Fly Ash Facts for Highway Engineers

Course No: T06-003

Credit: 6 PDH

Mark Rossow, PhD, PE, Retired

Continuing Education and Development, Inc.
9 Greyridge Farm Court
Stony Point, NY 10980

P: (877) 322-5800
F: (877) 322-4774

info@cedengineering.com

Report No.

FHWA-IF-03-019

Title

Fly Ash Facts for Highway Engineers

Report Date

06-13-2003

Authors

American Coal Ash Association

Performing Organization

American Coal Ash Association
15200 East Girard Avenue, Suite 3050
Aurora, CO 80014

Contract No.

DTHF61-02-X-00044

Sponsoring Agency

Federal Highway Administration
400 7th Street, SW
Washington, DC 20590

PREFACE

Coal fly ash is a coal combustion product that has numerous applications in highway construction. Since the first edition of Fly Ash Facts for Highway Engineers in 1986, the use of fly ash in highway construction has increased and new applications have been developed. This document provides basic technical information about the various uses of fly ash in highway construction.

Fly ash has been used in roadways and interstate highways since the early 1950s. In 1974, the Federal Highway Administration encouraged the use of fly ash in concrete pavement with Notice N 5080.4, which urged states to allow partial substitution of fly ash for cement whenever feasible. In addition, in January 1983, the Environmental Protection Agency published federal comprehensive procurement guidelines for cement and concrete containing fly ash to encourage the utilization of fly ash and establish compliance deadlines.

This document is sponsored by the U.S. Department of Transportation, through the Federal Highway Administration, in cooperation with the American Coal Ash Association and the United States Environmental Protection Agency. The United States Government assumes no liability for its contents or use. The Federal Highway Administration endorses no products or manufacturers. This publication does not constitute a standard, specification, or regulation.

The United States Environmental Protection Agency supports the beneficial use of coal combustion products as an important priority and endorses efforts by the Federal Highway Administration as described in this document.

CONTENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER.1

FLY ASH - AN ENGINEERING MATERIAL

WHY FLY ASH?

What is fly ash? Fly ash is the finely divided residue that results from the combustion of pulverized coal and is transported from the combustion chamber by exhaust gases. Over 61 million metric tons (68 million tons) of fly ash were produced in 2001.

Where does fly ash come from? Fly ash is produced by coal-fired electric and steam generating plants. Typically, coal is pulverized and blown with air into the boiler's combustion chamber where it immediately ignites, generating heat and producing a molten mineral residue. Boiler tubes extract heat from the boiler, cooling the flue gas and causing the molten mineral residue to harden and form ash. Coarse ash particles, referred to as bottom ash or slag, fall to the bottom of the combustion chamber, while the lighter fine ash particles, termed fly ash, remain suspended in the flue gas. Prior to exhausting the flue gas, fly ash is removed by particulate emission control devices, such as electrostatic precipitators or filter fabric baghouses (see Figure 1-1).

Where is fly ash used? Currently, over 20 million metric tons (22 million tons) of fly ash are used annually in a variety of engineering applications. Typical highway engineering applications include: portland cement concrete (PCC), soil and road base stabilization, flowable fills, grouts, structural fill and asphalt filler.

What makes fly ash useful? Fly ash is most commonly used as a pozzolan in PCC applications. Pozzolans are siliceous or siliceous and aluminous materials, which in a finely divided form and in the presence of water, react with calcium hydroxide at ordinary temperatures to produce cementitious compounds.

The unique spherical shape and particle size distribution of fly ash make it a good mineral filler in hot mix asphalt (HMA) applications and improves the fluidity of flowable fill and grout. The consistency and abundance of fly ash in many areas present unique opportunities for use in structural fills and other highway applications.

Environmental benefits. Fly ash utilization, especially in concrete, has significant environmental benefits including: (1) increasing the life of concrete roads and structures by improving concrete durability, (2) net reduction in energy use and greenhouse gas and other adverse air emissions when fly ash is used to replace or displace manufactured cement, (3) reduction in amount of coal combustion products that must be disposed in landfills, and (4) conservation of other natural resources and materials.

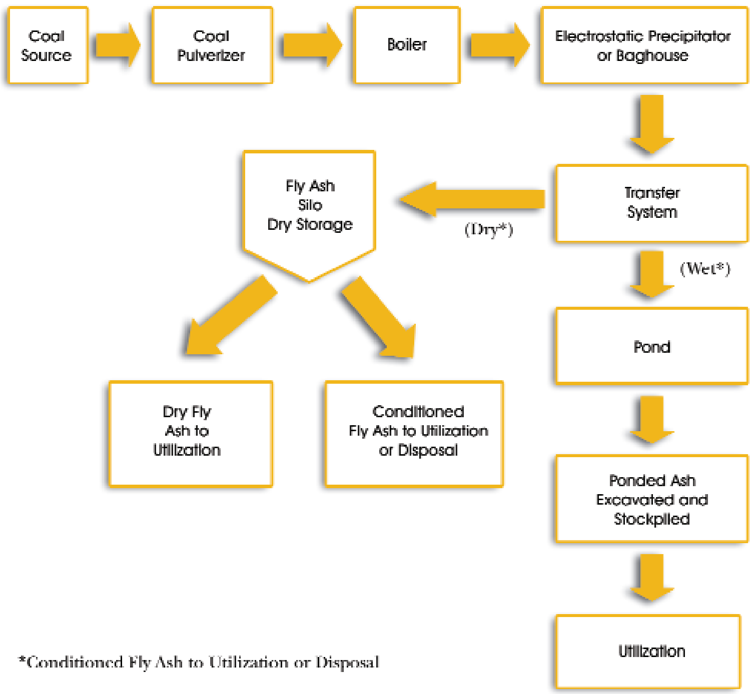

Figure1-1. Method of fly ash transfer can be dry, wet or both.

PRODUCTION

Fly ash is produced from the combustion of coal in electric utility or industrial boilers. There are four basic types of coal-fired boilers: pulverized coal (PC), stoker-fired or traveling grate, cyclone, and fluidized-bed combustion (FBC) boilers. The PC boiler is the most widely used, especially for large electric generating units. The other boilers are more common at industrial or cogeneration facilities. Fly ashes produced by FBC boilers are not considered in this document. Fly ash is captured from the flue gases using electrostatic precipitators (ESP) or in filter fabric collectors, commonly referred to as baghouses. The physical and chemical characteristics of fly ash vary among combustion methods, coal source, and particle shape.

	Million Metric Tons	Million Short Tons	Percent
Produced	61.84	68.12	100.0
Used	19.98	22.00	32.3

Table 1-1. 2001 Fly ash production and use.

As shown in Table 1-1, of the 62 million metric tons (68 million tons) of fly ash produced in 2001, only 20 million metric tons (22 million tons), or 32 percent of total production, was used. The following is a breakdown of fly ash uses, much of which is used in the transportation industry.

	Million Metric Tons	Million Short Tons	Percent
Cement/Concrete	12.16	13.40	60.9
Flowable Fill	0.73	0.80	3.7
Structural Fills	2.91	3.21	14.6
Road Base/Sub-base	0.93	1.02	4.7
Soil Modification	0.67	0.74	3.4
Mineral Filler	0.10	0.11	0.5
Mining Applications	0.74	0.82	3.7
Waste Stabilization/Solidification	1.31	1.44	6.3
Agriculture	0.02	0.02	0.1
Miscellaneous/Other	0.41	0.45	2.1
Totals	19.98	22.00	100

Table 1-2. Fly ash uses

HANDLING

The collected fly ash is typically conveyed pneumatically from the ESP or filter fabric hoppers to storage silos where it is kept dry pending utilization or further processing, or to a system where the dry ash is mixed with water and conveyed (sluiced) to an on-site storage pond.

The dry collected ash is normally stored and handled using equipment and procedures similar to those used for handling portland cement:

- Fly ash is stored in silos, domes and other bulk storage facilities
- Fly ash can be transferred using air slides, bucket conveyors and screw conveyors, or it can be pneumatically conveyed through pipelines under positive or negative pressure conditions
- Fly ash is transported to markets in bulk tanker trucks, rail cars and barges/ships
- Fly ash can be packaged in super sacks or smaller bags for specialty applications

Dry collected fly ash can also be moistened with water and wetting agents, when applicable, using specialized equipment (conditioned) and hauled in covered dump trucks for special applications such as structural fills. Water conditioned fly ash can be stockpiled at jobsites. Exposed stockpiled material must be kept moist or covered with tarpaulins, plastic, or equivalent materials to prevent dust emission.

CHARACTERISTICS

Size and Shape. Fly ash is typically finer than portland cement and lime. Fly ash consists of silt-sized particles which are generally spherical, typically ranging in size between 10 and 100 micron (Figure 1-2). These small glass spheres improve the fluidity and workability of fresh concrete. Fineness is one of the important properties contributing to the pozzolanic reactivity of fly ash.

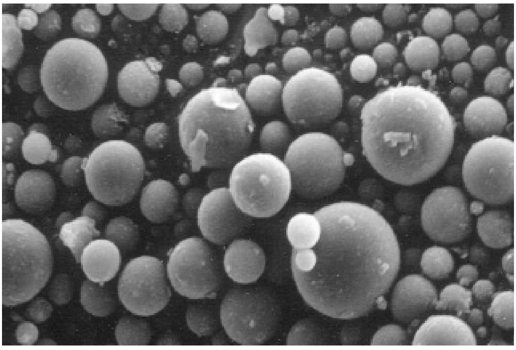

Figure 1-2. Fly ash particles at 2,000x magnification.

Chemistry. Fly ash consists primarily of oxides of silicon, aluminum iron and calcium. Magnesium, potassium, sodium, titanium, and sulfur are also present to a lesser degree.

When used as a mineral admixture in concrete, fly ash is classified as either Class C or Class F ash based on its chemical composition. American Association of State Highway Transportation Officials (AASHTO) M 295 [American Society for Testing and Materials (ASTM) Specification C 618] defines the chemical composition of Class C and Class F fly ash.

Class C ashes are generally derived from sub-bituminous coals and consist primarily of calcium alumino-sulfate glass, as well as quartz, tricalcium aluminate, and free lime (CaO). Class C ash is also referred to as high calcium fly ash because it typically contains more than 20 percent CaO.

Class F ashes are typically derived from bituminous and anthracite coals and consist primarily of an alumino-silicate glass, with quartz, mullite, and magnetite also present. Class F, or low calcium fly ash has less than 10 percent CaO.

Compounds	Fly Ash Class F	Fly Ash Class C	Portland Cement
SiO_2	55	40	23
Al_2O_3	26	17	4
Fe_2O_3	7	6	2
CaO (Lime)	9	24	64
MgO	2	5	2
SO_3	1	3	2

Table 1-3. Sample oxide analyses of ash and portland cement

Color. Fly ash can be tan to dark gray, depending on its chemical and mineral constituents. Tan and light colors are typically associated with high lime content. A brownish color is typically associated with the iron content. A dark gray to black color is typically attributed to an elevated unburned carbon content. Fly ash color is usually very consistent for each power plant and coal source.

