apparent from a number of private communications from interested production and research personnel that changes are occurring rapidly in some areas. Thus, some of the answers recorded for this questionnaire may be outdated quickly. For example, almost all states were to have changed their specifications as of January 1, 1986 to allow the use of FAC for some applications.

CANADA

Even though the Canada Center for Mineral and Energy Technology (CANMET) has reported a number of developments pertaining to the use of fly ash and other mineral admixtures in concrete, the Canadian transportation agencies replying to the questionnaire indicated that they had not used fly ash in their concrete except for limited experimental projects. Either a good source of suitable fly ash was not available or there was no interest by commercial groups to market the by-product. Research is being conducted.

UNITED STATES

The following is the general consensus of the situation in each of the Federal Highway Administration regions (Figure 2) of the United States as developed from the replies to the present questionnaire and augmented by earlier replies to a similar questionnaire conducted by the Virginia Highway and Transportation Research Council in 1980 (*39*) and recent reports made at several seminars on fly ash use sponsored by the FHWA and state departments of transportation or other communications.

Region 1

The 1980 survey showed that none of the state highway agencies in this region was using fly ash in concrete. The principal reason for this was that very little suitable fly ash was available in the region and there were no apparent advantages to its use under the conditions that existed in that area. Replies to the present questionnaire indicate that most of the agencies are now reevaluating the situation and will likely revise their specifications to comply with federal requirements by January 1986 but extensive use is not expected in the near future. New Jersey is planning an experimental project for use of fly ash in pavements and a research study has begun at the University of New Hampshire for the New Hampshire Department of Public Works and Highways.

The New York Department of Transportation (NYDOT) is conducting a study of fly ash in structural concrete. Progress on this project was reported in April 1985 at the Fly Ash Workshop sponsored by FHWA and the Pennsylvania Department of Transportation (*46*). The fly ash used was required to meet ASTM C 618 except that the maximum loss on ignition was set at 4.0 percent. The fly ash was pretested at the source before shipment to the project. Conclusions to date include the observation that the air content in FAC is more difficult to

Figure 2 Federal Highway Administration regions.

control than in conventional concrete mixtures; workability of the FAC is better than conventional concrete and the strength gain of FAC was good even at low ambient temperatures. The system of pretesting and acceptance of fly ash at the source worked well for this project but it is recognized that such a system ties up silos and transport tanks while tests for acceptance are being made. As an alternative quality assurance procedure, NYDOT is considering acceptance by certification after establishing the suitability of the fly ash. Monitor testing by NYDOT would also be used. It is reported that only the loss on ignition and fineness are necessary for routine acceptance testing of fly ash from established sources.

Region 3

All states in this region now have specifications permitting the use of FAC in some or all applications at the option of the contractor and with approval by the state. Maryland does not permit its use in structural concrete or bridge decks but does permit it in pavements. Robson reports that West Virginia began experiments with the use of fly ash in 1968 and in 1976 provisions were adopted allowing the use of fly ash in pavement concretes (*47*). These specifications allowed the replacement of up to one bag of cement with an equal volume of fly ash conforming to the requirements of ASTM C 618, Type F. Successful experience using water reducers in the concrete has led to considerable use in West Virginia. Approximately 200 lane-miles of FAC pavement were placed between 1977 and 1984 and use is continuing. In eight projects, strengths of cores taken from West Virginia pavements in which one of the usual six bags of cement was replaced by an equal volume of fly ash varied from 4660 to 6440 psi. These values are well above the minimum required in West Virginia specifications.

West Virginia's specifications initially required special permission be attained for placement of FAC after October 1. However, permission has generally been given with the condition that normal cold-weather precautions be exercised. Some projects have been monitored up to four years without any indication of adverse effects from placement after October 1. Observations are continuing. Additional laboratory work has been done by West Virginia University to show that concretes with fly ash as a cement replacement are equal in durability at an early age provided the concretes are of equal air entrainment and of equal strength (*17*). On the basis of field observations and the research findings, West Virginia has removed the restrictions on the use of FAC after October 1.

Robson believes the successful use of fly ash in West Virginia is related to three things (*47*):

1. Contractors are required to develop mixture proportions with the material chosen for their work. The mixture proportions must include data to evaluate the potential of the particular combination of materials to provide adequate strength, air content, and workability.
2. A stable source of high-quality fly ash is available. Considerable testing of the fly ash used in West Virginia has established not only compliance to the specification (ASTM C 618, Class F) but has also demonstrated good uniformity.
3. A viable quality assurance system has been established that includes a contractor quality-control program. This allows the contractor to control the process to ensure specification compliance. The first two items are a part of the total quality assurance system and help provide assurance that the pavement is of high quality at the lowest possible cost to the state.

The Virginia Department of Highways and Transportation (VDHT) participated in the early evaluation of fly ash in concrete by installing experimental curbs and gutters (*19*). This project in Louisa, Virginia was built in 1954 and involved two concrete mixtures in which 20 percent and 33 percent of the cement was replaced by fly ash. Control concretes were made with Type II cement. A recent evaluation of the long-time performance of these installations showed that after 25 years of service the FACs were internally sound and retained compressive strengths equal to or greater than those of the control concrete. However, greater surface scaling had occurred for the FAC than for the controls. The concrete with 33 percent fly ash replacement exhibited greater scaling than did that with 20 percent replacement. Over the years, all of the concretes have had severe exposure to deicing salts.

The VDHT changed its specifications in 1984 to permit the use of FAC in all applications at the option of the contractor with approval by the state. As yet, since the Louisa experiments, little has been placed except in more recent experimental research studies. As discussed in Chapter 4, the problem of ensuring that adequate entrained air is in the hardened FAC is a major concern to the VDHT.

Region 4

Five states in this region permit the use of FAC in most applications and the others are in a transition period evaluating experimental work or considering changes to their concrete specifications to permit fly ash use.

The Alabama Department of Transportation is the pioneer among all state agencies using fly ash in its pavement construction. Class F fly ash has been used in Alabama since 1953 and Alabama standard specifications have required the use of fly ash as an admixture or type 1P cement in all pavement concrete since 1960. The primary reason for using fly ash is for greater sulfate resistance. No scaling or durability problems have occurred. It is reported that problems with proper air entrainment are not usually encountered if loss on ignition content of the fly ash is less than 4 percent. With higher losses on ignition, potentially low entrained air contents with the usual dosage of air-entraining agent can usually be corrected by the use of additional air-entraining agent. Class C fly ash is now also approved for use in Alabama and some use has begun.

The use of fly ash in structural concrete by the Florida Department of Transportation (FDOT) is summarized in a report by Larsen (*22*). He reports that during the 1970s deterioration of structural concrete in Florida was observed to relate to environmental conditions. After extensive study, a map was produced that identified areas of slightly aggressive, moderately aggressive, and extremely aggressive environments. The aggressiveness was related to the pH, resistivity, sulfates, and chlorides.

Research by the FDOT showed Type F fly ash in the concrete improved sulfate resistance and provided better protection to embedded steel against corrosion. The fly ash also reduced the maximum temperature and the temperature differential during the initial curing of structural concrete in hot weather and for mass concrete at all times.

FDOT accepts two techniques in mixture proportioning—the fly ash may replace a portion of the cement or it may be added as an admixture without reducing the usual portland cement used. In the former case the usual slower rate of strength development was observed but in the latter the strength of the FAC always exceeded the strength of the concrete without fly ash at equivalent ages.

According to FDOT specifications, Class F fly ash may be used as a cement replacement or admixture in all classes of concrete when Type I, Type II, Type III, or Type V cement is used with the following limitations:

1. Except in mass concrete, the quantity of fly ash replacing cement shall not exceed 20 percent of the minimum cementitious factor normally used. Up to 50 percent replacement is permitted for mass concrete.
2. Use of fly ash as an admixture must be approved by the State Materials and Research Engineer; such approval requires submission of statistical evidence supporting successful laboratory and field trial mixtures that demonstrate improved concrete quality or handling characteristics with the materials to be used.

When fly ash replaces cement on a weight basis, there are indications that the weight of fly ash to that of cement replaced should be substantially larger for low cement contents and decrease as the cement increases. Larsen (*22*) suggests that, under these conditions of replacement, strengths at 56 or 90 days are appropriate for specification requirements. When fly ash is used as an admixture without replacing cement, the amount of fly ash is not restricted. The acceptability of the concrete is based on statistical performance evidence from field or laboratory tests.

Even though more than 20 percent replacement is permissible in mass concrete (defined in FDOT specifications as an installation for which the minimum dimension exceeds 2 ft), Larsen recommends that the 20 percent limitation be adhered to for structural mass concrete. For installations such as footings and piers where early strength is not important, he suggests that the fly ash content may increase to 50 percent of the total cementitious material with acceptable results.

The FDOT fly ash specification cites ASTM C 618 but adds the following limitations:

1. The loss on ignition shall not exceed 4.0 percent.
2. The sulfur trioxide content shall not exceed 2.0 percent.
3. Fly ash produced at a plant where ammonium sulfate or ammonium nitrate is introduced into the stack for purposes of air quality will not be allowed.

The use of fly ash as an admixture with types IS or IP cement is not permitted.

Generally the contractor's quality control program calls for one random sample for each 250 tons of fly ash.

The sample is tested for loss on ignition and for sulfur trioxide (SO_3) content.

In considering the type of cement to be used in various environments the guide in Table 1 is used.

TABLE 1

TYPE OF CEMENT FOR VARIOUS ENVIRONMENTS AND STRUCTURAL ELEMENTS (FLORIDA) (*22*)

	Environmental Aggressiveness		
Structural Element	Slight	Moderate	Extreme[a]
Precast/prestressed	Type III	Type III + fa	Type II
Cast-in-place slabs and barriers	Type I	Type I + fa	Type II + fa
Cast in place	Type III	Type I + fa	Type II + fa
Piling, drilled shafts, and seals	Type I	Type I + fa	Type II

[a]The maximum C_3A content for the Type II cement shall be 5%.

To control concrete temperature, fly ash is used as a cementitious component in mass concrete (minimum dimension exceeds 2 ft) and during hot weather concreting. The FDOT specifications require that the maximum temperature differential within a mass concrete structure shall not exceed 35°F. For hot-weather concreting the specification states that the heat of hydration of the cementitious material shall not exceed 80 cal/g at 7 days. These requirements may be met in part or in full by the judicious use of fly ash. More information on the subject of heat generation can be found in ACI 207.1R on mass concrete (*48*).

Although the North Carolina Department of Transportation (NCDOT) reported in reply to the questionnaire that fly ash was not permitted in their standard specifications, they have experimentally used fly ash in a number of applications and now require its use for some foundation concrete. Consideration is now being given to permitting its use for other purposes and a specification is under preparation. A summary of NCDOT experience was reported by Cordel at the Fly Ash Seminar cosponsored by the Georgia Department of Transportation and the FHWA (*49*). He reported that experimental projects had been built in which FAC was used in bridge substructures, bridge superstructures, and slip-formed median barriers. Controlling the heat of hydration in mass concrete such as foundation seals was the primary reason for using fly ash. The fly ash lowered the temperature differentials encountered so that cracking did not occur. Cracking was a frequent problem with concrete without fly ash.

The usual procedure used by NCDOT is that foundation seals are constructed underwater when the depth of the water is 20 ft or more. The contractor drives sheet piling around the site of the seal and excavates the resulting cofferdam to a solid foundation. Concrete is placed in the cofferdam by a tremie pipe. As the level of concrete rises, the tremie is raised, but the end of the pipe stays below the surface of the fresh concrete. When the placement is finished and the concrete hardens, the cofferdam is dewatered and footings are cast on the seal.

In the typical application described by Cordel (*49*), the minimum cementitious material was specified as 639 lb per yd^3. The fly ash was specified to be in the range of 15 to 30 percent by weight of the total cementitious material. The maximum water-cementitious material ratio was 0.594. Fly ash was required to meet ASTM C 618 and Type II cement was used. The heat of hydration requirement for the cement was set at 75 calories per gram at seven days. The increase from AASHTO M 85 requirement was necessitated by the fact that only one cement supplier could meet the 70 calories per gram limit in the standard specifications. Temperature restrictions at time of placement were that the concrete be not less than 50°F or more than 75°F. Water temperature at the water surface could not be less than 35°F. The compressive strength requirement for field cylinders was 3000 psi at 28 days. The trial mixture was required to have a laboratory strength at 28 days of 4000 psi. After two years no cracking has been observed in the concrete placed under these specifications.

Region 5

In this region Minnesota has made the most use of fly ash. Such use covers a period of over 10 years. Other states in the region have changed their specifications more recently and are now beginning to use fly ash in most applications. Indiana permits blended cement containing fly ash to be used but at the time of replying to the questionnaire had not permitted the use of fly ash as an admixture. However, a thorough study of fly ashes produced in Indiana has been completed by the Indiana Cooperative Highway Research Project at Purdue University to provide a data base for possible changes (*36*). It is noted that all of the states in this region do not permit the use of fly ash in concrete for bridge decks. Both Class F and Class C fly ashes are available in the region and either class is generally permitted. Illinois reports that Class C is not permitted in concrete subject to high-sulfate ground water. Information concerning specific restrictions on the use of Class C was not provided by the other states.

A description of the Illinois DOT approach to implementing the use of fly ash in its concrete was reported by Berry at the 7th International Symposium on fly-ash utilization (*50*). He reports that in 1984 comparative sections of 8.7 miles of pavement using the standard concrete specification without fly ash and 9.7 miles of FAC were constructed. The FAC contained 455 lb of portland cement and 120 lb of fly ash per yd^3 compared to 535 lb per yd^3 of cement in the regular concrete. Thus the ratio of fly ash added to cement removed is 1.5:1.0. General satisfaction has been expressed with the results but no performance data are as yet available. Additional FAC has been placed in Illinois since the initial project.

Region 6

New Mexico did not estimate the volume of FAC used but its use is required with certain types of aggregates to protect against potential alkali-silica reactive aggregates. Its use is optional in other cases. Either Class C or Class F may be used but the two classes shall not be mixed in the same job. Louisiana allows the use of fly ash up to 15 percent by weight in structural concrete and up to 20 percent in pavements and minor concrete applications. A well-defined evaluation procedure for qualifying a source of fly ash is used in Louisiana. The total time for evaluation is estimated to require seven months. Oklahoma reported experimental use of Class C fly ash in pavements.

The Texas State Department of Highways and Public Transportation has a number of projects under way using fly ash in several applications. Special provisions have been prepared permitting the use of fly ash at the option of the contractor. Texas specifies two classes of fly ash, A and B. Class A is similar to Class F and Class B is similar to Class C but the requirements differ to some extent. The specification requires prequalification of the source of the fly ash. Minimum and maximum replacement limits are set—20 to 30 percent by volume for Class A and 25 to 35 percent for Class B. The actual amount to be used is determined by a testing procedure involving the materials to be used on the job and strengths of specimens made with both the minimum and maximum replacement rates. The procedures are given in Supplement No. 2 to construction Bulletin C-11 (*51*).

In September 1985, the Arkansas State Highway and Transportation Department (AHTD) reported a study of the effects of substituting a Class C fly ash for a portion of the cement in both non-air-entrained concrete (AHTD—Class S) and air-entrained concrete [AHTD—Class S(AE1)] (*52*). The Class C fly ash used in this study had a calcium content of 25.2 percent expressed as CaO and its effects were measured with only one cement. Thus, the findings in this study cannot be assumed to be applicable for all combinations of Class C materials and cement. Nevertheless, the results are of interest because they demonstrate the high rates of cement replacement possible with some high-lime Class C fly ashes. In this study the authors concluded that for non-air-entrained concrete, up to 65 percent of the portland cement could be replaced by an equal volume of the Class C fly ash with no severe adverse effects on the characteristics measured in the study. For non-air-entrained concrete all of the fly-ash mixtures had higher compressive strengths than the comparable non-fly-ash mixture at all ages except 6 months, when only the 65 percent mixture had a higher strength. For air-entrained concrete, replacement of cement with fly ash produced lower strengths at 7 and 28 days but higher strengths at 3 and 6 months, except for the samples having 25 percent replacement. These samples had excessive air contents, which probably accounts for the lower than expected strengths. Fly-ash replacement for cement in amounts greater than 25 percent reduced the concrete's resistance to deicing chemicals for air-entrained concrete, but had a negligible effect on non-air-entrained concrete. It should be noted, however, that all the non-air-entrained specimens deteriorated rapidly when subjected to rapid freeze-thaw durability testing. None lasted more than 100 cycles before further testing was impossible. The air-entrained specimens were very durable when subjected to freeze-thaw testing. The use of the Class C fly ash was found to have no appreciable effect on the relative dynamic modulus of elasticity between non-fly ash and fly ash samples. The conclusions drawn by the authors were that for non-air-entrained concrete, the Class C fly ash tested could replace up to 65 percent of the cement by volume without significant adverse effects. For air-entrained concretes, substitution of fly ash for cement in amounts up to 25 percent caused no adverse effects. If resistance to deicing chemicals is not important for the specific intended use of the concrete, replacement in amounts as high as 65 percent could be used.

A study of the effects of a Class C fly ash on concrete properties has also been conducted by the Oklahoma State University in cooperation with the Oklahoma Department of Transportation. Only one Class C fly ash and one cement were used in this study (*53*). The fly ash contained 29.75 percent calcium expressed as CaO; thus, the results reported are generally typical of "high-lime" fly ashes and may not be applicable to all Class C materials. It was concluded from the tests made that all the concrete mixtures that contained 20 to 50 percent of the cement replaced on a weight basis had high resistance to freeze-thaw action. As the percentage of fly ash was increased, it was possible to reduce the amount of mixing water for essentially the same slump. However, it was necessary to increase the dosage of air-entraining agent to maintain the proper level of entrained air. Compressive strengths at 28 days were not strongly affected by this fly ash; a modest increase in strength compared to the control concretes with no fly ash was noted for 20 and 30 percent fly ash replacement. Replacement of 50 percent of the cement with fly ash resulted in only a small reduction in 28-day compressive strength. It is noted by the authors that many of these differences are attributable to a reduction in the mix water. They state that if the ratio of water to cement plus fly ash were held constant, the addition of fly ash would probably result in concretes with reduced 28-day strengths. The time of set increased significantly as the percentage of cement replacement with fly ash increased. The concretes with 50 percent replacement took approximately twice as long to set. This report also includes tests indicating the effects of temperature and extended agitation on the air contents of concretes with different percentages of fly ash. In general, such effects were minimal after 30 minutes of agitation.

Region 7

Use of fly ash is limited in this region. Iowa permits its use with high quality aggregates. Kansas plans to change its specifications to comply with the federal requirements and Missouri is planning for its use in the few select pavement projects. Special provisions have been prepared. Nebraska indicated in the VDHT questionnaire that fly ash as a replacement for part of the fine aggregate was required for high-alkali cements where reactive aggregates might be used.

Region 8

Four states in this region replied to the questionnaire. Colorado permits fly ash in concrete in all applications and requires its use under special circumstances. Montana stated that it did not permit the use of fly ash and gave no further information. Utah stated it permitted its use in pavements and pipe but did not report on other applications. North Dakota reported that its use is permitted in pavements but gave no information concerning other applications. An independent source reports that South Dakota is preparing a specification and that Wyoming permits up to 20 percent of C 618 with state approval for specific projects.

A report by Betenson concerning Utah's use of fly ash was presented at the seminar on fly ash utilization in highway construction held in Sacramento, California, February 1985 (*54*). The primary concern in Utah before publication of the EPA guideline on the procurement of concrete for federal projects was the use of Class F fly ash to counteract the effects of higher alkali contents of cement when used with potentially reactive aggregates.

Utah has observed delayed (2–3 years) expansion of concrete containing some aggregates of volcanic origin and high-alkali cement (0.72 percent equivalent alkali as Na_2O). The aggregates used were shown to be innocuous by the criterion used in standard ASTM test C 227 for mortar bar expansion; that is, less than 0.05 and 0.10 percent expansion at three and six months, respectively. However, extension of the test period up to five years showed rapid increase in expansions at two and three years for some aggregates. Fly ashes were tested as a means for counteracting this potential expansion. The fly ashes used were Type F. The cement-fly ash combinations tested by ASTM C 441 (reduction of expansion with pyrex glass) showed that reductions of expansion were 66 percent. This is less than the 75 percent reduction recommended in ASTM C 441 but was considered to be sufficiently beneficial to justify its use. Betensen reported that from 1978 to 1985, six projects had been constructed at the state's option using fly ash with potentially reactive aggregate and one project at the contractor's option using nonreactive aggregate. In the first 6 projects, 20 percent fly ash (weight of fly ash equals 20 percent of weight of cement) was added without a reduction in cement to a 6-bag (564 pounds per yd^3) mixture. In the latter case a reduction of ½ bag (47 pounds) of cement was allowed with the 20 percent addition of fly ash. Performance data are not yet available for these concretes.

Region 9

Arizona and California both report the use of substantial amounts of fly ash in pavements. In Arizona, only the use of Class F was reported. California uses about 95 percent Class F and 5 percent Class C. Hawaii reports that its specifications permit the use of fly ash at the option of the contractor but none has been used to date. In the earlier VDHT questionnaire, Nevada indicated that fly ash as an admixture was not permitted; the use of IP cement is approved on a project-by-project basis for use in sidewalks, curbs, and gutters. However, an independent survey indicates that Nevada now permits the use of 15 percent replacement of cement with Class F fly ash for some uses.

Region 10

Alaska reports that no fly ash is available in that state, thus there has been no consideration of its use. Idaho and Washington both have recently changed their specifications to permit the use of fly ash and Oregon expected to establish a specification by January, 1986. Idaho reports that no competitive bids have as yet been offered. Washington has permitted its use only since 1984 and has no performance data or records of the amounts used.

GENERAL CONSENSUS FROM QUESTIONNAIRE REPLIES

Specifications

Table B-2 shows that almost all states now permitting use of fly ash cite ASTM specification C 618 or its AASHTO equivalent M 295. In some cases the maximum limit for loss on ignition is lower than given in either specification. The limit established depends somewhat on the loss on ignition values for fly ashes being sold as pozzolans in the state.

In almost all cases a source of fly ash must be prequalified and a certification of compliance to the specification is required. Agencies often limit their direct tests on shipments of fly ash to a project to checks on loss on ignition and fineness.

Random checks on pre-approved sources are generally the option of the state. How frequently these are made depend somewhat on the volume of fly ash being used and the history of materials from a particular source.