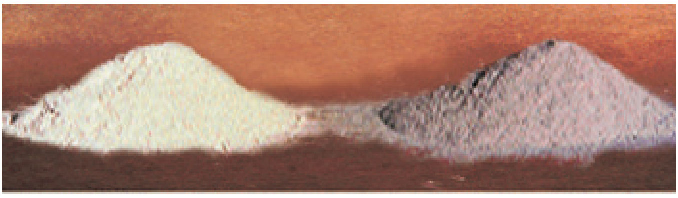

Figure 1-3. Typical ash colors.

QUALITY OF FLY ASH

Quality requirements for fly ash vary depending on the intended use. Fly ash quality is affected by fuel characteristics (coal), co-firing of fuels (bituminous and sub-bituminous coals), and various aspects of the combustion and flue gas cleaning/collection processes. The four most relevant characteristics of fly ash for use in concrete are loss on ignition (LOI), fineness, chemical composition and uniformity.

LOI is a measurement of unburned carbon (coal) remaining in the ash and is a critical characteristic of fly ash, especially for concrete applications. High carbon levels, the type of carbon (i.e., activated), the interaction of soluble ions in fly ash, and the variability of carbon content can result in significant air-entrainment problems in fresh concrete and can adversely affect the durability of concrete. AASHTO and ASTM specify limits for LOI. However, some state transportation departments will specify a lower level for LOI. Carbon can also be removed from fly ash.

Some fly ash uses are not affected by the LOI. Filler in asphalt, flowable fill, and structural fills can accept fly ash with elevated carbon contents.

Fineness of fly ash is most closely related to the operating condition of the coal crushers and the grindability of the coal itself. For fly ash use in concrete applications, fineness is defined as the percent by weight of the material retained on the 0.044 mm (No. 325) sieve. A coarser gradation can result in a less reactive ash and could contain higher carbon contents. Limits on fineness are addressed by ASTM and state transportation department specifications. Fly ash can be processed by screening or air classification to improve its fineness and reactivity.

Some non-concrete applications, such as structural fills are not affected by fly ash fineness. However, other applications such as asphalt filler, are greatly dependent on the fly ash fineness and its particle size distribution.

Chemical composition of fly ash relates directly to the mineral chemistry of the parent coal and any additional fuels or additives used in the combustion or post-combustion processes. The pollution control technology that is used can also affect the chemical composition of the fly ash. Electric generating stations burn large volumes of coal from multiple sources. Coals may be blended to maximize generation efficiency or to improve the station environmental performance. The chemistry of the fly ash is constantly tested and evaluated for specific use applications. Some stations selectively burn specific coals or modify their additives formulation to avoid degrading the ash quality or to impart a desired fly ash chemistry and characteristics.

Uniformity of fly ash characteristics from shipment to shipment is imperative in order to supply a consistent product. Fly ash chemistry and characteristics are typically known in advance so concrete mixes are designed and tested for performance.

ACI 229R	Controlled Low Strength Material (CLSM)
ASTM C 311	Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete
AASHTO M 295 ASTM C 618	Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
ASTM C 593	Fly Ash and Other Pozzolans for Use With Lime
ASTM D 5239	Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization
ASTM E 1861	Guide for the Use of Coal Combustion By-Products in Structural Fills

Table 1-4. Guidance documents used for fly ash quality assurance

Quality Assurance and Quality Control criteria vary for each use of fly ash from state to state and source to source. Some states require certified samples from the silo on a specified basis for testing and approval before use. Others maintain lists of approved sources and accept project suppliers' certifications of fly ash quality. The degree of quality control requirements depends on the intended use, the particular fly ash, and its variability. Testing requirements are typically established by the individual specifying agencies.

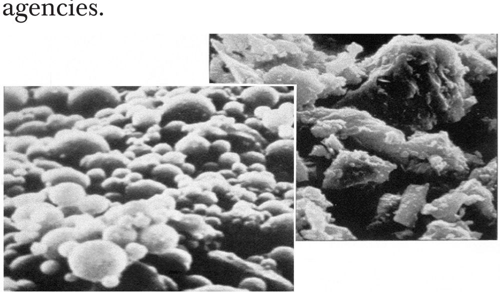

Figure 1-4. Microscopic photographs of fly ash (left) and portland cement (right).

AASHTO M 295 (ASTM C 618) - Classes F and C

Chemical Requirements		**Class F**	**Class C**
$SiO_2 + Al_2O_3 + Fe_2O_3$	min %	70	50
SiO_3	max %	5	5
Moisture Content	max %	3	3
Loss on Ignition (LOI)	max %	5[1]	5[1]
Optional Chemical Requirements			
Available Alkalies	max %	1.5	1.5
Physical Requirements			
Fineness (+325 Mesh)	max %	34	34
Pozzolanic Activity/Cement (7 Days)	min %	75	75
Pozzolanic Activity/Cement (28 Days)	min %	75	75
Water Requirement	max %	105	105
Autoclave Expansion	max %	0.8	0.8
Uniformity Requirements:[2] Density	max %	5	5
Fineness	max %	5	5
Optional Physical Requirements			
Multiple Factor (LOI x Fineness)		255	--
Increase in Drying Shrinkage	max %	0.03	0.03
Uniformity Requirements: Air Entraining Agent	max %	20	20
Cement/Alkali Reaction: Mortar Expansion (14 Days)	max %	0.020	--

Table 1-5. Specifications for fly ash in PCC.

Notes:

1 ASTM requirements are six percent

2 The density and fineness of individual samples shall not vary from the average established by the 10 preceding tests, or by all preceding tests if the number is less than 10, by more than the maximum percentages indicated

CHAPTER.2

HIGHWAY APPLICATIONS

FLY ASH IN PORTLAND CEMENT CONCRETE

Overview. Fly ash is used in concrete admixtures to enhance the performance of concrete. Portland cement contains about 65 percent lime. Some of this lime becomes free and available during the hydration process. When fly ash is present with free lime, it reacts chemically to form additional cementitious materials, improving many of the properties of the concrete.

Benefits. The many benefits of incorporating fly ash into a PCC have been demonstrated through extensive research and countless highway and bridge construction projects. Benefits to concrete vary depending on the type of fly ash, proportion used, other mix ingredients, mixing procedure, field conditions and placement. Some of the benefits of fly ash in concrete:

- Higher ultimate strength
- Improved workability
- Reduced bleeding
- Reduced heat of hydration
- Reduced permeability
- Increased resistance to sulfate attack
- Increased resistance to alkali-silica reactivity (ASR)
- Lowered costs
- Reduced shrinkage
- Increased durability

Cautions. Care should be taken when using fly ash in concrete due to:

- Potential for decreased air entraining ability with high carbon fly ash may reduce durability
- Reduced early strength
- Reduced heat of hydration in colder climates

These concerns can be accommodated using proper design and construction practices. See Chapter 3 for additional information.

FLY ASH IN STABILIZED BASE COURSE

Overview. Fly ash and lime can be combined with aggregate to produce a quality stabilized base course. These road bases are referred to as pozzolanic-stabilized mixtures (PSMs). Typical fly ash contents may vary from 12 to 14 percent with corresponding lime contents of three to five percent. Portland cement may also be used in lieu of lime to increase early age strengths. The resulting material is produced, placed, and looks like cement-stabilized aggregate base

Benefits. PSM bases have advantages over other base materials:

- Use of locally available materials
- Provides a strong, durable mixture
- Lower costs
- Autogenous healing
- Increased energy efficiency
- Suitable for using recycled base materials
- Can be placed with conventional equipment

Cautions. PSM bases require attention to:

- Seasonal limitations
- Traffic loading before complete curing
- Proper sealing and protection with asphalt or other surface treatment is required to improve skid resistance

Chapter 4 provides a more thorough discussion of stabilized base course.

FLY ASH IN FLOWABLE FILL

Overview. Flowable fill is a mixture of coal fly ash, water, and portland cement that flows like a liquid, sets up like a solid, is self-leveling, and requires no compaction or vibration to achieve maximum density. In addition to these benefits, a properly designed flowable fill may be excavated later. For some mixes, an optional filler material such as sand, bottom ash, or quarry fines, is added. Flowable fill is also referred to as controlled low-strength material, flowable mortar, or controlled density fill. It is designed to function in the place of conventional backfill materials such as soil, sand, or gravel and to alleviate problems and restrictions generally associated with the placement of these materials.

The benefits of using flowable fill include:

- ➤ Allows placement in any weather, even under freezing conditions
- ➤ Achieves 100 percent density with no compactive effort
- ➤ Fills around/under structures inaccessible to conventional fill placement techniques
- ➤ Increases soil-bearing capacities
- ➤ Prevents post-fill settlement problems
- ➤ Increases the speed and ease of backfilling operations
- ➤ Decreases the variability in the density of the backfilled materials
- ➤ Improves safety at the job site and reduces labor costs
- ➤ Decreases excavation costs
- ➤ Allows easy excavation later when properly designed

Cautions. When using flowable fill, care must be taken to:

- ➤ Anchor lighter weight pipes to prevent floating
- ➤ Provide confinement before initial set of the material
- ➤ Evaluate corrosion of metal pipe at interface of soil

Chapter 5 includes a detailed discussion of flowable fill applications.

FLY ASH IN STRUCTURAL FILLS/EMBANKMENTS

Overview. Fly ash can be used as a borrow material to construct fills and embankments. When fly ash is compacted in lifts, a structural fill is constructed that is capable of supporting highway buildings or other structures. Fly ash has been used in the construction of structural fills/embankments that range from small fills for road shoulders to large fills for interstate highway embankments.

Benefits. When used in structural fills and embankments, fly ash offers several advantages over soil and rock:

- ➤ Cost-effective where available in bulk quantities
- ➤ Eliminates the need to purchase, permit, and operate a borrow pit
- ➤ Can be placed over low bearing strength soils
- ➤ Ease of handling and compaction reduce construction time and equipment costs

Cautions. Be aware that:

- State or local environmental regulations may require consideration of the potential impacts to ground water at adjoining properties
- Requires dust control and erosion prevention measures

Chapter 6 provides additional information.

FLY ASH IN SOIL IMPROVEMENT

Overview. Fly ash is an effective agent for chemical and/or mechanical stabilization of soils. Soil density, water content, plasticity, and strength performance of soils. Typical applications include: soil stabilization, soil drying, and control of shrink-swell.

Benefits. Fly ash provides the following benefits when used to improve soil conditions:

- Eliminates need for expensive borrow materials
- Expedites construction by improving excessively wet or unstable subgrade
- By improving subgrade conditions, promotes cost savings through reduction in the required pavement thickness
- Can reduce or eliminate the need for more expensive natural aggregates in the pavement cross-section

Cautions. The most important considerations for soil improvement projects are:

- The rate of the hydration reaction upon exposure to water
- Soil moisture content at the time of compaction
- Fly ash with a sulfate content greater than 10 percent may cause soils to expand more than desired
- In many cases, leaching tests may be required by local and state agencies

Soil improvement is discussed more thoroughly in Chapter 7.

FLY ASH IN ASPHALT PAVEMENTS

Overview. Fly ash can be used as mineral filler in HMA paving applications. Mineral fillers increase the stiffness of the asphalt mortar matrix, improving the rutting resistance of pavements, and the durability of the mix.

Benefits. Fly ash will typically meet mineral filler specifications for gradation, organic impurities, and plasticity. The benefits of fly ash include:

- Reduced potential for asphalt stripping due to hydrophobic properties of fly ash
- Lime in some fly ashes may also reduce stripping
- May afford a lower cost than other mineral fillers

Chapter 8 has additional information.

FLY ASH IN GROUTS FOR PAVEMENT SUBSEALING

Overview. Grouts are proportioned mixtures of fly ash, water, and other materials used to fill voids under a pavement system without raising the slabs (subsealing), or to raise and support concrete pavements at specified grade tolerances by drilling and injecting the grout under specified areas of the pavement.

Benefits. Fly ash grouts can:

- Be used to correct undermining without removing overlying pavement
- Be accomplished quickly with minimum disturbance to traffic
- Develop high ultimate strength

Cautions. Fly ash grouts:

- Require curing period before extremely heavy loading because of low early strength
- Require confinement of the grout mixture under pavement

Chapter 9 presents more information on this topic.

CHAPTER.3

FLY ASH IN PORTLAND CEMENT CONCRETE

INTRODUCTION

The use of fly ash in portland cement concrete (PCC) has many benefits and improves concrete performance in both the fresh and hardened state. Fly ash use in concrete improves the workability of plastic concrete, and the strength and durability of hardened concrete. Fly ash use is also cost effective. When fly ash is added to concrete, the amount of portland cement may be reduced.

Benefits to Fresh Concrete. Generally, fly ash benefits fresh concrete by reducing the mixing water requirement and improving the paste flow behavior. The resulting benefits are as follows:

Improved workability. The spherical shaped particles of fly ash act as miniature ball bearings within the concrete mix, thus providing a lubricant effect. This same effect also improves concrete pumpability by reducing frictional losses during the pumping process and flat work finishability.

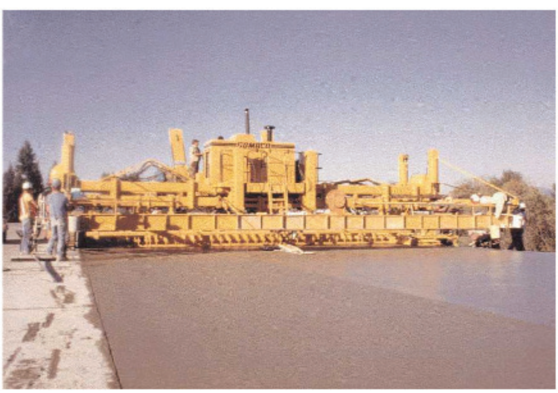

Figure 3-1. Fly ash improves workability for pavement concrete.

- **Decreased water demand.** The replacement of cement by fly ash reduces the water demand for a given slump. When fly ash is used at about 20 percent of the total cementitious, water demand is reduced by approximately 10 percent. Higher fly ash contents will yield higher water reductions. The decreased water demand has little or no effect on drying shrinkage/cracking. Some fly ash is known to reduce drying shrinkage in certain situations.

- **Reduced heat of hydration.** Replacing cement with the same amount of fly ash can reduce the heat of hydration of concrete. This reduction in the heat of hydration does not sacrifice long-term strength gain or durability. The reduced heat of hydration lessens heat rise problems in mass concrete placements.

Benefits to Hardened Concrete. One of the primary benefits of fly ash is its reaction with available lime and alkali in concrete, producing additional cementitious compounds. The following equations illustrate the pozzolanic reaction of fly ash with lime to produce additional calcium silicate hydrate (C-S-H) binder:

Cement Reaction: $$C_3S + \underset{\text{(hydration)}}{H} \rightarrow \text{C-S-H} + \text{CaOH}$$

Pozzolanic Reaction: $$\text{CaOH} + \underset{\text{silica from ash constituents}}{S} \rightarrow \text{C-S-H}$$

- **Increased ultimate strength.** The additional binder produced by the fly ash reaction with available lime allows fly ash concrete to continue to gain strength over time. Mixtures designed to produce equivalent strength at early ages (less than 90 days) will ultimately exceed the strength of straight cement concrete mixes (see Figure 3-2).

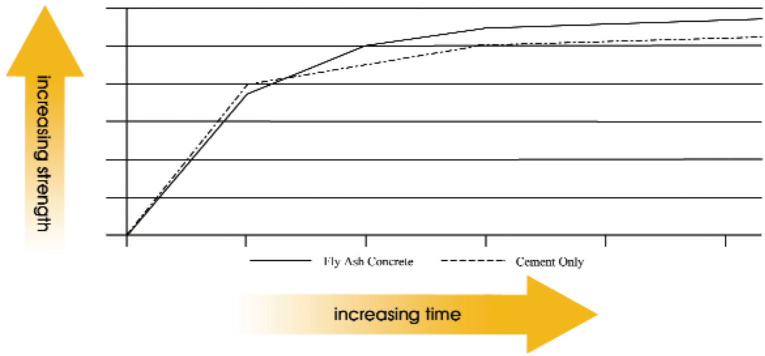

Figure 3-2. Typical strength gain of fly ash concrete.

- **Reduced permeability.** The decrease in water content combined with the production of additional cementitious compounds reduces the pore interconnectivity of concrete, thus decreasing permeability. The reduced permeability results in improved long-term durability and resistance to various forms of deterioration (see Figure 3-3)

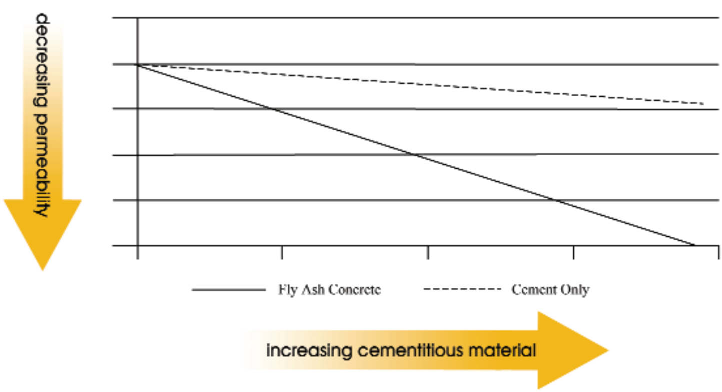

Figure 3-3. Permeability of fly ash concrete

- **Improved durability.** The decrease in free lime and the resulting increase in cementitious compounds, combined with the reduction in permeability enhance concrete durability. This affords several benefits:

-Improved resistance to ASR. Fly ash reacts with available alkali in the concrete, which makes them less available to react with certain silica minerals contained in the aggregates.

-Improved resistance to sulfate attack. Fly ash induces three phenomena that improve sulfate resistance:

- Fly ash consumes the free lime making it unavailable to react with sulfate
- The reduced permeability prevents sulfate penetration into the concrete
- Replacement of cement reduces the amount of reactive aluminates available

-Improved resistance to corrosion. The reduction in permeability increases the resistance to corrosion.

Figure 3-4. Fly ash concrete is used in severe exposure applications such as the decks and piers of Tampa Bay's Sunshine Skyway Bridge.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Procedures for proportioning fly ash concrete (FAC) mixes necessarily differ slightly from those for conventional PCC. Basic guidelines for selecting concrete proportions are contained in the American Concrete Institute (ACI) Manual of Concrete Practice, Section 211.1. Highway agencies generally use variations to this procedure, but the basic concepts recommended by ACI are widely acknowledged and accepted. There is very little on proportioning in ACI 232.2.

Fly ash is used to lower the cost and to improve the performance of PCC. Typically, 15 percent to 30 percent of the portland cement is replaced with fly ash, with even higher percentages used for mass concrete placements. An equivalent or greater weight of fly ash is substituted for the cement removed. The substitution ratio for fly ash to portland cement is typically 1:1 to 1.5:1.

A mix design should be evaluated with varying percentages of fly ash. Time versus strength curves can be plotted for each condition. To meet specification requirements, curves are developed for various replacement ratios and the optimum replacement percentage ratio is selected. A mix design should be performed using the proposed construction materials. It is recommended that the fly ash concrete being tested incorporates local materials in performance evaluation.

Cement Factors. Because fly ash addition contributes to the total cementitious material available in a mix, the minimum cement factor (portland cement) used in the PCC can be effectively reduced for FAC. The ACI acknowledges this contribution and recommends that a water/ (cement plus pozzolan) ratio be used for FAC in lieu of the conventional water/cement ratio used in PCC.

Fly ash particles react with free lime in the cement matrix to produce additional cementitious material, and thus, to increase long-term strength.

FLY ASH PROPERTIES

Fineness. The fineness of fly ash is important because it affects the rate of pozzolanic activity and the workability of the concrete. Specifications require a minimum of 66 percent passing the 0.044 mm (No. 325) sieve.

Specific gravity. Although specific gravity does not directly affect concrete quality, it has value in identifying changes in other fly ash characteristics. It should be checked regularly as a quality control measure, and correlated to other characteristics of fly ash that may be fluctuating.

Chemical composition. The reactive aluminosilicate and calcium aluminosilicate components of fly ash are routinely represented in their oxide nomenclatures such as silicon dioxide, aluminum oxide and calcium oxide. The variability of the chemical composition is checked regularly as a quality control measure. The aluminosilicate components react with calcium hydroxide to produce additional cementitious materials. Fly ashes tend to contribute to concrete strength at a faster rate when these components are present in finer fractions of the fly ash.

Sulfur trioxide content is limited to five percent, as greater amounts have been shown to increase mortar bar expansion.

Available alkalis in most ashes are less than the specification limit of 1.5 percent. Contents greater than this may contribute to alkali-aggregate expansion problems.

Carbon content. LOI is a measurement of unburned carbon remaining in the ash. It can range up to five percent per AASHTO and six percent per ASTM. The unburned carbon can absorb air entraining admixtures (AEAs) and increase water requirements. Also, some of the carbon in fly ash may be encapsulated in glass or otherwise be less active and, therefore, not affect the mix. Conversely, some fly ash with low LOI values may have a type of carbon with a very high surface area, which will increase the AEA dosages. Variations in LOI can contribute to fluctuations in air content and call for more careful field monitoring of entrained air in the concrete. Further, if the fly ash has a very high carbon content, the carbon particles may float to the top during the concrete finishing process and may produce dark-colored surface streaks.

OTHER CONSTITUENTS

Aggregates. As with any concrete mix, appropriate sampling and testing are needed to ensure that the aggregates used in the mix design are of good quality and are representative of the materials that will be used on the project. Aggregates containing reactive silica may be used in the FAC.