Cement Replacement

As discussed in Chapter 4, there is a wide range of requirements limiting the amount of cement that can be replaced by fly ash. The preponderance of research results show that replacements rates in the range of 20 to 25 percent with equal or greater amounts of fly ash being added result in FAC that meets usual strength requirements at 28 days. However, differences in fly ashes and a conservative approach generally have resulted in maximum limits being set around 15 percent. The low limits of 8 percent used by a few states probably permit some advantage from better workability but reductions in cost from such a low rate of replacement are likely to be minimal. Higher replacement limits in the range of 30 to 50 percent are used where heat build-up in mass concrete is of concern and early strength is not considered important.

Air Entrainment

The reports concerning frequency of tests for entrained air content vary with the range of loss on ignition of the fly ashes being used. Generally it is indicated that no problems with entrained air occur when the loss on ignition values are in the 1.0 to 1.5 percent range. Very little trouble is experienced up to 3 percent. Thus, how often air content tests are needed must be established by experience with the materials being used on any given project. An air-entraining agent other than Vinsol resin has been reported to provide improved stability and uniformity of entrained air content for FAC (*55*).

Use of Admixtures

Although some states do not permit use of admixtures other than air entrainment, others have no restrictions. Water-reducing agents are being used by some agencies to make possible lower water-cement ratios and thus compensate for loss of early strength from the smaller amount of cement. The use of such agents should be a part of the proportioning of the FAC to provide optimum placement and performance characteristics at the lowest cost.

Advantages and Disadvantages

Replies concerning advantages and disadvantages generally confirm earlier discussions included in this report. The most frequently cited advantages are less cost (25 agencies), better workability (17 agencies), lower heat of hydration (14 agencies), sulfate resistance (10 agencies), and higher ultimate strengths (9 agencies). Some of the other advantages mentioned are reduction in alkali-aggregate reaction, lower permeability, better durability, longer set times in hot weather, reduction of cracking, and energy savings.

The most frequent disadvantages listed are increased testing and quality control problems (17 agencies), lack of knowledge of field personnel (16 agencies), nonuniformity of fly ash (16 agencies), lack of cost-effectiveness since lower cost of ingredients are not passed on to state and state has additional control problems (10 agencies), nonavailability of good fly ash within the state (8 agencies), and control of air content in the FAC (7 agencies.)

CHAPTER SIX

DEVELOPING TECHNOLOGY

The preceding summary of the literature, discussions with a number of people in the field, as well as published statements at workshops reveal a changing situation with respect to the use of FAC. As indicated, the pozzolanic properties of fly ash from the burning of bituminous coal are well documented. This material, generally classified as Type F by ASTM standard C 618, has been used extensively in the construction of dams and other massive concrete structures. For a number of reasons as discussed in this synthesis only a few state highway agencies used the material in construction of transportation facilities.

The state highway agencies are well aware of the necessity for changing their specifications for hydraulic cement concrete to eliminate restrictions against the use of fly ash in concrete, but they may not be fully aware of developing technology in the field that may significantly alter the impact of such change on their procurement practices. Until recently, little new information had been developed since the 1950s. However, after the oil embargo and the switch from petroleum to coal as the major fuel for electric power generation with the accompanying substantial increase in the amount of fly ash collected, the situation changed. Since 1980 there has been a surge of research and evaluative effort with respect to fly ash and its properties with considerable emphasis on its use as an ingredient in hydraulic cement concrete. In particular, in the United States a number of studies to evaluate Class C materials derived from western coals have been reported.

INDUSTRY EFFORTS

Significant progress has been made by cooperative efforts among fly ash marketers for proper quality control of their product. The loss on ignition is frequently monitored and efforts are made to eliminate from the market products obtained during start up and upset conditions at power plants that are the source of considerable variability.

The American Coal Ash Association has issued guidelines for a fly-ash quality assurance program. This is shown in Appendix C. If followed by the ash supplier, such a program should assure the purchaser that the product is suitable and has adequate uniformity.

The Electric Power Research Institute has an on-going project for fly ash classification. This project consists of the collection and testing of fly ashes from all regions of the country. The selection has been designed to obtain the full spectrum of fly-ash characteristics as now being produced in the United States. The project's goal is to relate concrete performance to the physical and chemical characteristics of the fly ashes and to develop a fly-ash classification system that will assist utility or marketing companies in assessing potential fly ash usefulness in cement and concrete applications. Such a system will also be extremely useful to consumer agencies if it is able to eliminate uncertainties, now encountered with the current specifications, in fly ash-cement reactions.

RATIONAL METHODS OF MIXTURE PROPORTIONING

Consideration is being given to better proportioning procedures to gain maximum economy and optimum properties of FAC. Munday et al. (*56*) made a critical review of various procedures for incorporating fly ash into concrete as a partial replacement of the portland cement. These authors recognize that fly ash can be added as an ingredient of the blended cement, but consider the most effective method of use to be as an admixture at the concrete mixer. As previously discussed in this report, this procedure makes it possible to use optimum proportions of specific fly ashes and cements.

The shortcomings of the simple replacement method whereby a mass or volume of fly ash replaces an equal mass or volume of cement are noted. The normal result of this procedure is a concrete that has lower strength at early ages, possibly up to 90 days but thereafter usually has higher strengths than the control concrete made with all portland cement.

This result led to the modified replacement method now being used by most transportation agencies. It works reasonably well in most cases but does not properly recognize differences in cement-fly ash interactions. Strength developments of a given fly ash may vary with different cements just as strength development of different fly ashes will be different with the same cement.

Munday et al. (*56*) credit Smith (*57*) as being the first to develop a rational approach to the proportioning of fly ash concrete by his assumption that every fly ash possesses a unique cementing efficiency (K) such that K multiplied by the mass of the fly ash would be equivalent to a mass of cement. Thus, cementitious material in a given concrete is the cement plus KF where F is the mass of the fly ash. However, as later research has shown, K is not a constant. It varies depending on the type of cement used as well as the amount. Different water demands for different fly ashes also require adjustments of aggregate contents of concretes.

Two alternatives are suggested. One is to modify a control mixture so that the concrete containing fly ash with a portion of the cement replaced will have corresponding properties of workability and strength, the assumption being that other properties of the concrete will be equal or better. The ultimate goal, as suggested by these authors, is to proportion fly-ash concrete without reference to a control mixture. However, they recognize that more research is needed to better understand the interacting relationships before this goal can be reached. Full discussion of the various proposals concerning mixture proportioning techniques are beyond the scope of this synthesis. However, it is noted that research under way in 1986 (as yet unpublished) should ultimately provide procedures for proportioning fly ash concrete for optimum needed characteristics (such as most economical, least permeable, highest strength, lowest heat of hydration, etc.), whatever the needs may be.

FUNDAMENTAL STUDIES

In the scientific field, new analysis techniques are being developed that identify compound composition within the fly ash and reaction products that will provide a much better understanding of the fly ash-cement interactions (*32*). Improved scanning electron microscopy and better measurement of particle-size distribution provide better evaluation of physical properties (*36*). These efforts should permit better identification of the potential for new sources of fly ash and ultimately lead to a more meaningful pozzolanic activity test than those now included in ASTM C 618 and AASHTO M 295.

INTERNATIONAL SYMPOSIA

National and international symposia to exchange information were planned for 1986. These conferences are not limited to the use of fly ash in concrete but included consideration of the full range of mineral admixtures—slags, fly ashes, silica fumes, and natural pozzolans. The synopsis of Mehta's paper prepared for the Second International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete (held in Madrid, Spain, April 1986) provides a summary of the current situation and proposes "performance" standards (*58*). The synopsis states:

> There is a growing concern that the existence of prescriptive and separate standards is one of the obstacles preventing the large scale use of by-product mineral admixture for concrete, such as fly ash, granulated slag, and condensed silica fume. Since natural pozzolans as well as by-product pozzolanic and cementitious admixtures offer similar technical benefits when used in concrete, it is desirable to develop a single performance-oriented standard. With this objective, the principal chemical and physical requirements of a few selected standards are critically reviewed. With a special focus on fly ash, the significance of these requirements and their relevance to today's materials are examined. In the end a rational approach is suggested and specific recommendations are made towards the goal of developing a performance standard covering all mineral admixtures.

AVAILABLE GUIDELINES

The results of these and other efforts are not now known or predictable; thus, they are not of value to state highway agencies faced with the immediate necessity to establish specifications for fly ash and proportioning procedures for FAC that will be fully acceptable as an alternative to the usually specified portland cement concrete. Needs vary from state to state. However, the FHWA has issued a materials notebook containing a section relating to the use of fly ash in concrete. This section summarizes briefly many of the items discussed in this chapter of the synthesis and provides recommendations to the states concerning appropriate action with respect to specifications and quality assurance procedures for FAC. This section is included as Appendix D of this synthesis. The FHWA has also issued a report (*59*) on fly ash that summarizes in a question-and-answer format most of the basic information on the use of fly ash in concrete as well as in other highway applications.

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This document is a synthesis of world-wide information available from 1934 to 1959. The information provided deals principally with fly ashes from bituminous coal (Class F) since this was essentially the only source during the time period covered. The author summarizes various uses and findings concerning the effects of fly ash on concrete. He traces the chronological development of fly ash use in concrete during various periods within the overall time period. Conclusions are presented concerning the value of fly ash in concrete, most of which are still valid with respect to Class F material. An annotated bibliography of 275 publications concerning fly ash is included.

American Concrete Institute, *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete,* Special Publication SP-79, 2 vols., American Concrete Institute, Detroit, Mich. (1983) 1196 pp.

This publication, contained in two volumes, constitutes the proceedings of the first international conference on the use of fly ash, silica fume, slag, and other mineral by-products in concrete. Sixty-two papers relating to various aspects of the technology are included—generally, Volume 1 contains the papers relating to the use of fly ash in concrete. Papers likely to be of interest with respect to the use of fly ash in highway concrete are the review paper by Mehta (Vol. 1, p. 1); the paper by Gebler and Klieger on the effect of fly ash on the air void stability of concrete (Vol. 1, p. 103); the review of international specification by Manz (Vol. 1, p. 187); and the critical review of the mix proportioning of concrete with fly ash by Munday, Ong, and Dhir (Vol. 1, p. 267). Papers on Australian and French experiences with fly ash concrete (Vol. 1, pp. 143 and 471) may also be of interest.

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This is a state-of-the-art report that gives an overview of the production of fly ash and its proper use in production of portland cement concrete. It discusses the quality control of fly ash, provides guidance regarding the handling and use of fly ash in concrete, and the use of fly ash in specific applications. It references documents that provide more specific information on each topic. It includes references to attributes of Class C fly ashes and differences from Class F not covered by the earlier summaries and state-of-the-art presentations.

Berry, E. E. and V. M. Malhotra, "Fly Ash in Concrete (SP-85-3)," Canada Center for Mineral and Energy Technology (CANMET), Ottawa, Canada (February 1986).

This volume represents an excellent starting point and reference for engineers and researchers entering the field as well as providing an update of current knowledge for those who have been long involved. As well as historical background, it presents a state-of-the-art review of the principal advances in research, development, and practical application of fly ash in concrete including those that have been made between 1976 and 1984. Recommendations are included with regard to aspects of fly ash technology requiring further research.

The significant differences between low-calcium and high-calcium fly ashes are discussed and the lack of complete knowledge with respect to behavior of some of the newer products from burning subbituminous coal or lignite is emphasized.

The potential of the self-cementing (or self-hardening) fly ashes for providing a unique contribution whose early strength development is required or for very high strength concretes is discussed. The inadequacy of present specifications and codes of practice, as well as testing procedures associated with quality control of fly ash for use in concrete, is also discussed.

In general, this volume discusses fly ash technology from an international viewpoint and pertains to all potential uses for concrete. The report lists 224 references.

Berry, E. E. and V. M. Malhotra, "Compilation of Abstracts of Papers from Recent International Conferences and Symposia on Fly Ash in Concrete," Division Report MRP/MSL 85-2, Canada Center for Mineral and Energy Technology, Ottawa, Canada (1985).

This report is a compilation of abstracts of papers from international conferences held in Europe and North America between 1980 and 1983. The papers included were selected on the basis of their direct relevance to the use of fly ash in concrete.

Berry, E. E. and V. M. Malhotra, "Fly Ash for Use in Concrete—A Critical Review," *ACI Journal* (March–April 1980).

This article is a comprehensive review of the effects of fly ash on the properties of hydraulic cement concretes. Effects on properties of fresh concrete such as workability, water requirement, and bleeding are discussed as well as effects on hardened concrete. These include temperature effects, strength development, sulfate resistance, and alkali aggregate interactions. Sixty-two references are cited.

Electric Power Research Institute, *Coal Combustion By-Products Utilization Manual,* Vol. 1: "Evaluating the Utilization Option," Vol. 2: "Annotated Bibliography," Electric Power Research Institute, Palo Alto, Calif. (February 1984).

Volume 1 of this manual provides information on all aspects of utilization and/or disposal of coal combustion by-products from the viewpoint of the power-generating company. Twelve sections are included among which are by-product collection procedures, quantities, national market assessment, regulatory and institutional impacts, quality control and specifications, case histories, and existing utilization practices.

Volume 2 is a comprehensive catalog of published information. It provides for a literature search in 24 subject areas. Approximately 600 references are annotated.

Electric Power Research Institute, "Workshop Proceedings: Research and Development Needs for Use of Fly Ash in Cement and Concrete," EPRI CS-2616-SR, Electric Power Research Institute, Palo Alto, Calif. (1982).

Participants of this workshop were drawn from the electric power industry, the cement and concrete industry, universities, independent research institutes, consulting firms, and government. Attendance and participation were international in scope.

The stated objectives of the workshop were:

1. To bring together and to increase communication among recognized authorities in the fields of fly ash, cement, and concrete production, utilization, and research.

2. To establish the present status of fly ash production, utilization, and supporting research and development around the world.

3. To determine the technical barriers against the increased use of fly ash in cement and concrete and to recommend research and development activities to remove such barriers.

4. To recommend research and development areas that may stimulate new applications for, or increased use of, fly ash in cement and concrete.

5. To discuss basic research needed to increase our understanding of various fly ashes in cement and concrete.

6. To improve technical communication between the producers and users of fly ash.

The proceedings include papers dealing with the various objectives and summaries of the findings of the four panel sessions. The panel sessions focused on the following topics:

(a) Production of Fly Ash
(b) Utilization of Fly Ash
(c) Short-term R & D Opportunities
(d) Long-term R & D Opportunities

This document provides an excellent summary of the 1985 status of fly ash utilization in cement and concrete and the potential of fly ash concrete as a technology in its own right and not just a way to use up an annoying waste or by-product.

Frohnsdorff, G. and J. R. Clifton, "Fly Ashes in Cements and Concretes: Technical Needs and Opportunities," NBSIR 81-2239, National Bureau of Standards, Washington, D. C. (March 1981).

This report represents, in part, the response of the National Bureau of Standards to the mandate of subtitle E of the Resources Conservation and Recovery Act. It addresses the use of fly ash in both cements and concrete. Estimates are made of the amount that could be used as a by-product and the economic and technological benefits that might be attained. It also recognizes factors that currently account for the relatively low levels of use of fly ash as a by-product. Major research needs to increase use are discussed.

Lane, R. O. and J. F. Best, "Properties and Uses of Fly Ash in Portland Cement Concrete," *Concrete International* (July 1982).

This report is based on the experience of the Tennessee Valley Authority (TVA) in using fly ash in concrete over a period of 25 years. The article summarizes the advantages and disadvantages in using fly ash and reports that the advantages far outweigh the disadvantages. A procedure for mixture proportioning of fly ash concrete is presented. Special applications such as zero-slump concrete and pumped concrete are also discussed.

National Technical Information Service, "Fly Ash," NTIS, Springfield, Virginia (March 1982, February 1985).

This is an annotated bibliography of recent publications concerning fly ash. It includes 279 citations dealing with all aspects of fly ash production, handling, use, and disposal. References to fly ash use in cement and concrete are included in other documents so that it is useful as a tool for conducting a literature search for recent information.

Proceedings of the International Symposia on Ash Utilization.

Since its inception, the National Ash Association (now the American Coal Ash Association) has cosponsored seven symposia on the use of ash from the burning of coal with the U.S. Department of Energy, other governmental agencies, and other technical trade associations. Collectively, the information presented in the published proceedings covers a large proportion of the total literature available concerning fly ash use.

The title and publication data for each symposium are as follows:

1. Faber, J. H., J. P. Capps, and J. D. Spencer, *Fly Ash Utilization—Proceedings of Edison Electric Institute, National Coal Association, Bureau of Mine Symposium,* Pittsburgh, Penn., March 1967, Information Circular 8348, U. S. Department of the Interior, Bureau of Mines, Washington, D. C. (1967).

2. Faber, J. H., N. H. Coates, and J. D. Spencer, *Ash Utilization—Proceedings: Second Ash Utilization Symposium,* Information Circular 8488, U. S. Department of the Interior, Bureau of Mines, Washington, D. C. (March 1970).

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4. Faber, J. H., A. W. Babcock, and J. D. Spencer, *Ash Utilization—Proceedings: Fourth International Ash Utilization Symposium,* March 1976, Report No. MERC/SP-76/4, Energy Research and Development Administration, Morgantown, West Virginia (1976).

5. Spencer, J. D. and C. E. Whieldon, *Proceedings: Fifth International Ash Utilization Symposium,*" Atlanta, Georgia, February 1979, Report No. METC/SP-79/10, U. S. Department of Energy, Morgantown, West Virginia (1979).

6. Halow, J. S. and J. N. Covey (eds.), *The Challenge of Change—Sixth International Ash Utilization Symposium Proceedings,* DOE/MWRX/82-52, Vols. 1 & 2, Morgantown Energy Technology Center, U. S. Department of Energy and National Ash Association, Morgantown, West Virginia (July 1982).

7. U. S. Department of Energy, *Proceedings of the Seventh International Ash Utilization Symposium and Exposition,* DOE/METC-85/6018, National Technical Information Services, U. S. Department of Commerce, Springfield, Virginia (May 1985).

Singleton Materials Engineering Laboratory, "Properties and Use of Fly Ash in Portland Cement Concrete," Tennessee Valley Authority, Knoxville, Tenn. (1979).

This is a technical report that provides a summary of 1979 knowledge and practice based on TVA experience and research results from independent studies. It provides information on the physical and chemical properties of fly ash, primarily Class F, and the effects of fly ash on the plastic and hardened properties of concrete. Mixture proportioning, materials sampling, and testing are also included. The significance of specific quality control and specification tests is also discussed.

APPENDIX A

FHWA MEMORANDUM: EPA's GUIDELINE ON THE USE OF FLY ASH IN CONCRETE

U.S. Department of Transportation
Federal Highway Administration

Memorandum

Washington, D.C. 20590

Subject: EPA's Guideline on the Use of Fly Ash in Concrete   Date: January 4, 1985

From: Deputy Administrator   Reply to Attn. of: HHO-33

To: Regional Federal Highway Administrators
Regions 1-10
Direct Federal Program Administrator

Your attention is invited to Associate Administrator for Engineering and Operations Rex C. Leathers' August 4, 1983, memorandum on EPA's Guideline on the Use of Fly Ash in Concrete, issued pursuant to the Resource Conservation and Recovery Act (RCRA).

You were advised in that memorandum that while we did not object to the intent and substance of the guideline, we did not agree with EPA's determination that it applied to the Federal-aid program. Federal Highway Administrator Ray A. Barnhart wrote to EPA Administrator William D. Ruckelshaus setting out our position in detail with supporting arguments. The EPA's formal reply was in a letter from the Office of the EPA Administrator to Mr. Barnhart. This letter states that "In the recently passed reauthorization of RCRA, Congress unequivocally states that Section 6002 applies to direct procurement and indirect Federal-aid programs of the FHWA. . . ." This congressional clarification appears in the Joint Explanatory Statement of the Committee of Conference, Congressional Record, October 3, 1984, page H11138. Therefore, the disagreement has been resolved and Section 6002 of the RCRA is fully applicable to States in the Federal-aid program.

Please advise the States in your region of this development and the need to comply with Section 6002 of the RCRA. We suggest that the SHA's be requested to develop a commitment on how they intend to comply with the EPA regulations. Their commitment and activity schedule should be such as to ensure full implementation of a program meeting the intent of the guideline as soon as possible and at least within 1 year of the date of this memorandum.

Basically the guideline requires that all affected agencies revise their specifications, standards, and procedures to remove any discrimination against the use of fly ash in cement and concrete unless such use is found to be technically inappropriate in a particular application. A finding of technical inappropriateness should be documented, open for public scrutiny and a review process established to settle any disagreements. Your attention is invited on page 4246, Column 3, second paragraph of the preamble in the attached copy of the pertinent section of the Federal Register which states:

> "EPA expects a high level of compliance with the guideline. If necesary, the Agency is prepared to take appropriate measures to ensure that the objectives of the guideline are met. In addition, there are other methods available to interested parties to encourage compliance with Section 6002. One of these methods is the citizen suit provision of Section 7002 of RCRA which states:
>
> > (a) * * * any person may commence a civil action of his own behalf -- (1) against any person (including (a) the United States, and (b) any other governmental instrumentality or agency * * *) who is alleged to be in violation of any permit, standard, regulation, condition, requirement, or order which has become effective pursuant to this Act.
>
> A second method which may be useful in encouraging compliance with Section 6002 is the filing of formal protests by aggrieved bidders. A bidder who is willing and able to supply a 'designated' recovered material product to procuring agencies who is precluded from bidding by failure of a procuring agency to comply with Section 6002, may be able to obtain satisfaction through this process."

The SHA's specification revisions on the use of fly ash in concrete will require careful regional and interregional reviews for uniformity of interpretation and adequate documentation on technically inappropriate applications, if any. Therefore, we request that copies of the States' revised specifications be sent to Washington Headquarters, HHO-33. That office, HHO-33, will act as national coordinator and will be happy to provide technical advice as requested by the field offices.

In addition to the standards listed in Sub-section 249.12, the 1984 AASHTO Subcommittee on Materials Interim Specifications and Methods of Sampling and Testing contains AASHTO M 295-84I on fly ash in portland cement concrete.

L. P. Lamm

Attachment

APPENDIX B

RESPONSES FROM QUESTIONNAIRE

Questionnaire

To determine the present status of use of fly ash in concrete by member agencies of the American Association of State Highway and Transportation Officials, a questionnaire was submitted to the materials engineer or equivalent of each agency. A copy of the letter of transmittal and the questionnaire follow Table B-4 of this appendix.

Fifty-one of the 59 agencies to which this questionnaire was sent responded. The 51 include 46 states, the District of Columbia, and 4 provinces of Canada. Tables B-1 through B-4 summarize the information provided by each agency.