Cement. Fly ash can be used effectively in combination with all types of cements: portland cement, performance cement, and blended cements. However, special care should be taken when using fly ash with high early strength or pozzolanic cements. Appropriate mix design and testing should be conducted to evaluate the impact of fly ash addition on the performance of high early strength concrete. Blended or pozzolanic cements already contain fly ash or other pozzolan. Additional cement replacement would affect early strength development. Characteristics of cement vary, as do fly ashes, and not all combinations produce a good concrete. The selected portland cement should be tested and approved on its own merit, as well as evaluated in combination with the specific fly ash to be used.

Air Entraining Admixtures (AEAs). The higher the carbon content in the fly ash, the more difficult it is to control the air content. Further, if the carbon content varies, air content must be closely monitored and admixture dosage rates changed to insure proper levels of air entrainment.

Retarders. Adding fly ash should not appreciably alter the effectiveness of a chemical retarder. Some fly ashes may delay the time of set and may reduce the need for a retarder.

Water reducers. Fly ash concrete normally requires less water, but it can be further improved with the use of a water-reducing admixture. The effectiveness of these admixtures can vary with the addition of fly ash.

CONSTRUCTION PRACTICES

Fly ash concrete mixes can be developed to perform essentially the same as PCC mixes with minor differences. When mixing and placing any FAC, some minor changes in field operation may be desirable. The following general rules-of-thumb will be useful:

Plant Operations. Fly ash requires a separate watertight, sealed silo or holding bin for storage. Take care and clearly mark the loading pipe for fly ash to guard against cross-contamination when deliveries are made. If a separate holding bin cannot be provided, it may be possible to divide the cement silo. If available, use a double-walled divider to prevent cross-contamination. Due to its particle spherical shape, dry fly ash is more flowable than dry portland cement. The angle of repose of fly ash is typically less than that of cement.

As with any concrete mix, mixing time and conditions are critical to producing quality concrete. The increase in paste volume and concrete workability (ball bearings effect) associated with the use of fly ash typically improve mixing efficiency.

Field Practices. Beginning with the first concrete delivery to the job site, every load should be checked for entrained air until the project personnel are confident a consistent air content is being obtained. After that, periodic testing should continue to ensure consistency. Concrete should be placed as quickly as possible to minimize entrained air loss by extended agitation. Normal practices for consolidation should be followed. Excessive vibration should be avoided to minimize the loss of in-place air content.

FAC mix workability characteristics allow it to be placed easily. Many contractors report improved smoothness of FAC pavements over those constructed with conventional PCC. FAC contains more paste than conventional PCC, which is beneficial to the finishing. The slower early strength development of FAC may also result in longer moisture retention.

Figure 3-5. Fly ash concrete finishing

Troubleshooting. First-time users of fly ash in concrete should evaluate the performance of proposed mixes prior to construction. All concrete ingredients must be tested and evaluated to develop the desired mix design.

Air content. The fineness of fly ash and the improved workability of FAC make it naturally more difficult to develop and hold entrained air. Also, residual unburned carbon in ash adsorbs some of the air entraining agent and make it more challenging to develop the desired air content. Higher carbon content ashes naturally require higher AEA contents. Quality assurance and quality control testing of ash at the source must ensure that the fly ash used maintains a uniform carbon content (LOI) to prevent unacceptable fluctuations in entrained air. New technologies and procedures to address unburned carbon in fly ash are described in Chapter 10.

Lower early strength. Fly ash concrete mixes typically result in lower strengths at early ages. The slower strength gain may require forms to be strengthened to mitigate hydraulic loads. It should be noted that form removal and opening to traffic may be delayed due to the slower strength gains. Lower early strengths can be overcome by using accelerators.

Seasonal limitations. Construction scheduling should allow time for FAC to gain adequate density and strength to resist de-icing applications and freeze-thaw cycling prior to the winter months. Strength gain of FAC is minimal during the colder months. Although pozzolanic reactions are significantly diminished below 4.4 degrees C (40 degrees F), strength gain may continue at a slower rate resulting from continued cement hydration. Chemical admixtures can be utilized to off-set seasonal limitations.

DESIGN AND CONSTRUCTION REFERENCES
See Appendix C.

CHAPTER.4

FLY ASH IN STABILIZED BASE COURSE

INTRODUCTION

Fly ash stabilized base courses are proportioned mixtures of fly ash, aggregate, and an activator (cement or lime) that, when properly placed and compacted, produce a strong and durable pavement base course. Fly ash stabilized base courses are cost-effective substitutes for properly engineered full-depth asphalt, cement-treated, and crushed stone base courses. Fly ash stabilized base course is suitable for both flexible and rigid pavements.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Mix design. The stabilization of aggregate road bases with fly ash has a long and successful history. This application, termed pozzolanic-stabilized mixture (PSM) uses several materials and material combinations to construct stabilized aggregate bases. Class C fly ash can be used as a stand-alone material. Class F fly ash can be used when blended with lime, portland cement or cement kiln dust (CKD). Typical proportions for the Class F fly ash lime blends are two to eight percent lime blended with 10 to 15 percent Class F fly ash. Also, 0.5 to 1.5 percent Type I portland cement can be blended with Class F fly ash to produce the stabilizing agent. The stabilization of aggregate bases provides several advantages:

- Adds significant strength and durability
- Allows the use of marginal or low quality aggregates
- Permits better use of open graded base courses
- Reduces project cost

Strength. Closely controlled curing conditions are important as both time and temperature significantly affect strength. Use standard proctor-sized specimens; normal curing for lime/fly ash/aggregate mixtures is at plus 38 degrees C (100 degrees F) for 7 days. Some states use different curing times and temperatures.

Durability. It is important to ensure that adequate resistance to freeze-thaw cycling is achieved before the onset of colder months. The vacuum saturation test is normally used per ASTM C 593.

TESTING TO DETERMINE MIX PROPORTIONS
The following steps summarize the procedures for a laboratory determination of mix proportions:

- Obtain a representative sample of aggregate. Determine the particle size distribution of the aggregate. Screen the aggregate through a three-quarter-inch sieve, and use the portion passing the three-quarter-inch sieve for testing.

- Use proctor-size molds for all test samples. Add fly ash to the aggregate in five different proportions, starting at the lower limit (10 percent for coarse aggregate) and proceed in convenient increments to the upper limit (20 percent for coarse aggregate). Mold one test specimen at each fly ash content in accordance with ASTM C 593 compaction procedures at an estimated optimum moisture content.

- Determine the molded dry density of each aggregate-fly ash blend. Plot the test results to identify a peak value or maximum dry density.

- Select an optimum matrix content at least two percent above the matrix content found at the maximum dry density. Then determine the optimum moisture content and maximum dry density for that blend.

- Determine the most suitable proportions of activator to fly ash. Use five different activator-to-fly ash combinations at the optimum matrix content. The five combinations should span the recommended range of ratios for each activator. The typical range of activator to fly ash ratio is 1:3 to 1:4 using lime or portland cement; with either lime kiln dust or cement kiln dust as an activator, the typical range is 1:1 to 1:2.

- Prepare six proctor-size specimens for each combination in accordance with the compaction procedures in ASTM C 593. Cure all six test specimens for seven days in sealed containers. For lime or kiln dust activators, cure at 37.8 degrees C (100 degrees F). For portland cement as the activator, cure in a moist room at ambient conditions of 22.8 degrees C (73 degrees F) and 100 percent relative humidity.

- Test three specimens for compressive strength and test the other three specimens for durability at the end of the seven-day curing period, as described in ASTM C 593. Some agencies utilize the ASTM D 560 freezing and thawing test, which incorporates a brushing procedure and related performance criteria developed by the Portland Cement Association for soil-cement mixtures. In areas with virtually no freezing and thawing, durability testing may be waived in accordance with local practices.

- Plot a curve of compressive strength as a function of activator percentage for each of the five activator-to-fly ash combinations. Only test mixtures with a seven-day compressive strength exceeding 2,760 kPa (400 psi) and acceptable durability should be considered as a potential PSM for field use.

- Select the most economical (lowest percentage activator) mixture that exceeds the compressive strength and durability requirements. The PSM actually used in the field should contain a higher percentage of activator (a 0.5 percent increase for lime or portland cement; and a one percent increase for lime kiln dust or cement kiln dust) than the most economical mixture identified in the laboratory. This assures an adequate factor of safety for placement techniques available in the field

Control of Materials

Lime. Hydrated lime is the most popular form used, although quick lime and other products containing lime (kiln dust, etc.) can be used successfully with appropriate precautions. Type 1 portland cement has also been used successfully as a reactant when higher early strength requirements or reactant market conditions dictate. Determine actual lime content from samples using approved titration methods (ASTM D 2901, AASHTO T 232).

Fly ash. Unconditioned (dry) or conditioned (water added) fly ash can be used successfully. Check the reactivity of fly ash with cement in accordance with ASTM C 593 and for comparison and mix design results. Reactivity and fineness are the fly ash characteristics that most directly affect PSM quality.

Aggregates. Aggregates must be sound and resist deterioration from environmental elements. They may include sands, gravels, or crushed stones. Gradation should be such that the final mixture is mechanically stable and highly compactable

CONSTRUCTION PRACTICES

Blending of materials. Central plant mixing provides the best quality, although in-place mixing has also been successful. Most plants use a continuous pugmill, but central mix concrete plants also work well. When unconditioned (dry) fly ash is used, a silo and surge bin are needed for lime or cement and fly ash. When belt feeding, drop dry fly ash on top of the aggregate to keep it from rolling down the belt during pugmill loading. Conditioned Class F fly ash can be routinely added through an aggregate.

In-place mixing. In-place mixing involves the use of portable pulverizing and mixing equipment to blend granular soil or aggregate materials with PSM reagent material and water in pre-determined proportions at the project site. Class F fly ash is usually added in conditioned form, although it may also be added dry. The reagent materials (lime and/or portland cement) are usually added after the fly ash and are most often introduced in a dry form, although they may be added in a slurry form in order to minimize dusting. Water is usually sprayed on the mixture as needed just prior to in-place mixing.

Full depth reclamation. When deteriorated asphalt pavements are recycled in place, a technique known as full-depth reclamation can be used. The flexible pavement and a pre-determined portion of the underlying base material are milled and pulverized to a depth that can range from 150 to 300 mm (6 to 12 inches) or more. The pulverized material is mixed within the reclaiming machine while stabilization reagents (such as lime or portland cement and fly ash) and water are introduced and blended with the pulverized recycled paving aggregate. The reclaimer is then followed by grading, spreading, and compaction equipment working in the same manner and sequence as if plant-mixed PSM material were delivered and placed at the project site.

S**preading.** A PSM can be placed with spreader boxes or asphalt laydown machines. Equipment with automated grade control is highly recommended. Layers are normally spread to a thickness of 15 to 30 percent greater than the desired compacted thickness. Maximum lift thickness is 200 to 250 mm (8 to 10 in). Place the second lift on the same day or take appropriate measures to ensure adequate sealing and subsequent bonding of additional lifts.