TABLE B-1 FLY ASH UTILIZATION BY HIGHWAY AGENCIES (PART 1)

	Application[a]									
State	Pavements	Bridge Decks	Curbs, Gutters	Foundations, Seals	Median Barriers	Pipe & Misc.	Fly Ash Type[b]	Blended Cement[c]	Volume FAC (1000 yd^3)[d]	Remarks
					Region 1					
Maine	NP	NP	NP	NP	NP	NP	-	NR	0	Specifications now being reevaluated.
Massachusetts		NP	NP	NP	NP	NP	-	NP	0	Will revise to comply with EPA-FHWA.
New Hampshire	NR	NP	NP	NP	NP	NP	-	NP	0	Specifications now being reevaluated.
New Jersey	NP	NP	NP	NP	NP	NP	F	NP	0	Special provisions, experimental project.
New York	NP	NP	NP	NP	NP	NP	F	NP	0	Experimental project under way, will revise specifications.
Rhode Island	NP	NP	NP	NP	NP	NP	-	-	0	No use to date, may change.
Vermont	NP	NP	NP	NP	NP	NP	-	NR	0	Will revise specifications to comply with EPA-FHWA.
					Region 3					
Delaware	P-C	P-C	P-C	P-C	P-C	P-C	C-F	NP	0	Recent specification change, no use to date.
District of Columbia	P-C	P-C	P-C	P-C	P-C	P-C	C-F	P-S	0.3	Recent specification change.
Maryland	P-C	NP	P-C	NP	P-C	P-C	F	NP	0	Quantities used unknown.
Pennsylvania	P-C	P-C	P-C	P-C	P-C	P-C	C-F	P-S	187	No reduction in cement for pumping concrete.
Virginia	P-C	P-C	P-C	P-C	P-C	P-C	F	P-O	8	Recent specification change.
West Virginia	P-C	P-C	P-C	P-C	P-C	P-C	F	P-S	532	Considerable use in pavements.
					Region 4					
Alabama	R	P-C	P-C	P-C	P-C	P-C	C&F	NR	-	Extensive use of type F. Type C now approved.
Florida	P-C	P-A	P-A	P-A	P-A	P-A	F	P-F	425	Fly ash required in aggressive environments.
Georgia	P-C	P-C	P-C	P-C	P-C	P-C	F	P-S	NR	
Kentucky	P-C	NP	P-C	P-C	P-C	P-C	F	P-S	NR	
Mississippi	P-C	P-C	P-C	P-C	P-C	P-C	F	P-S	NR	Recent specification change.
North Carolina	NP	NP	NP	R	NP	P-C	F	NP	NR	Required in Seal Concrete. Other uses experimental, change under consideration.
South Carolina	NR	NR	NR	NR	P-A	P-A	F	P-S	NR	Very little experience.

TABLE B-1 FLY ASH UTILIZATION BY HIGHWAY AGENCIES (PART 1) (Continued)

State	Application[a]						Fly Ash Type[b]	Blended Cement[c]	Volume FAC (1000 yd^3)[d]	Remarks
	Pavements	Bridge Decks	Curbs, Gutters	Foundations, Seals	Median Barriers	Pipe & Misc.				
Tennessee	NP	NP	NP	NP	NP	NP	C&F	NP	0.7	Experimental Use. Change in specifications planned.
					Region 5					
Illinois	P-A	NP	P-A	NR	P-A	P-A	C&F	P-O	256	Recent specification change - Provisions and Policy.
Indiana	NP	NP	NP	NP	NP	NP	-	P-S	NR	Fly ash as an admixture not permitted.
Michigan	P-C	NP	P-C	P-C	P-C	P-C	C&F	P-F	200	Very limited use except in pavements.
Minnesota	P-C	NP	P-C	P-C	P-C	NR	C&F	P-S	1M	Extensive use, greatest use of Class F.
Ohio	P-C	NP	P-C	NR	P-C	P-C	C&F	P-S	0	Recent specification change.
Wisconsin	P-C	NP	NP	NP	NP	P-C	C&F	NP	240	Pavement use only - 67% Class C, 33% Class F.
					Region 6					
Arkansas	P-C	P-C	P-C	P-C	P-C	P-C	C&F	P-S	NR	
Louisiana	P-A	NP	P-A	P-A	P-A	P-A	C&F	NP	NR	Has detailed prequalification procedure.
New Mexico	P-C	P-C	P-C	P-C	P-C	P-C	C&F	NP	NR	Fly ash required with some aggregates, no records on quantities used.
Oklahoma	P-C	NR	NR	NR	NR	NR	C&F	NP	112	
Texas	P-C	P-C	P-C	P-C	P-C	P-C	C&F	-	-	Special provisions, state specifications used.
					Region 7					
Iowa	P-C	NP	P-C	P-C	P-C	P-C	C&F	P-O	120	Permitted only with high quality coarse aggregate. Class C, experimental use.
Kansas	NP	NP	NP	NP	NP	NP	-	-	0	Will change specifications to comply with EPA-FHWA.

TABLE B-1 FLY ASH UTILIZATION BY HIGHWAY AGENCIES (PART 1) (Continued)

	Application[a]									
State	Pavements	Bridge Decks	Curbs, Gutters	Foundations, Seals	Median Barriers	Pipe & Misc.	Fly Ash Type[b]	Blended Cement[c]	Volume FAC (1000 yd^3)[d]	Remarks
Missouri	P-C	NP	NP	NP	NP	NP	C&F	P-O		Blended cement permitted for limited uses, special provision for experimental use in pavements.
					Region 8					
Colorado	P-C	P-C	P-C	P-C	P-C	NR		NP		Required under some conditions.
Montana	NP	NP	NP	NP	NP	NP	-	NP	0	No additional information.
North Dakota	P-C	NR	NR	NR	NR	NR	-	NP	-	
Utah	P-C	P-C	P-C	P-C	P-C	P-C	F	NP	300	Experimental, performance with high alkali cements.
					Region 9					
Arizona	P-C	P-C	P-C	P-C	P-C	P-C	F	P-F	182	
California	P-C	P-C	P-C	P-C	P-C	P-C	C&F	P-S	635	Approximately 95% Class F, 5% Class C.
Hawaii	P-C	P-C	P-C	P-C	P-C	P-C	C&F	NP	0	No use of fly ash to date.
					Region 10					
Alaska	NP	NP	NP	NP	NP	NP	-	-	-	No experience with fly ash concrete.
Idaho	P-C	NR	P-C	P-C	P-C	P-C	C&F	P-S	0	No competitive bids as yet.
Oregon	NP	NP	P-C	P-C	P-C	P-C	C&F	NP	NR	
Washington	P-C	P-C	P-C	P-C	P-C	P-C	C&F	NP	NR	Recent specification change.
					Canadian Provinces					
Alberta	NP	NP	NP	NP	NP	NP		NP		Now conducting research.
New Brunswick	NP	NP	NP	NP	NP	NP		NP		Does not use fly ash in concrete.
Nova Scotia	NP	NP	NP	NP	NP	NP		NP		Research conducted on local fly ash.
Ontario	NP	NP	NP	NP	NP	NP		NP		No good source, industry does not use.
Saskatchewan	NP	NP	NP	NP	NP	NP		NP		Very little use, source of good fly ash not available.

[a]R = required; P-C = permitted at option of contractor; P-A = permitted at option of highway agency; NP = not permitted by standard specifications; NR = not reported.
[b]C = Class C (from subbituminous coal and lignite); F = Class F (from bituminous coal). Both C&F shown where reply indicated ASTM C 618 used and class was not designated.
[c]NP = not permitted or not available in state; P-S = permitted but seldom used; P-F = permitted and frequently used; P-0 = permitted but no use reported.
[d]Total volume reported all applications (most used in pavements).

TABLE B-2 SPECIFICATIONS AND CONTROL PROCEDURES FOR FLY ASH (PART 2)

State	Specification Cited	Acceptance Procedure[a] SA	C	AT	Test Frequency and Other Comments
					Region 1
Maine		Not reported			
Massachusetts		Not reported			
New Hampshire		Not reported			
New Jersey	C 618	X	X	X	Random verification of producer's results. Specifications for experimental project.
New York	C 618	X		X	LOI and fineness for routine acceptance - one test for each tanker before shipment. Specifications experimental project.
Rhode Island		Not reported			
Vermont		Not reported			
					Region 3
Delaware	C 618		X	X	Not reported.
District of Columbia	M 295	X	X		Producer tests weekly for quality control.
Maryland	C 618[b]	X	X	X	LOI, moisture, fineness, chemical, all samples; 1 full test/2 weeks. Maximum moisture 1%.
Pennsylvania	C 618	X		X	All C 618 except optional. After source approval, random spot checks.
Virginia	C 618[c]	X		X	All required by C 618. Check test on LOI and fineness 1 test/week - Shipments to project; 1 per month approved source.
West Virginia	C 618	X		X	All required by C 618 - 1 test/400 tons fly ash.
					Region 4
Florida	C 618[c]		X	X	All required by C 618 - 1 per 3 months or 1 per 250 tons.
Georgia	C 618[c]	X	X	X	Chemical analysis - pozzolanic activity in cement - 1/month minimum.
Kentucky	C 618	X	X	X	LOI, fineness, specific gravity - 1 each 100 tons fly ash.
Mississippi	C 618	X	X	X	Pozzolanic activity, chemical analysis, LOI - same as ASTM C 311.
North Carolina	C 618[c]		X		Infrequent tests for LOI, chemical analysis gradation - Specifications for use in seal concrete or experimental projects.
South Carolina	C 618[c]	X	X	X	Tests and frequency not established - specifications recently adopted.
Tennessee	C 618	X	X	X	Monthly quality control - all C 618 test 1/2000 tons; LOI, fineness on project basis approved sources 1/400 tons - Special quality assurance procedure.
					Region 5
Illinois	C 618[b]	X	X	X	Chemical tests infrequently (source uniform). Concrete tests each job with actual materials to be used. Max LOI, 5%, autoclave, 0.5%.

TABLE B-2 SPECIFICATIONS AND CONTROL PROCEDURES FOR FLY ASH (PART 2) (Continued)

State	Specification Cited	Acceptance Procedure[a] SA	C	AT	Test Frequency and Other Comments
Indiana					Fly ash not used as an admixture.
Michigan	C 618[b]	X	X	X	Verification tests for LOI, pozzolanic activity, soundness, specific gravity. LOI max 4.0%, retained on No. 325 sieve.
Minnesota	C 618[b]	X	X	X	All C 618. One sample taken per week and 1 of 10 samples tested for LOI, fineness, pozzolanic activity, autoclave complete chemical analysis on 1% of samples on which physical tests are made.
Ohio	C 618			X	As required by ASTM - one each project.
Wisconsin	C 618[bc]		X	X	LOI, specific gravity, fineness - 1 per 100 tons fly ash.
Region 6					
Arkansas	C 618	X		X	All C 618 - Complete tests yearly for each FA source, 1 per 500 tons on projects for fineness, LOI, specific gravity, CaO (Texas procedure).
Louisiana	C 618	X	X	X	Detailed qualification procedure. Accepted on project by certification.
New Mexico	C 618	X	X	X	Submittal of test data from independent laboratory that fly ash conforms to specification. Verification tests made.
Oklahoma	C 618	X	X	X	Testing in accordance with ASTM C 311, except as modified.
Texas	State	X	X	X	Uses state specification, Type A equivalent to Class F, Type B equivalent to Class C.
Region 7					
Iowa	C 618	X	X	X	All C 618, minimum 1 per month per source + assurance samples. Non-certified source, 1/lot.
Kansas		Not reported			
Missouri	C 618[b]	X	X	X	Detailed qualification procedure. Approved fly ash in special stored silos. Test by fly ash producer.
Region 8					
Colorado	C 618[b]			X	All C 618 - 1 per project. Plan to adopt pre-approved source - Minimum 1/year on approved sources.
Montana		Not reported			Fly ash not used.
North Dakota	M 295	X	X	X	All C 618.
Utah	C 618[b]				All C 618, frequency as in ASTM C 311. LOI - 3% maximum.
Region 9					
Arizona	C 618		X	X	Time of set for FAC, autoclave expansion, LOI, SO_3, total alkali, 28-day cube strength; 2/month from single source.