Compaction. Achieving a high degree of compaction is crucial to the successful performance of PSM roadbases. Final density should be reached as quickly as possible to achieve the highest ultimate strengths. This is especially the case when using Class C fly ash as the stabilization reagent, since nearly all Class C fly ashes are rapid setting and will not achieve the desired density unless compacted immediately following spreading. Compacting this noncohesive material with steel-wheel pneumatic, and vibratory rollers has been successful. The PSM surface should be kept moist throughout compaction. PSM moisture should be on the low side of optimum to achieve the best field compaction. If placed with a spreader box, the final surface should be fine graded with a motor grader before final rolling with a steel-wheeled roller. When fine grading, take care not to fill in the low spots because the feathering-in will tend to reduce bonding at that location, thus creating a potential trouble spot. If equipment with graded control is used, fine grading is not required.

Curing. Compacted layers should be quickly sealed to prevent drying. Apply a prime coat of 0.45 to 0.90 liters per square meter (0.1 to 0.2 gal/sy) of cut back or emulsified asphalt to the moist surface within 24 hours of final compaction. Multiple applications of lighter coats tend to produce better penetration and improve adhesion.

CAUTIONS

Ash quality. Fly ashes, which contain sulfur in excess of 5.0 percent as SO_3 or contain scrubber residues, should be carefully evaluated with specific project soils to evaluate the expansion potential of the materials combination.

Seasonal limitations. PSMs often require several weeks of warmer weather to develop adequate strength to resist freeze-thaw cycling of the first winter. If late season placements are necessary, add portland cement in lieu of some of the lime to increase early strength.

DESIGN AND CONSTRUCTION REFERENCES

See Appendix C.

Figure 4-1. Full-depth reclamation of a bituminous road

CHAPTER.5

FLY ASH IN FLOWABLE FILL

GENERAL

Flowable fill includes a family of products usually consisting of water, fly ash, portland cement, and sometimes, coarse or fine aggregates, or both. Flowable fill is an engineered, strength controlled, fill material that is self-leveling, self-compacting and non-settling. This material is also known as:

- Controlled density fill (CDF)
- Controlled low strength material (CLSM)
- Flowable fly ash
- High slump fly ash grout
- Lean concrete slurry
- Lean mix backfill
- Unshrinkable fill

Figure 5-1. Flowable fill used in a utility trench application

Flowable fill mixtures make up a class of engineering materials having characteristics and uses that overlap those of a broad range of traditional materials including compacted soil, soil-cement, and concrete. Consequently, flowable fills are proportioned, mixed, and delivered in a form that resembles a very workable concrete; and they provide for an in-place product that is equivalent to a high-quality compacted soil without the use of compaction equipment and related labor.

Virtually any coal fly ash can be used in flowable fill mixes. The fly ash does not have to meet AASHTO M 295 (ASTM C

618) specification requirements as a concrete admixture to be suitable for use in flowable fill, even fly ash with high LOI or carbon content is suitable. The individual specifying agencies may have applicable specifications or regulations regarding fly ash flowable fill. Regardless of the type of handling practices, fly ash for flowable fill can be used in a dry or moisture conditioned form. Fly ash recovered from storage ponds has been used successfully. Flowable fill mixes using high-calcium fly ash may not require any cement. Mix design and performance testing are typically prepared to determine the suitability of a fly ash and other ingredients for the specific flowable requirements.

Upon comparison, flowable fill materials usually offer an economic advantage over the cost of placing and compacting earthen backfill materials. Depending on the job conditions and costs involved, significant savings are possible. The closer the project location is to the source of the flowable fill, the greater the potential cost savings. Flowable fill also becomes more economical than conventional earthen backfill if shoring and/or sloping of the trench is necessary for worker safety within the excavated area. With flowable fill, workers need not be in the excavation, resulting in cost savings from less excavation and no shoring.

Figure 5-2. Flowable fill eliminates the need for manual compaction

Figure 5-3. Flowable fill can be used to backfill very narrow trenches

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Flowable fill mixes typically contain fly ash, portland cement and water. Other cementing compounds (e.g., Class C ash, cement kiln dust, etc.) may be used in lieu of portland cement in certain applications. Filler materials such as bottom ash, sand (including some foundry sands) or other aggregates can also be used in the mix. The flowable character of these mixtures derives from the spherical particle shape of fly ash or from a distribution of spherical and irregular particle shapes and sizes in fly ash and sand combinations when mixed with enough water to lubricate the particle surfaces.

Fly ash can be a major ingredient in a flowable fill mix. It can be less expensive than sand. Flowable fills can use non-concrete grade fly ash, which may be obtained at a reduced cost. However, when sand is more economical, fly ash can be limited to 300 or fewer kilograms per cubic meter (500 or fewer pounds per cubic yard). Water requirements for mixture fluidity will depend on the surface parameters of all solids in the mixture, however, a range of 250 to 400 liters per cubic meter (50 to 80 gallons per cubic yard) would satisfy most materials combinations. Portland cement is added, typically in quantities from 30 to 60 kilograms per cubic meter (50 to 100 pounds per cubic yard) to provide a weak cementitious matrix.

The two basic types of flowable fill mixes are high fly ash content and low fly ash content. The high fly ash content mixes typically contain almost all fly ash with a small percentage of portland cement and enough water to make the mix flowable. The low fly ash content mixes contain a high percentage of fine aggregate or filler material (usually sand), a low percentage of fly ash sufficient to help the sand particles flow, a small percentage of portland cement (similar to that used in high fly ash content mixes), and enough water to make the mix flowable.

ACI Committee 229 has designated low fly ash content mixes that contain high percentages of fine aggregate as CLSM. According to the ACI definition, CLSM has an upper compressive strength limit of 8,300 kPa (1,200 psi), however, strengths can be designed as low as 345 kPa (50 psi). Most flowable fill mixes are designed to achieve a maximum strength of 1,000 to 1,400 kPa (150 to 200 psi) so as to allow for excavation at a later time. It is important to remember that flowable fill mixes with an ultimate strength in the 345 to 480 kPa (50 to 70 psi) range have at least two to three times the bearing capacity of well-compacted earthen backfill material.

Usually, flowable fill mix designs are proportioned based on the percentage of fly ash, on a dry weight basis. The high fly ash content mixes normally contain 95 percent fly ash and 5 percent portland cement. In some areas, self-cementing fly ash accounts for 100 percent of the cementitious material. Because the low fly ash content mixes contain an additional ingredient (sand or filler), there is a much broader range of mix proportions. Some typical mix designs for high and low fly ash content mixes are included in Tables 5-1 and 5-2. The most important physical characteristics of flowable fill mixtures are: strength development, flowability, hardening time, and bleeding/subsidence.

Component	Range kg/m^3 (lb/yd^3)		Mix Design kg/m^3 (lb/yd^3)	
Fly Ash	949 to 1,542	(1,600 to 2,600)	1,234	(2,080)
Cement	47 to 74	(80 to 125)	62	(104)
Added Water	222 to 371	(375 to 625)	247	(416)*
			1,543	(2,600)

*Equal to 189 liters (50 gallons)

Table 5-1. High fly ash content mixes.

Component	Range kg/m^3 (lb/yd^3)		Mix Design kg/m^3 (lb/yd^3)	
Fly Ash*	119 to 297	(200 to 500)	178	(300)
Cement	30 to 119	(50 to 200)	59	(100)
Sand	1,483 to 12,780	(2,500 to 3,000)	1,542	(2,600)
Added Water	198 to 494	(333 to 833)	297	(500)**
			2,076	(3,500)

* High calcium fly ash is used in lower amounts than low calcium fly ash.
**Equal to 227 liters (60 gallons)

Table 5-2. Low fly ash content mixes.

Strength development. Strength development in flowable fill mixtures is directly related to the amount of cementitious material and water content. With low CaO (Class F) fly ashes, the cement content and water content relate directly to strength development. With high CaO (Class C) fly ashes, no cement may be required and strength is related directly to the fly ash and water content. Most high fly ash content mixes only require from three to five percent portland cement by dry weight of the fly ash to develop 28-day compressive strengths in the 345 to 1,000 kPa (50 to 150 psi) range. Long-term strength may gradually increase beyond the 28-day strength. Water content of mix also influences strength development. Water is added to achieve a desired flowability or slump. At a given cement content, increased water content usually results in a slight decrease in compressive strength development over time. With high air (greater than 20 percent) flowable fill mixtures, the water content is reduced and strength is limited by the presence of air voids.

Flowability. Flowability is basically a function of the water and entrained air content. The higher the water and air content, the more flowable the mix. It is usually desirable to make the mix as flowable as practical in order to take advantage of the self-compacting qualities of flowable fill. Typical flowable fill mixes with high air content are shown in Table 5-3.

Component	Range kg/m^3 (lb/yd^3)		Mix Design kg/m^3 (lb/yd^3)	
Fly Ash	119 to 297	(200 to 500)	160	(350)
Cement	30 to 119	(50 to 200)	30	(50)
Sand	1,483 to 1,780	(2,500 to 3,000)	1,365	(2,300)
Water	115 to 150	(30 to 40)	132	(35)
Air Content, %	20 to 30		20 to 30	

Table 5-3. Flowable fill mixes with high air content.

Hardening time. Hardening time is directly related to the cement content. Typical high fly ash flowable fill mixes containing five percent cement achieve a sufficient set to support the weight of an average person in about three to four hours, depending on the temperature and humidity. Within 24 hours, construction equipment can move across the surface without any apparent damage. Some low fly ash flowable fill mixes containing high calcium fly ash have reportedly set sufficiently to allow street patching within one to two hours after placement.

Bleeding and subsidence. Bleeding and subsidence are possible in high fly ash flowable fill mixes with relatively high water contents (corresponding to a 254 mm/10-in slump). Evaporation of the bleed water and absorption into the surrounding soil often results in a subsidence of approximately 11 mm/m (1/8-in/ft) of depth of the fill. This shrinkage may occur laterally as well as vertically, but no additional shrinkage or long-term settlement of flowable fill occurs after initial set. Prior to hardening, flowable fill mixes are self-leveling.

Because the flowable fill is commonly obtained from ready-mixed concrete producers, quality control of the fill is easily maintained with the materials scales and metering devices already in use at the concrete plant. Delivery is usually by conventional ready-mix trucks. Flowable fill can also be pumped or placed by bucket, conveyor, or hose. It does not usually segregate even if dropped from considerable heights or pumped for long distances.

Applications of flowable fills include, but are not limited to: backfill for bridge abutments, culverts, and trenches; fill for embankments, bases, and subbases; bedding for slabs and pipes; insulating fill; fill for caissons and piles; and fill for abandoned storage tanks, shafts, and tunnels.

An important requirement for flowable fills in many applications is that they can be removed with ordinary excavation equipment. This means that compressive strength should be limited to 700 to 1,400 kPa (100 to 200 psi) with mechanical equipment and 345 kPa or less (50 psi) for manual excavation. Because of the combined concrete/soils technology associated with flowable mixtures, a variety of control tests have been applied to their use, including flowability as measured by a concrete slump cone, a flow cylinder, or a mortar flow cone and unit weight, as well as measures of compressive strength, bearing capacity, or penetration resistance (ACI 229R).

Figure 5-4. Bridge abutment backfill with flowable fill.

As with any construction application, quality control and quality assurance (QC/QA) of the materials and the mix are extremely important. Good QC/QA will take maximum advantage of the benefits of flowable fill.

Corrosion. Test methods developed to evaluate the potential for corrosion of metals in soil backfills can be used to evaluate the corrosion potential of flowable fills. ACI 229R describes several test methods specific to the material in contact with flowable fill.

Figure 5-5. Bridge replaced by culverts and flowable fill.

DESIGN AND CONSTRUCTION REFERENCES
See Appendix C.

CHAPTER.6

FLY ASH IN STRUCTURAL FILLS/EMBANKMENTS

INTRODUCTION

Specifications for fly ash structural fills and embankments are similar to specifications for engineered soil fills. Proper placement and compaction of fly ash fills is required to achieve the desired strength and compressibility characteristics assumed for design.

Figure 6-1. Highway embankment with fly ash structural fill.

DESIGN AND SPECIFICATION REQUIREMENTS

Ash sources. Fly ash for structural fill applications can be obtained as conditioned fly ash from a silo or as ponded fly ash from a pond or a stockpile. Silo fly ash can be delivered with close controls on moisture content and grain size distribution. Conversely, the moisture content or grain size distribution of ponded or stockpiled ash can vary considerably depending upon its location within the pond or stockpile. Therefore, using ponded or stockpiled ash may require several series of laboratory tests. If fly ash from more than one source is being used on the project at the same time, it is preferable to place and compact the ashes separately. Because of its self-hardening properties, high calcium ash is typically stored dry in silos and hauled to the construction site in pneumatic tank trucks, or is removed from a pond or temporary stockpile. This procedure may not be necessary if the site is close enough to the plant to allow the ash to be hauled in the moistened condition.

Site conditions. As with any embankment project, standard geotechnical techniques are used to evaluate subsurface soil and groundwater conditions. The two most important subsurface characteristics affecting embankment construction and performance are shear strength and compressibility of the foundation soils. ASTM E 1861 provides additional guidance concerning technical and environmental considerations.

Physical, engineering, and chemical properties of the ash. The physical and engineering properties of fly ash that will determine the behavior of the embankment are grain-size distribution, moisture-density relationships, shear strength, compressibility, permeability, capillarity, and frost susceptibility. Laboratory tests designed for testing soil properties may be applied to testing fly ash. The chemical characteristics of the fly ash affect the physical behavior as well as the quality of the leachate produced by the ash. The utility company or its marketing agent can provide information on the physical, engineering, and chemical composition of the ash and leachate characteristics.

Design issues. The mechanical behavior and compaction characteristics of fly ash are generally similar to those of silt. For this reason, fly ash also shares some of the difficulties that are characteristic of silt such as dusting, erosion and frost susceptibility. These difficulties can be properly addressed during the design of the embankment. For example, ice lenses grow in silt-sized soils by wicking water up from a shallow groundwater table. Such ice lenses expand during the winter and melt during the spring causing unstable and soft embankment conditions. The problem can be avoided by controlling upward seepage with a layer of coarse-grained material or geotextile at the base of the embankment. In general, avoid using fly ash as a fill material below the groundwater table or when the embankment design cannot provide adequate drainage.

Environmental impacts. The trace element concentrations in many fly ashes are similar to those found in naturally occurring soils. Although the leachates of some fly ashes may contain trace element concentrations that exceed drinking water quality standards, this is also true of certain soils. State environmental regulatory agencies can guide you through applicable test procedures and water quality standards. The amount of leachate produced can be controlled by assuring adequate compaction, grading to promote surface runoff, and daily proof-rolling of the finished subgrade to impede infiltration. When construction is finished, a properly seeded soil cover will reduce infiltration. For highway embankments, the pavement may be an effective barrier to infiltration.

Erosion and dust control. To prevent wind and surface water erosion of the fly ash embankment, use the same sediment and erosion control techniques common during earthwork operations. This includes wetting down exposed surfaces and installing silt fences or straw bales around construction areas. Dusting will likely occur when compacted fly ash is placed in dry, windy, or freezing weather, or during traffic disturbance. During construction, the surface should be kept moist, covered, or stabilized with lime or bitumen. To prevent erosion and dusting after completion of the embankment, protect the fly ash with topsoil and vegetation or by sealing with bituminous emulsion.

Specifications/quality control. There are two types of specifications used for the construction of fly ash embankments: performance specifications and method specifications. The construction quality control effort required depends greatly on the selected specification approach. Additional information on specifications and procedures can be found in ASTM E 1861.

Performance specifications. Performance specifications designate the required degree of compaction and the allowable moisture content range. For road embankments, a typical requirement is to compact the fly ash to 95 to 100 percent of maximum dry density, as determined by AASHTO T 99 (ASTM D 698). The allowable range for the moisture content is determined by plotting the laboratory moisture-density relationship. Figure 6-2 shows the dry density and moisture content relationship. Fly ash may be variable enough that several curves are required. It is preferable to place the ash at less than optimum moisture because it will be difficult to impossible to obtain compaction above optimum moisture contents.

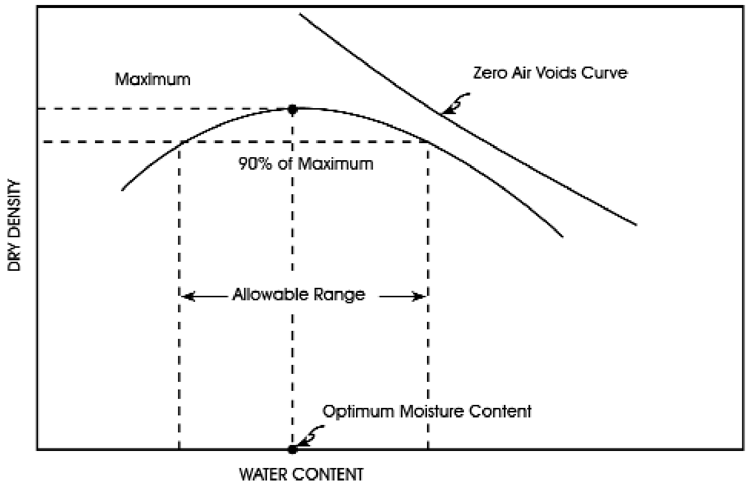

Figure 6-2. Allowable moisture content range below optimum moisture content

Method specifications. On some projects, method specifications are preferable over performance specifications. The method specification is based on the results of field compaction tests on trial strips. The required lift thickness, weight of compaction equipment, speed of compaction equipment, and the number of passes are thus specified so that the necessary degree of compaction is achieved. If vibratory compaction equipment is being used, the resonant frequency of each compactor in use is also established in the field. The method specification allows for simpler quality control because the compaction procedures can be monitored visually. Compactive efforts to achieve 95 percent of the standard proctor maximum dry density are shown in Table 6-1.

Equipment	Thickness	Passes	Comments
Vibratory Smooth Drum Roller (1 to 1-1/2 tons) (900 to 1,330 kg)	150 mm (6 in)	≥ 8	May slightly overstress surface; compaction may only reach 90 percent.
Vibratory Smooth Drum Roller (6 to 10 tons) (5,400 to 9,100 kg)	150 - 300 mm (6 - 12 in)	≥ 8	9100 kg (10 ton) roller may need as few as 3 passes at lower lift thickness; may overstress surface
Vibratory Smooth Drum Roller (10 to 20 tons) (9,100 to 18,200 kg)	200 - 300 mm (8 - 12 in)	4 – 6	May seriously overstress surface; ballast reduction and frequency change will reduce this problem
Pneumatic tired Drum Roller (10 to 12 tons) (9,100 to 11,000 kg)	150 - 300 mm (6 - 12 in)	> 8	Limit tire pressure to 250 kPa (35 psi): provides good smooth surface seal
Vibratory Padfoot Roller (6 to 20 tons) (5,400 to 18,200 kg)	150 - 300 mm (6 - 12 in)	≥ 8	Pad height should be roughly 100 mm (4 in) or less, pad area should be greater than 7750 mm^2 (12 in^2)
Vibrating Plate Tamper (large plate)	200 - 250 mm (8 - 10 in)	2 - 3	Used in confined areas and where ground loading must be kept low (e.g., backfills)
Sheepsfoot			Not recommended
Grid Roller			Not recommended

Table 6-1. Combinations required for 95 percent of the standard proctor maximum dry density, AASHTO Method T 99

CONSTRUCTION PRACTICES

General. Recommended construction procedures have been developed as the result of experience gained with trial embankments and construction projects. Adjustments to these standard procedures may be necessary, depending on actual field conditions.

Site preparation. Preparing the site for fly ash placement is similar to requirements for soil fill materials. The site must be cleared and grubbed. Topsoil should be retained for final cover. Special attention should be given to draining the site and to preventing seeps, pools, or springs from contacting the fly ash.

Delivery and on-site handling. Fly ash is usually hauled to the site in covered dump trucks or pneumatic tanker trucks. Adjust the water content of the ash to prevent dusting. In the case of lagoon ash, reduce the water through temporary stockpiling and/or mixing with drier silo ash to prevent road spillage during

hardening properties of high calcium ash, it is stored dry in silos or pneumatic tanker trucks. Low calcium ash can be stockpiled on-site if the ash is kept moist and if the ash is covered to prevent dusting and erosion.

Spreading. Fly ash is usually spread and leveled with a dozer, grader, or other equipment in loose lifts of 150 to 300 mm (6 to 12 in) thick. The lift is then tracked with the dozer or other equipment for initial compaction.

Compaction equipment. Begin compaction as soon as the material has been spread and is at the proper moisture content. The most successful compaction results have been achieved with self-propelled, pneumatic-tired rollers and self-propelled or towed vibratory rollers. Vibratory rollers operated at the resonant frequency of the fly ash will compact the ash more effectively and in fewer passes than non-vibratory rollers. Table 6-1 lists the types of compaction equipment that have been tested for use with fly ash.

Figure 6-3. Spreading and compaction of fly ash structural fill.

Moisture control. Control of the required range of moisture is an important consideration in the compaction procedure. Fly ash can be conditioned with water at the plant silo to achieve the desired moisture content. Be sure to compare the alternatives of hauling fly ash moistened to the desired water content at the plant, or adding water at the site. Hauling moist fly ash to the site means higher transportation costs, while adding water on-site sacrifices productivity in field placement.