TABLE B-2 SPECIFICATIONS AND CONTROL PROCEDURES FOR FLY ASH (PART 2) (Continued)

State	Specification Cited	Acceptance Procedure[a] SA	C	AT	Test Frequency and Other Comments
California	C 618[b]	X	X	X	All C 618 - 1 sample fly ash each 500 yd^3 concrete. Fly ash tested on a random basis - 10 to 20 percent of samples received.
Hawaii	C 618		X		All C 618 - certification required. No use of fly ash to date.
Region 10					
Alaska		Not reported			
Idaho	M 295	X	X	X	LOI on all samples. Random spot checks for other C 618 tests.
Oregon	C 618[b]	X		X	Fineness, moisture, specific gravity, LOI, air entrainment of mortar - 1 per 50 tons fly ash; LOI - 1.5 maximum.
Washington	C 618	X	X		No tests on fly ash - certification from approved sources required.
Canadian Provinces					
Alberta		Not reported			Fly ash not used, research being conducted.
New Brunswick		Not reported			Fly ash not used.
Nova Scotia		Not reported			
Ontario		Not reported			Fly ash not used, would consider if offered by industry.
Saskatchewan	M 295	X			Seldom used, would make trial mixtures for freeze-thaw durability on job aggregates.

[a]SA = source pre-approved before use; C = certification of compliance required; AT = acceptance tests are made by agency.
[b]Denotes specification is modified in some respects.
[c]Class F.

TABLE B-3 CONTROL PROCEDURES FOR FLY ASH CONCRETE (PART 3)

State	Mix Design By:	Cement Replaced (%)	Fly Ash Added[ab]	Entrained Air: Test Procedure[c]	Entrained Air: Frequency of Tests[d]	Additional Admixtures Permitted[e]	Comments
Region 1							
Maine							No information provided.
New Hampshire							No information provided.
New Jersey	Contractor	25	NR	PM	EL	WR	No experience, fly ash used only experimentally to date.
New York	Agency	15	1.0	PM	50 yd^3	WR, Ret	Experimental use only to date, need early test for quality of fly ash.
Rhode Island							No information provided.
Vermont							No information provided.
Region 3							
Delaware	Contractor	8	1.5	PM	NR	NR	No experience, fly ash not used to date.
District of Columbia	Agency	15	1.0	PM	NR	All	No problems with air reported, max LOI - 4.0% in specifications. Wants more distinction between Class F and Class C.
Maryland	Contractor	15	NR	PM	50 yd^3	None	Erratic behavior with air entraining agents, wants to eliminate LOI variability.
Pennsylvania	Contractor	10	1.0	PM	Varies	All	Reports uniform results with added air entraining agent, but loss of air during transit. Wants more rapid method for pozzolanic activity.
Virginia	Contractor	15	1.0	C, PM	EL	All	Air problem with low LOI; admixtures permitted but not used to date.
West Virginia	Contractor	See Comments	1.0	C, PM-VOL.	EL - random	All	No cement or air problems; 1 bag cement replaced with equivalent weight of fly ash.
Region 4							
Florida	Contractor	20, See Comments	NR	C, VOL.	Each pour	All	Up to 50% replacement - mass concrete; fly ash added without replacing cement some applications, erratic behavior - with air entraining agents - LOI max 4.0% target 3.5% - reduces air entrainment problems. Wants max LOI at 4.0% and max SO_3 20% in standard specifications.

TABLE B-3 CONTROL PROCEDURES FOR FLY ASH CONCRETE (PART 3) (Continued)

State	Mix Design By:	Cement Replaced (%)	Fly Ash Added[ab]	Entrained Air: Test Procedure[c]	Entrained Air: Frequency of Tests[d]	Additional Admixtures Permitted[e]	Comments
Georgia	Agency	8	1.5	PM	50 yd^3 random	WR, Ret	No air problems reported with LOI specifications at 6% max.
Kentucky	Agency	20	1.25	PM	5 loads	WR, Ret	No air problems with LOI 3.0%. Water retarders increase early strength.
Mississippi	Agency	20	NR	PM	EL	All	No air problems reported with LOI at 6% max; wants more control on fly ash.
North Carolina	Contractor	30 (mass concrete)	1.0	PM, C, VOL.	EL	WR, Ret.	No problem with air if LOI is less than 3.0%; most use in mass concrete, other uses experimental.
South Carolina	Contractor	20	NR	C, PM	-	All	No experience as yet, specifications adopted 6/10/85. C 618 may not be sufficient or practical.
Tennessee	Agency	15 - Class F 25 - Class C	1.25 (F) 1.0 (C)			NR	Only experimental use to date.
				Region 5			
Illinois	Agency	15	1.5	PM	250 ft pavement	WR, Ret.	No air problems. All fly ashes 1.0% LOI; wants more distinction between Class C and Class F.
Indiana							Fly ash not used as an admixture. No problems with Type IP cement.
Michigan	Agency	9	1.6	PM, VOL.	Random	WR, Ret.	Tighter limits on LOI. More distinction between Class C and Class F.
Minnesota	Agency	15	1.0	PM, VOL.	50 yd^3	All	No air problems - all fly ashes less than 2.0% LOI. More distinction between Class C and Class F.
Ohio	Agency	16.7	NR	PM, VOL.	EL	WR, Ret.	Limited experience - reducing LOI to 3.0% in specifications.
Wisconsin	Agency	8	1.6	PM	Random	None	Some loss of air in transit, no problems with air uniformity, all fly ashes ½ to 2% LOI. Specification requirement 5.0%.
				Region 6			
Arkansas	Contractor	25	1.0-Class C	PM	250 yd^3	WR, Ret.	No air problems, LOI less than 1% on fly ashes used. Need faster chemical tests.
Louisiana	Agency	20	NR	PM, VOL.	NR	None	No field experience with quality control.
New Mexico	Agency	20	NR	PM	3 loads	WR	Erratic behavior with air.
Oklahoma	Contractor	15	1.35	PM, C	EL	WR, R	No problem with air reported.
Texas	Agency	35 (vol)	NR	NR			Proportioning procedure being developed - amount of cement replacement variable.

TABLE B-3 CONTROL PROCEDURES FOR FLY ASH CONCRETE (PART 3) (Continued)

State	Mix Design By:	Cement Replaced (%)	Fly Ash Added[ab]	Entrained Air: Test Procedure[c]	Entrained Air: Frequency of Tests[d]	Additional Admixtures Permitted[e]	Comments
				Region 7			
Iowa	Agency	15	1.0-Class F 1.25 Class C	PM	1000 yd^3 (paving) 20 yd^3 (struc.)	None	No air control problems; all fly ashes below 0.5% LOI.
Kansas	Contractor	15					No experience. Changes in specifications under way.
Missouri	Agency	20	1.0 - 1.25	PM			Very limted experience. Field test procedures not established. Wants quick test for alkali - aggregate reactivity.
				Region 8			
Colorado	Contractor	20	1.0	PM	5 loads random	WR	One test for air each 5 loads after 3 loads show conformance. Believes improvements needed in specifications.
Montana							Does not use fly ash - no specifications to date.
North Dakota	Agency	15	1.0	PM	Random	All	No air control problems with LOI less than 4.0%.
Utah	Contractor	½ bag	NR	PM	750 yd^3	WR	Clustering of voids noted with vinsol resin. Specification max LOI 3% - Actual range 1.5 ± 0.8%.
				Region 9			
Arizona	Contractor	15	1.2	PM	50 yd^3 random	WR	LOI 3.0% max in specifications. Some loss of air in transit reported.
California	Agency	15	1.0	PM	EL	All	If problem arises each load is tested for air. Specifications provide for added time before loading FAC and stripping forms.
Hawaii	Contractor	15	1.0	PM			Specifications permit, but no fly ash used to date.
				Region 10			
Alaska							No fly ash used - no specifications.
Idaho	Agency	20	NR	PM	Random	All	Specifications permit but no fly ash used to date.
Oregon	Agency	20	1.1 - 1.25	PM	100 yd^3	All	No air control problems - LOI 1.5% max specified.
Washington	Contractor	20	1.1 - 1.25	PM	Random	WR, Ret.	No air control problems - LOI 1.5% max specified.

TABLE B-3 CONTROL PROCEDURES FOR FLY ASH CONCRETE (PART 3) (Continued)

State	Mix Design By:	Cement Replaced (%)	Fly Ash Added[ab]	Entrained Air: Test Procedure[c]	Entrained Air: Frequency of Tests[d]	Additional Admixtures Permitted[e]	Comments
Canadian Provinces							
Alberta							No fly ash permitted - ongoing research.
New Brunswick	Agency						No fly ash used to date.
Nova Scotia	Agency	25					Experimental use only.
Ontario							Suitable fly ash not available - would try if offered by industry.
Saskatchawan							Procedures not established - fly ash seldom used.

[a]Ratio of parts by weight of fly ash to cement replaced.
[b]NR = not reported.
[c]PM = pressure meter; C = Chace; VOL. = volumetric.
[d]EL = each load.
[e]WR = water reducers, Ret. = retarders, All = no restrictions in specifications.

TABLE B-4 IMPLEMENTATION POTENTIAL (PART 4)

State	Advantages	Disadvantages	Information Needs
New Hampshire	Higher ultimate strength Less cost	Nonuniformity of fly ash Nonavailability of fly ash Lack of knowledge - field	Proper use; rapid quality tests; uniform test methods
New York	Reduction in alkali-aggregate reaction Better sulfate resistance Less cost	Nonuniformity of fly ash Increased testing and control	Solutions to practical problems, especially air entrainment
District of Columbia	Lower permeability Better workability especially for pumping	Plant control Increased testing Cold weather concreting	Sources, types, and amounts of fly ash available that meet ASTM specifications and procedures
Maryland	Better workability or lower w/c ratio Better pumpability	Nonuniformity of fly ash Not cost-effective Additional testing cost greater than savings	Suggested specifications and quality control programs
Pennsylvania	Lower permeability - less corrosion, less leaching Less cost Better sulfate resistance Higher ultimate strength	Reluctance to use the unfamiliar	No comment
Virginia	Better sulfate resistance Better durability Less cost Lower heat of hydration	Control of air content Nonavailability of fly ash Low early strength Not always cost-effective	
West Virginia	Less cost Lower heat of hydration Better workability	No comment	Use of fly ash in structures
Florida	Lower heat of hydration Better sulfate resistance Less cost	Nonuniformity of fly ash Control of air content Compatibility with chemical admixtures	No comment

TABLE B-4 IMPLEMENTATION POTENTIAL (PART 4) (Continued)