Weather restrictions. Fly ash can often be placed during inclement weather. In the winter months, frost usually penetrates only the upper layer of the compacted ash, which can be re-compacted upon thawing. During compaction, if the water freezes too fast, the operation should be suspended until the temperature rises. Construction can also proceed during wet weather even if the moisture content of the ash is too high. However, the equipment may bog down and it may be difficult to achieve proper compaction.

Insensitivity to moisture variations. Because water is added to low calcium fly ash during unloading from storage silos, fly ash can be obtained at any moisture content that is desired. Although the optimum moisture content is greater than that of silty soils, the compaction behavior of low calcium fly ash is relatively insensitive to variations in moisture content when placed dry of optimum. High calcium fly ash, however, will self-harden when water is added and becomes difficult to handle if not placed in a timely manner.

DESIGN AND CONSTRUCTION REFERENCES
See Appendix C.

CHAPTER.7

FLY ASH IN SOIL IMPROVEMENT

INTRODUCTION

Soil stabilization is the alteration of soil properties to improve the engineering performance of soils. The properties most often altered are density, water content, plasticity and strength. Modification of soil properties is the temporary enhancement of subgrade stability to expedite construction.

Class C fly ash and Class F-lime product blends can be used in numerous geotechnical applications common with highway construction:

- To enhance strength properties
- Stabilize embankments
- To control shrink swell properties of expansive soils
- Drying agent to reduce soil moisture contents to permit compaction

Class C fly ash can be used as a stand-alone material because of its self-cementitious properties. Class F fly ash can be used in soil stabilization applications with the addition of a cementitious agent (lime, lime kiln dust, CKD, and cement). The self-cementitious behavior of fly ashes is determined by ASTM D 5239. This test provides a standard method for determining the compressive strength of cubes made with fly ash and water (water/fly ash weight ratio is 0.35), tested at seven days with standard moist curing. The self-cementitious characteristics are ranked as shown below:

Very self-cementing	> 500 psi (3,400 kPa)
Moderately self-cementing	100 - 500 psi (700 - 3,400 kPa)
Non self-cementing	< 100 psi (700 kPa)

It should be noted that the results obtained from ASTM D 5239 only characterizes the cementitious characteristics of the fly ash-water blends and does not alone provide a basis to evaluate the potential interactions between the fly ash and soil or aggregate.

The use of fly ash in soil stabilization and soil modification may be subject to local environmental requirements pertaining to leaching and potential interaction with ground water and adjacent water courses.

SOIL STABILIZATION TO IMPROVE SOIL STRENGTH

Fly ash has been used successfully in many projects to improve the strength characteristics of soils. Fly ash can be used to stabilize bases or subgrades, to stabilize backfill to reduce lateral earth pressures and to stabilize embankments to improve slope stability. Typical stabilized soil depths are 15 to 46 centimeters (6 to 18 inches). The primary reason fly ash is used in soil stabilization applications is to improve the compressive and shearing strength of soils. The compressive strength of fly ash treated soils is dependent on:

- In-place soil properties
- Delay time
- Moisture content at time of compaction
- Fly ash addition ratio

Figure 7-1. Mixing and shaping of fly ash stabilized soil.

Delay time. Delay time is the elapsed time measured between when the fly ash first comes into contact with water and final compaction of the soil, fly ash and water mixture. Compressive strength is highly dependent upon delay time. Both densities and strength are reduced with increasing delay to final compaction. Delay time is critical due to the rapid nature of the tricalcium aluminate ($C3A$) reaction that occurs when Class C fly ash is mixed with water. Densities and strengths are reduced because a portion of the compactive energy must be used to overcome the bonding of the soil particle by cementation and because a portion of the cementation potential is lost. Maximum strength in soil-fly ash mixtures is attained at no delay. Typically, a one-hour compaction delay is specified for construction purposes.

Moisture content. The water content of the fly ash stabilized soil mixture affects the strength. The maximum strength realized in soil-fly ash mixtures generally occurs at moisture contents below optimum moisture content for density. For silt and clay

Figure 7-2. Compaction of fly ash stabilized soil.

soils the optimum moisture content for strength is generally four to eight percent below optimum for maximum density. For granular soils the optimum moisture content for maximum strength is generally one to three percent below optimum moisture for density. Therefore, it is crucial that moisture content be controlled during construction. Moisture content is usually measured using a nuclear density measurement device.

Addition Ratios. Typical fly ash addition rates are 8 percent to 16 percent based on dry weight of soil. The addition rate depends on the nature of the soil, the characteristics of the fly ash and the strength desired. The addition rate must be determined by laboratory mix design testing. In general the higher the addition rate the higher the realized compressive strength. Fly ashes for state department of transportation projects are usually specified to meet AASHTO M 295 (ASTM C 618), even though the requirements of this specification are not necessary for this application and may increase the ash supply costs. Increasingly non-AASHTO M 295 compliant materials are being successfully used. It should be noted that virtually any fly ash that has at least some self-cementitious properties can be engineered to perform in transportation projects.

Soil Properties. The plasticity of soils treated with Class C or other high-calcium fly ash is influenced by the types of clay minerals present in the soil and their adsorbed water. Soils containing more than 10 percent sulfates have been prone to swell excessively in some applications. Also, organic soils are difficult to stabilize using fly ash.

SOIL STABILIZATION TO CONTROL SHRINK SWELL

Many clay soils (plastic soils) undergo extensive volumetric changes when subjected to fluctuating moisture contents. These volumetric changes if not controlled can lead to movements in structures and impose loads which can cause premature failure.

The plasticity of soils has historically been quantified by the plasticity index, as determined by ASTM D 4318. Typically specifications limit the plasticity index of a soil to no more than 10-12 to ensure a stable material. In general terms, the higher the plasticity index, the higher the potential to shrink or swell as the soil undergoes moisture content fluctuations.

Figure 7-3. Mixing and compaction of fly ash into a plastic soil

Historically, plastic soils have been treated with quick lime (CaO) or hydrated lime [Ca (OH)2] to lower their plasticity. The lime chemically reacts with the soil particles, effectively changing the soil grains from clay size (less than 0.002 mm) to silt size (0.05 to 0.002 mm). The determination of the plasticity index is geared towards measuring this chemical change in the soil.

Fly ash reduces the potential of a plastic soil to undergo volumetric expansion by a physical cementing mechanism, which cannot be evaluated by the plasticity index. Fly ash controls shrink-swell by cementing the soil grains together much like a portland cement bonds aggregates together to make concrete. By bonding the soil grains together, soil particle movements are restricted. Typical addition rates based on dry weight of soil are 12 to 15 percent.

It should be noted that a Class C fly ash may contain 15 percent or more calcium expressed as calcium oxide, but very little of this calcium is in the form of free calcium oxide (CaO). Therefore, the determination of the plasticity limits is inappropriate when evaluating the effect of fly ash on the shrink-swell characteristics of a soil. To properly evaluate a fly ash for shrink-swell control, the soil-fly ash blends should be tested with a soil expansion test such as ASTM D 4829 or ASTM D 1883.

The swell potential of fly ash treated soils is typically less than 0.5 percent under confining pressures of 48 kPa (100 psf) even when compacted two to four percent below optimum moisture content for maximum density.

SOIL MODIFICATION TO REDUCE WATER CONTENT

Soils must be compacted to their maximum practical density to provide a firm base for overlying structures. For soils to be compacted the moisture content must be controlled because of the relationship between soil density and moisture content. If the soil to be compacted is either to wet or too dry, the moisture content must be adjusted to near optimum to achieve maximum density. If a soil is too dry, moisture is simply added. If a soil is too wet, the moisture content of the soil must be lowered. Class C fly ash and other high lime fly ash have been found to be very effective drying agents, capable of reducing soil moisture content by 30 percent or more.

The fly ash dries the soil by two basic mechanisms, chemical reactions that consume moisture in the soil and by simple dilution. Class C fly ashes contain tricalcium aluminate (C3A), which is highly reactive with water. C3A is the chemical compound present in ordinary portland cement which is responsible for early strength. The C3A present in fly ash reacts with the water, lowering the overall moisture content of the soil. The drying effect of fly ash in wet soil is very rapid and immediate, permitting the contractor to quickly proceed with construction. In addition to the speeding up of the construction process the use of fly ash provides several other benefits, such as making the soil more resistant to additional water infiltration, provides additional support for traffic, creates a more stable work platform and reduces dusting from construction traffic.

CAUTIONS
Some state or local environmental agencies may require a leaching test of the ash prior to use.

DESIGN AND CONSTRUCTION REFERENCES
See Appendix C.

CHAPTER.8

FLY ASH IN ASPHALT PAVEMENTS

INTRODUCTION

Fly ash can be used as a cost-effective mineral filler in hot mix asphalt (HMA) paving applications. Where available locally, fly ash may cost less than other mineral fillers. Also, due to the lower specific gravity of fly ash, similar performance is obtained using less material by weight, further reducing the material cost of HMA. Mineral fillers increase the stiffness of the asphalt mortar matrix, improving the rutting resistance of pavements. Mineral fillers also help reduce the amount of asphalt drain down in the mix during construction, which improves durability of the mix by maintaining the amount of asphalt initially used in the mix.

Fly ash will normally meet mineral filler specification requirements for gradation, organic impurities and plasticity. Also, fly ash is hydrophobic (non-water wettable) , reducing the potential for asphalt stripping; the presence of lime in some fly ashes may also reduce stripping.

Mineral fillers have become more necessary as mixture gradations have become coarser. Asphalt pavements with coarse gradations are increasingly being designed because they perform well under heavy traffic conditions. Some mixtures require higher dust to asphalt ratios than can be gained through the recycling of baghouse fines alone.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Fly ash must be in a dry form when used as mineral filler. Typically, fly ash is handled in a similar manner to hydrated lime - it is transported to the HMA plant in pneumatic tankers; stored in watertight silos at the plant; and metered into the HMA using an auger.

Engineering Properties. The physical requirements for mineral filler in bituminous paving are defined in AASHTO M 17, Table 8-1.

Organic impurities. Although no standard for carbon content or LOI is specified for fly ash used as mineral filler, laboratory asphalt mortar evaluations incorporating fly ashes with LOIs up to 10 percent perform satisfactorily.

Plasticity. Fly ash is a non-plastic material.

Figure 8-1. Stone matrix asphalt.

Particle Sizing		Organic Impurities	Plasticity Index
Sieve Size	Percent Passing		
600 µm (No. 30)	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
300 µm (No. 50)	95 - 100		
75 µm (No. 200	70 - 100		

Table 8-1. AASHTO M 17 specification requirements for mineral filler usein asphalt paving mixtures.

Gradation. Most fly ashes typically fall within a size range of 60 to 90 percent passing the 75 µm (No. 200 sieve).

Fineness. There is no fineness standard for mineral filler beyond the AASHTO M 17 gradation requirements; however, when Stone Matrix Asphalt (SMA) was first introduced to the U.S. in 1990, often a requirement for a maximum percent passing the 20 µm (No. 635) sieve was specified. Typically, fly ash has 40 to 70 percent passing the 20 µm sieve and performs well in mortar testing and field performance.