State	Advantages	Disadvantages	Information Needs
Georgia	Less cost Better workability Higher ultimate strength	None	Substitution rates used by other agencies
Kentucky	Less cost Better sulfate resistance Lower heat of hydration	No comment	No comment
Mississippi	Better sulfate resistance Higher ultimate strength	Nonuniformity of fly ash Lower early strengths Lack of knowledge - field Nonavailability of fly ash	Rapid sulfate resistance tests; how to control mixes with nonuniform fly ash
North Carolina	Lower heat of hydration Use of waste product to save resources Better workability Less cost	Control of air content Nonuniformity of fly ash	Other states' specifications for fly ash, experience, and test data
South Carolina	Better sulfate resistance Lower heat of hydration	Nonuniformity of fly ash Increased testing and control Lack of knowledge - field Not cost-effective	Specific effects of fly ash variability on concrete durability
Tennessee	Less cost Better workability Lower water requirements Higher ultimate strength	Increased testing and control Lack of knowledge - field Nonuniformity of fly ash Not always cost-effective	How testing and quality control are handled routinely; control of air content in FAC
Illinois	Better workability Less cost	Increased testing and control	Admixture interactions; aggregate/ash interactions; accelerators for fly ash reactions
Indiana	Satisfies EPA-FHWA requirements	Control of air content Lack of experience Not cost-effective	Types of air entraining agents that work better than Vinsol resin
Michigan	Less cost Better consolidation with crushed concrete as aggregate	Nonavailability of fly ash Control of air content Nonuniformity of fly ash	Specific requirements for Type F and Type C fly ashes and recommended mixes for each

TABLE B-4 IMPLEMENTATION POTENTIAL (PART 4) (Continued)

State	Advantages	Disadvantages	Information Needs
Michigan (cont.)	Lower heat of hydration	Differences in activity of different fly ashes Differences in performance with different cements	
Minnesota	Less cost Better workability Longer set times in hot weather Reduced "D" cracking	Control of air content	No comment
Ohio	Less cost, if true lower heat of hydration Utilization of waste product	Increased testing and control	No comment
Wisconsin	Less cost Better workability Energy savings Lower heat of hydration	Increased testing and control Nonavailability of fly ash Nonuniformity of fly ash	Means and specifications to ensure quality and uniformity
Arkansas	Less cost Lower heat of hydration Better durability Utilization of by-product	Lack of knowledge - field Nonuniformity of fly ash Increased testing and control	Information on field testing and quality control; experience in use for bridge foundations and substructures
Louisiana	Better workability Higher ultimate strength Lower heat of hydration	Danger of alkali reaction Nonuniformity of fly ash Increased testing and control Cost-effectiveness	Correlation of field performances and variation in chemical composition of fly ash
New Mexico	Reduction in alkali-aggregate reaction	Lack of knowledge - field Non uniformity of fly ash	No comment
Oklahoma	Possibly less cost Higher ultimate strength Better workability Longer set time in hot weather	Increased testing and control Lack of knowledge - field Nonuniformity of fly ash	Guidance in establishing acceptance program for user and quality control for supplier
Iowa	Less cost Better sulfate resistance Better workability Lower water demand	Lower frost resistance with some aggregates Increased testing and control	General information regarding use and reasons for restrictions

TABLE B-4 IMPLEMENTATION POTENTIAL (PART 4) (Continued)

State	Advantages	Disadvantages	Information Needs
Missouri	Less cost	Potential decrease in durability Possible delayed alkali-aggregate reaction Questions concerning adequacy of current specifications Increased testing and quality control	Information on quality control and quick reliable tests for potential concrete durability problems
Colorado	Less cost Reduction in alkali-aggregate reactivity	Nonuniformity of fly ash Lack of knowledge - field	No comment
North Dakota	Less cost	Increased testing and control	No comment
Utah	Reduction in alkali-aggregate reactivity Satisfies EPA-FHWA requirements	Lack of knowledge - field Lack of testing equipment by small cities and counties	Use of Type F in flat work; types of admixture and relative performance with fly ash
Arizona	Less cost Lower heat of hydration Better sulfate resistance Better workability	Complicates mix design Additional silo - uneconomical No field test for fly ash content	Sulfate resistance of Type C fly ashes
California	Reduction of alkali-aggregate reaction Lower heat of hydration Better sulfate resistance	Not cost-effective Low early strength and abrasion resistance Increased testing and control Control of air content	Conclusive evidence that fly ash reduces alkali-aggregate reactivity; evidence that long-term creep is negligible in FAC; evidence that fly ash is not a health hazard
Hawaii	Lower heat of hydration Higher ultimate strength	Nonavailability of fly ash Increased testing and control Lack of knowledge - field	No comment
Idaho	No comment	No comment	States that have used fly ash that may be used in Idaho
Oregon	Less cost Better workability Higher ultimate strength Lower heat of hydration	Lack of knowledge Nonuniformity of fly ash Increased testing and control Need for additional storage silo on project	Uses and limitations; specifications and testing requirements

TABLE B-4 IMPLEMENTATION POTENTIAL (PART 4) (Continued)

State	Advantages	Disadvantages	Information Needs
Washington	Satisfies EPA-FHWA requirements Less cost (more competitive bidding) Better workability	Lack of knowledge - field Variable reactions with different cements	No comment
Saskatchewan	Less cost Lower heat of hydration Improved durability	Lack of knowledge Increased testing and control	Mix design methods; analysis of fly ashes that are known to work well
New Brunswick	No comment	Lack of knowledge	Agencies using fly ash; successes or failures with fly ash; specifications used
Ontario	No comment	Nonavailability of fly ash Not cost-effective	No comment

LETTER SENT TO TRANSPORTATION AGENCIES IN THE UNITED STATES AND CANADA

Dear

The Transportation Research Board is preparing a synthesis on "Use of Fly Ash in Concrete." This a a part of the AASHTO-sponsored NCHRP Project 20-5 "Synthesis of Information Related to Highway Problems." This synthesis is being done by Woodrow Halstead and will report on the advantages and disadvantages of fly ash use in concrete.

In order to provide a document with the maximum benefit to our sponsors it is important that the current status of fly ash use by transportation agencies be surveyed. Woody prepared the attached Survey of Practice to aid in the collection and organization of data. He will appreciate your prompt completion of the survey, hopefully by May 31, 1985 or as soon as possible thereafter.

We appreciate your assistance with this synthesis effort.

Sincerely,

Thomas L. Copas, P.E.
Special Projects Engineer

Attachment

SURVEY OF PRACTICE

NCHRP Project 20-5
Topic 16-07

"Use of Fly Ash in Concrete"

PART 1 - GENERAL UTILIZATION

1.1 Please check the appropriate spaces and provide rough estimates of the amounts of fly ash concrete (FAC) used for the various applications.

Specific Application	Is Use of Fly Ash						Approximate Amt. FAC Used Since 1978 - Yd^3			
							Class F		Class C	
	Required	Permitted	Prohibited	Increasing	Decreasing	Constant	Experi-mental	Routine	Experi-mental	Routine
Pavements										
Bridge Decks										
Curbs - Gutters										
Foundation										
Medium Barriers										
Other (State type of use)										
( )										
( )										
( )										
Comments: ______										

1.2 When permitted, is the use of fly ash as an admixture at the option of the contractor ______ or the agency ______? (Check which.)

1.3 Are types IP and I(PM) cements permitted as an alternative to portland cement? Yes ______ No ______

1.4 If yes what is the extent of use? No use _____ Seldom _____ Frequent _____

PART 2 - SPECIFICATIONS AND CONTROL PROCEDURES FOR FLY ASH

(If available, copies of appropriate sections of standard specifications or special provisions pertaining to use of fly ash in concrete would be appreciated.)

2.1 What specification do you use for fly ash?

ASTM C628 _____

AASHTO M295 _____

Other _____

(Provide copy if possible)

2.2 What procedures do you use for acceptance of fly ash?

Pre-approved source	Yes ____	No ____
Supplier certification	Yes ____	No ____
Agency tests for compliance	Yes ____	No ____

2.3 What tests are made by your agency? ______________________________

____

____

____

2.4 What is the frequency of such tests? ______________________________

____

____

____

PART 3 - SPECIFICATIONS AND CONTROL PROCEDURES FOR FLY ASH CONCRETE (FAC)

3.1 Who establishes mix design?

Contractor (or concrete producer) ____

Highway agency ____

3.2 How is the amount of fly ash to be used determined? (check boxes that apply)

3.2.1 Replacement for portion of the cement in previously designed mix? ____

3.2.1.1 Replacement on basis of _______ parts of fly ash to one part of cement by volume _____ mass (wt) _____

3.2.2 Fly ash added as additional ingredient without reducing cement. ____

3.2.3 Fly ash concrete mix designed for optimum characteristics without regard to "reduction" of portland cement content ____

3.3 When the replacement procedure is used, what is the maximum amount of portland cement that can be replaced? _____ percent

3.4 What test procedure is used to determine the entrained air content of FAC?

_________ Air pressure meter ________Chace

_________ Other (please state)

3.5 When difficulties are experienced with air entrainment, does the use of additional air-entraining agent provide uniform results ____ or give erratic behavior ____? (check which)

3.6 Are problems encountered from loss of entrained air during transit? Yes ____ No ____

3.7 How frequently are tests for entrained air made? each load ____; one each ____ loads (give number); randomized testing ____? State basis of randomization

____

____

____

3.8 Have you observed a maximum loss on ignition for fly ash below which difficulties in air entrainment are not encountered? Yes ____ No ____

Comment: ____

____

____

____

3.9 What additive(s) does your state allow to be used in fly ash concrete other than air-entraining agents? (water-reducers, retarders, accelerators, etc.)

____

____

____

____

3.10 What problems or advantages have been associated with the use of additives other than air-entraining agents in fly ash concrete?

____

____

____

____

3.11 Have you recorded any lower strength gains in the early strength of FAC concrete? Yes ____ No ____

3.12 Do your requirements for strength of FAC differ in any respect from the strength requirements for other hydraulic cement concretes? Yes ____ No ____

If yes please state differences

____

____

____

____

3.13 Is there a need for new or improved standards for fly ashes or blended cements containing fly ash? Yes ____ No ____. If yes please indicate needed changes.

____

____

____

____

PART 4 - IMPLEMENTATION POTENTIAL AND DRAWBACKS

4.1 List in order of importance what you consider the advantages to your agency in using fly ash concrete. (For example - less cost, greater sulfate resistance, higher ultimate strength, lower heat of hydration, etc.)

1 ____________________

____

2 ____________________

____

3 ____________________

____

4 ____________________

____

4.2 List in order of importance the negative factors relating to use of fly ash concrete (For example - increased testing and control problems, lack of knowledge by field personnel, overall cost-effectiveness, availability of fly ash, uniformity of fly ash, alkali aggregate reaction, etc.)

1 ____________________

____

2 ____________________

____

3 ____________________

____

4 ____

____

4.3 What type of information in the synthesis would be of the greatest assistance to your agency? Please add any additional comments you care to make.

____

____

____

____

____

Who is the person to contact for additional information, if needed.

Name ______________________________

Title ______________________________

Phone no. ______________________________

PLEASE MAIL THE COMPLETED QUESTIONNAIRE TO:

Woodrow J. Halstead
Route 3, Box 351
Palmyra, Virginia 22963

APPENDIX C

AMERICAN COAL ASH ASSOCIATION GUIDELINES FOR A FLY ASH QUALITY PROGRAM

AMERICAN COAL ASH ASSOCIATION
GUIDELINES FOR A
FLY ASH QUALITY PROGRAM
MARCH, 1986

I. Specification Limits

A. Fly ash must meet current ASTM C 618 physical and chemical requirements (optional requirements applicable only when requested by purchaser).

1. Density Uniformity --
As according to ASTM C 618, an individual value shall not vary by more than 0.10 Mg/m^3 from the moving average established by the 10 preceding results.

2. 45-µm (No. 325) Sieve Residue Uniformity --
As according to ASTM C 618, an individual value for percent retained shall not vary by more than 5% retained from a moving average established by the 10 preceding results.

B. LOI (Carbon) Uniformity -- Applicable to air-entrained concrete only. An individual value shall not vary by more than 1.5% LOI (or C) from a moving average established by the 10 preceding results (e.g., moving average = 3% LOI, then LOI can't exceed 4.5% or be less than 1.5% for next individual value). Note: If variations greater than 1.5% from the moving average do not cause a change in the required air-entraining admixture dosage, such variations need not be cause for rejection.

II. Pre-Qualification

Each fly ash from a particular power plant and made available for sale, must be pre-qualified before use in portland-cement concrete. At least six months of test results shall be included in the quality history of a new source.

A. An ASTM C 618 certification at least once per month shall be included in the quality history.

B. A quality history also shall include at least 40 of the most recent individual test results, no greater than 2 years old, for each of the following: LOI (or carbon) 45-µm (No. 325) sieve residue, and density.

C. If the fly ash (individual values) meets the C 618 specification limits and the uniformity requirements given above, the fly ash is pre-qualified. This pre-qualification continues, provided the test data required in III(A) continues to meet or exceed specification and uniformity limits.

III. Post-Qualification

A. Once a fly ash is pre-qualified, a quality control program is set up to test the most significant fly ash parameters during the course of the project. At a minimum, each fly ash shall be tested daily for LOI (or carbon) and 45µm (No. 325) sieve residue. If all LOI (C) test values are below 1%, test LOI according to C 311 frequency. Density shall be tested according to C 311 frequency or weekly, whichever is more frequent.

B. A complete C 618 is performed according to C 311 frequency or monthly, whichever is more frequent (optional requirements applicable as requested by buyer).

C. The quality control data records shall be made accessible to the purchaser.

IV. Qualification of the Lab Performing the Tests

A. Each laboratory testing for the required complete C 618 shall comply with the applicable provisions of ASTM E 329 which require laboratory inspection by a qualified national authority.

APPENDIX D

FHWA MATERIALS NOTEBOOK SECTION 5-4-6

Memorandum

U.S. Department
of Transportation

Federal Highway Administration
Washington, D.C. 20590

Subject: Use of Fly Ash in Concrete

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From: Director, Office of Highway Operations

Reply to Attn. of: HHO-33

To: Regional Federal Highway Administrators
Regions 1-10
Direct Federal Program Administrator

The attached is Section 5-4-6 of the Materials Notebook which concerns the use of fly ash in portland cement concrete. The Materials Notebook will be issued in final form in July. Section 5-4-6 is being issued at this time due to the issuance of EPA guidelines on the subject.

This section covers fly ash properties, substitution ratios, replacement percentages, blended cements, and acceptance procedures for fly ash and mix design procedures. It is suggested that this section be provided to the division offices and State highway departments for their use in developing the specification for allowing the substitution of fly ash for cement in portland cement concrete.

The Geotechnical and Materials Branch is available for technical assistance in developing specifications. To request technical assistance or if there are any questions or comments concerning the attached information, please call Mr. Michael Rafalowski at FTS 426-0436.

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Attachment

U. S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

5	PORTLAND CEMENT CONCRETE
4	ADMIXTURES
6	FLY ASH

1. BACKGROUND.

The following is guidance for the substitution of fly ash for cement in portland cement concrete. This is in response to the EPA guidelines on the use of fly ash in concrete.

Five topics are discussed: fly ash - general properties; fly ash - requirements; mix design procedures; blended cements; and exemptions.

2. FLY ASH - GENERAL PROPERTIES.

Fly ash is a pozzolanic material. A pozzolan by itself has little or no cementing properties but in the presence of lime and moisture has cementing properties. Three types of pozzolans are listed in ASTM C-618 and AASHTO M-295. Class "N" is a naturally occurring material. Classes "C" and "F" are fly ashes that are produced from burning coal. These fly ash classes, "C" and "F," will be discussed in length.

Fly ash is a finely divided residue that results from the combustion of ground or powdered coal. The properties of fly ash depend on the coal that was burned and the power plant operations. Class "C" fly ash is typically produced from lignite or subbituminous coal. This material has free lime which gives it cementing properties of its own. Class "F" fly ash is typically produced from anthracite or bituminous coal. This fly ash depends on the free lime in the cement for its cementing properties.

Fly ash which is produced at base loaded electric generating plants is usually very uniform. The base loaded plants are those plants that operate continuously. The only exception to this uniformity is in the start-up and the shut-down of the plant. Contamination may occur from using other fuel to start the plant, and an inconsistency in carbon content occurs until the plant reaches full operating efficiency. The ash produced from the start-up and shut-down must be separated from that which is produced when the plant is running efficiently. In addition, when sources of coal are changed, it is necessary to separate the two fly ashes. Peak load plants are subjected to many start-up and shut-down cycles. Because of this, these plants may not produce much uniform fly ash.

The two properties of fly ash that are of most concern are the carbon content and the fineness. Both of these properties will affect the air content and water demand of the concrete.

The finer the material the higher the water demand due to the increase in surface area. The finer material requires more air-entraining agent to give the mix the desired air content. The important thing to remember is uniformity. If the fly ash is uniform in size, the mix design can be adjusted to give a good uniform mix.

The carbon content, which is indicated by the loss on ignition, also affects the air entraining agents and reduces the entrained air for a given amount of air-entraining agent. An additional amount of air-entraining agent will need to be added to get the desired air content. The carbon content will also affect water demand since the carbon will absorb water. Again uniformity is important since the differences from non-fly ash concrete can be adjusted in the mix design.

The use of fly ash in concrete will result in a more workable mix. This is due to the fineness of the material and its almost spherical shape.

Fly ash will also reduce bleeding. This is again due to its fineness. The use of fly ash will also reduce the permeability of the concrete. The by-product of the pozzalanic activity reduces the permeability of the concrete.

Some fly ash will also reduce the alkali-reactive aggregate reaction.

3. FLY ASH - REQUIREMENTS.

A. Discussion.

1) Specifications.

As stated earlier, there are currently two existing specifications for pozzolanic material, AASHTO M-295 and ASTM C-618. The following is a comparison of major differences between the two specifications.

	ASTM	AASHTO
Loss on Ignition		
- Class "N"	10%	5%
- Class "C"	6%	5%
- Class "F"	6%	5%
Pozzolanic Activity Index, minimuim % of Control with Cement	75% at 28 days	60% at 7 days
Available Alkalies, 1.5 Percent	Optional	Requirement
Water Requirement, Maximum Percent of Control		
- Class "N"	115	100
- Class "C"	105	100
- Class "F"	105	100

Currently most State highway agencies are specifying fly ash using ASTM C-618 with the exception of the requirement on loss on ignition (LOI). Most States are currently specifying a maximum LOI of 5 percent.

2) Acceptance Requirements.

The standard method for sampling and testing fly ash is contained in ASTM C-311. The same procedure is listed in AASHTO M-295.

The procedure calls for a sampling frequency of one sample for each 400 tons of fly ash. This would amount to one test for 7,000 cubic yards of concrete, if the fly ash replaces 20 percent of the cement in a six-bag mix on a ratio of 1 pound of fly ash to 1 pound of cement.

Most States that are currently using fly ash have used approved sources and certification programs with check tests. The frequency of the check tests are either one every 100-500 tons or one per shipment.

The State needs to insure that the fly ash is of uniform consistency. This will result in a concrete with uniform properties.

B. Recommendations.

1) The standard specifications for fly ash (ASTM C-618 or AASHTO M-295) should be used. The included optional specification for uniformity as described below should also be required. This concerns the variation in the amount of air-entraining agent to maintain an 18 percent air content in the mortar. A maximum variation in the amount of air entraining agent of 20 percent is specified.

2) The State highway agencies should develop certification programs similar to those in existence for portland cement. This program should include testing by the supplier with check tests on grab samples taken by the agency. The plan should also require that the supplier's laboratory participate in the Cement and Concrete Reference Laboratory (CCRL) program which includes inspection of facilities and testing of comparative samples.

Until the certification programs are in place, it is suggested that the States test the fly ash and use sealed silos and transports. Five tests per silo should be run to insure uniformity of the fly ash. Once uniformity of a source is established, sampling could be reduced to one per 400 tons as specified in ASTM C-311. It is recommended that 10,000 tons of fly ash be tested before reducing the testing frequency.

3) It is also recommended that the air content of each load of concrete be monitored at least in the beginning of production. This would indirectly monitor the uniformity of the fly ash.

4. MIX DESIGN PROCEDURES.

A. Discussion.

1) Rate of Substitution.

The substitution rate of fly ash for portland cement will vary depending upon the chemical composition of both the fly ash and the portland cement. The rate of substitution typically specified is a minimum of 1 to 1-1/2 pounds of fly ash to 1 pound of cement. It should be noted that the amount of fine aggregate will have to be reduced to accommodate the additional volume of fly ash. This is due to the fly ash being lighter than the cement.

2) Amount of Substitution.

The amount of substitution is also dependent on the chemical composition of the fly ash and the portland cement. Currently, States allow a maximum substitution in the range of 15 to 25 percent.

3) Time Of Set.

The use of fly ash will affect the time of set. Both classes of fly ash will extend the set time from 2 to 4 hours and will vary from fly ash source to fly ash source. The set time can be controlled by using accelerators.

B. Recommendations.

1) Specifications should contain strength requirements with minimum substitution ratio and maximum replacement. This would allow maximum substitution without sacrificing strength. The water cement ratio should be based on the total cementious materials, i.e., the portland cement plus the fly ash substituted.

2) Substitution ratios of a minimum of 1 to 1 on a mass basis with a maximum substitution should be specified. A substitution rate of 15 to 25 percent is currently being specified for typical concrete production. These values should be established based on the actual fly ashes and portland cements that are available.

3) Mix designs should be performed by the State on each combination of materials, or by the contractor with the requirement to provide the test data to the State for verification with trial batches.

Since the chemical composition of fly ashes and portland cements vary considerably, substantial problems could result if fixed rates and percentages of substitutions are used for all combinations of fly ashes and cements.

5. BLENDED CEMENTS.

The following will discuss only the Type "IP," Type "P," and Type "I (PM)" cements. The specifications for these cements are in AASHTO M-240 and ASTM C-595.

Blended cements can be manufactured by either intimate blending of portland cement and pozzolan or intergrinding of the pozzolan with the cement clinker in the kiln. Type "I" (PM) (pozzolan modified cement) allows up to 15 percent replacement of cement with fly ash. The Type "IP" and Type "P" are pozzolan-modified portland cements which allow 15-40 percent replacement with pozzolans. The differences in the two types of cements is in the ultimate strength and the rate of strength gain of the concretes. Most States specify limits on the pozzolanic content on Type "IP" cement. These limits are between 15 and 25 percent.

6. EXEMPTIONS.

The EPA guideline on the substitution of fly ash requires the State highway agency to document the reasons for not allowing the substitution of fly ash for cement if it feels that it is technically inappropriate. The following two cases will not require documentation.

A. Fly ash should not be substituted for a portion of Type "IP," Type "I" (PM), or Type "P."

B. Substitution should not be specified for high early strength concrete. In this case, concrete that contains fly ash gains strength slower so it would not be capable of having high early strength.