Specific gravity. The specific gravity of fly ash varies from source to source; it is typically 2.0 to 2.6. Most "non-fly ash" mineral fillers have a specific gravity ranging from 2.6 to 2.8; therefore, HMA designed with fly ash will usually require a lower percentage by weight to obtain the same performance (e.g., voids in mineral aggregate, stiffness, drain down, etc.).

Rigden voids. Research indicates that mineral fillers with more than 50 percent voids as determined using the modified Rigden's voids test tend to overly stiffen the asphalt binder. Most fly ashes have a Rigden void of less than 50 percent.

DESIGN AND CONSTRUCTION REFERENCES

See Appendix C.

CHAPTER.9

FLY ASH GROUTS FOR PAVEMENT SUBSEALING

INTRODUCTION

Fly ash grouts are used for sealing voids beneath pavement slab sections. The unconfined compressive strength requirements for a grout mixture will usually exceed 8,300 kPa (1,200 psi) at 28 days and will range between 4,100 and 5,500 kPa (600 and 800 psi) at 7 days. This strength profile for grouts differentiates them from flowable fill materials inasmuch as the flowable fill definition (or controlled low strength material) sets an unconfined compressive strength limit of 8,300 kPa (1,200 psi) at 28 days. Furthermore, the relatively small size of the void filled with the grout mixture further differentiates this application from the larger voids where the lower strength flowable fills are utilized.

The principal requirements for a slab stabilization material is that it can flow to fill very small voids and still have adequate strength to support the slab. A good stabilization material should remain insoluble, incompressible, and not erode after it has been placed and hardened. It should also have sufficiently low internal friction to flow into very small voids and water channels. If the material is too stiff, it will create a seat below the grout hole and not fill all voids. If it is too wet, it will not have enough strength to support the slab and may have a large amount of shrinkage. Finally, it should have sufficient body to displace free water from under the slab and develop adequate strength and durability.

Figure 9-1. Fly ash grouts for pavement subsealing

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Mix design. A typical cement-fly ash (Class F) mix design calls for 1 part cement (Type I, II, or III), 3 parts fly ash, and enough water for flowability, usually about 1.5 to 3.0 parts water. It may be possible to reduce the cement component if a Class C ash is used. Water content is determined using a flow cone and ASTM C 939. The flow cone measures the flowability of the grout mixture. The time of efflux is the flow time in seconds required to empty the cone. A time of efflux in the range of 10 to 16 seconds gives the best flowability and strengthens cement-fly ash grout slurries. The determination of initial set time of the grout in laboratory tests is useful in comparing various mixes. Usually, the Proctor Needle Test (AASHTO T 197/ASTM C 403) is used. Typical set times with these tests are 1½ to 2 hours.

Additives. It may be necessary to use additives or admixtures in fly ash-cement grouts to achieve the required goals of flow, set time, shrinkage and strength.

Types of additives may include accelerators such as calcium chloride to reduce set times; retarders to increase set time; expanding materials such as powdered aluminum to offset shrinkage; friction reducers or pumping aids to ease pumping, increase flow, and aid in cleanup; wetting and dispersing agents to get a more uniform mixture; and water-reducing agents to lower the water content.

Strength. A minimum strength requirement is normally used to ensure the durability of the grout. A typical value is 4,100 kPa (600 psi) at 7 days measured by the standard mortar cube test, AASHTO T 106 (ASTM C 109). A pozzolan-cement grout is typically designed to achieve a 7-day compressive strength of 4,100 to 5,500 kPa (600 to 800 psi). The ultimate strength of the grout will be much higher (10 to 28 mPa/1,500 to 4,000 psi).

CONSTRUCTION PRACTICES

Equipment. In the past, most grouting/stabilization contractors used batch mixers and bagged materials. Today's contractors use very mobile, self-contained units that carry all the equipment and materials needed for slab stabilization. The dry materials are packaged in either uniform-volume bags or measured by bulk weight.

A colloidal mixer is needed to produce the cement-fly ash grouts. Grout mixes made by these mixers stay in suspension and resist dilution by free water. The two most common types of colloidal mixers are the centrifugal pump and the shear blade. The first pulls the grout through a high-pressure centrifugal pump at high velocity. The shear blade slices through the grout at speeds between 800 rpm and 2000 rpm. The high shearing action and subsequent pressure release of these mixers de-aerate the solid particles, which allows them to be wetted to make a more homogeneous mixture.

It is not recommended to use paddle-type drum mixers to produce cement-fly ash grouts. Grout should never be mixed using a screw conveyor, a mortar mixer, or a ready mix truck. Mixes made with these devices will not be homogenous and will require more water to promote flowability.

Injection holes. Grout injection holes are drilled in a pattern determined by the contracting agency in consultation with the contractor. They are typically no larger than 50 mm (2 in) in diameter, drilled vertically and to a depth sufficient to penetrate any stabilized base and into the subgrade material to a depth of no more than 76 mm (3 in). The holes can be washed with water or blown with air to create a small cavity to better intercept the voids beneath the pavement.

Upon completion of the subsealing, all drilled holes are sealed flush with the pavement surface with a fast-setting concrete or other patching material approved by the engineer.

Pumping and vertical grade control. String lines are established above the pavement to monitor movement during subsealing. An expanding rubber packer or other approved device is lowered into the drilled holes. The discharge end of the packer or hose must not extend below the lower surface of the concrete pavement.

The pressure in the grout must be monitored by an accurate pressure gauge in the grout line that is protected from the grout slurry. Continuous grout pressures to 1,400 kPa (200 psi) are typical, with pressures to 2,100 kPa (300 psi) allowed only for short periods. In the event the pavement is bonded to the subbase, brief pressure rises (10 seconds or fewer) to 4,100 kPa (600 psi) are not unusual. Allow the water displaced from pavement system voids by the grout to flow freely. Take appropriate measures to prevent excessive loss of the grout through cracks and joints or in the shoulder area.

Opening to traffic. The time allowed before traffic can get back on the grouted slabs varies considerably. Deflection measurements taken after slab stabilization have shown that the deflections are reduced over a period of 30 minutes to 3 hours. Grout hardening depends on the temperature, degree of confinement, and grout properties.

CAUTIONS

Pavement movements above the specified tolerances may require grinding or even removal and replacement of the pavement. Existing cracks in the pavement should be marked prior to subsealing operations. New cracks radiating diagonally through the grout injection holes typically will be presumed to have been caused by improper injection techniques and could result in penalties to the contractor or even removal and replacement of the pavement.

When the ambient air temperature is between 2 degrees C and 10 degrees C (35 degrees F and 50 degrees F), add an accelerator to the grout mix. When calcium chloride is used, it must be thoroughly pre-mixed with the water before the addition of dry ingredients. Cement-fly ash grouts should not be used when the ambient temperature is below 2 degrees C (35 degrees F) or when the subgrade is frozen.

DESIGN AND CONSTRUCTION REFERENCES

See Appendix C.

CHAPTER.10

DEVELOPMENTS IN FLY ASH UTILIZATION

INTRODUCTION

Several new and important technologies are being commercialized in the areas of fly ash beneficiation and utilization to bring fly ash into conformance with current AASHTO and ASTM specifications for use in concrete. As the fly ash utilization industry has matured, quality control, quality assurance, and improved product performance have increasingly become important. Technologies have been commercialized to improve and assure fly ash quality for conventional concrete applications. Also, fly ash utilization technologies have been developed to produce high performance concrete products.

Changes in boiler operations or alteration of air emissions control systems at power plants will alter the quality of fly ash produced. Factors that may impact ash quality in this way include:

- A reduction in the pozzolanic reactivity caused by increased proportion of coarse particles
- The presence in the fly ash of excessive unburned carbon (UBC)
- Chemical residuals from post-combustion emission control

PARTICLE SIZE CONTROL

Screening. In mineral processing, it is common practice to use screens to remove coarse particles from powdered products. In general, dry screening of powders is not economically feasible at below 45 µm (325 screen mesh size). Typical fly ash has a large proportion of the particles (typically more than 50 percent) finer than 45 µm. The use of coarse screens (100 or 80 mesh), might be effective for the removal of most of the coarse particles, many of which comprise UBC. The ability to remove carbon by this method depends on the degree to which the carbon-rich particles are discrete (liberated), and the size and shape of the carbon particles. As such, screening may be effective as part of a general ash processing scheme to reduce coarse particle content, reduce carbon content, reduce variability, and improve concrete workability.

Air classification. Classification systems that use air to separate particles by size and weight are also used to retain the finer ash fraction. Air classification may be performed on ash for the removal of coarse particles or the selective concentration of fine particles. In some instances, the products differ not only in particle fineness, but also in carbon content. The type of carbon removed by air classification is comprised of the coarse unburned coal particles.

CARBON REDUCTION TECHNOLOGIES

Carbon removal by combustion. A simple approach to remove carbon is to re-burn it, producing a pozzolan quality fly ash. Carbon removal by combustion is commercially available.

Electrostatic separation. Electrostatic separation exploits the forces acting upon charged particles in an electrical field. This technology basically involves passing fly ash through a high voltage electric field, thus inducing opposite charges on the mineral fly ash particles and residual carbon. The fly ash is separated into a low carbon (less than three percent) pozzolan fraction and a carbon rich reject. Electrostatic separation is commercially available.

TREATMENT PROCESSES

Chemical treatment/carbon modification. Residual carbon in fly ash, as represented by the LOI value, is not the only factor that may affect the performance of AEAs in concrete. Adsorption of AEA due to the level and type of unburned carbon and conductance due to the interaction of soluble ions from the trace mineral components of the fly ash are also factors that interfere with the performance of AEAs. Fly ash can be treated using a chemical reagent to passivate the carbon adsorptive properties. In this technology, carbon is not removed, but its effect on air entrainment is minimized. The chemical treatment of fly ash for carbon passivation is commercially available.

Ammonia removal processes. Certain air emissions control systems may deposit excess ammonia on the fly ash. Technologies under development to deal with ammoniated fly ash include: heat treatment, wet washing/stripping, and chemical treatment. Low concentrations of ammonia have no impact on concrete properties, however, a strong ammonia odor may be emitted.

OTHER DEVELOPMENTS IN TECHNOLOGY

Ultra fine fly ash. As compared to typical fly ash, with a mean particle diameter ranging from 20-30 micrometers, ultra fine fly ash can be produced with a mean particle diameter of 1-5 microns. The reduced particle size means that the pozzolanic reaction, which is normally a slow process is accelerated. Further, the finer particles may more completely react than the coarser particles of fly ash. So, the durability and strength benefits that one observes with a typical fly ash at a late age (more than one year) can be attained at a much earlier age (less than 90 days) and with a smaller dosage of an ultra fine fly ash. Table 10-1 shows typical mix designs containing ultra fine fly ash.

Typically, ultra fine fly ash is used at a replacement rate of 5 to 15 percent of the cement weight. At these dosage levels, it has been demonstrated that ultra fine fly ashes contribute more to concrete strength gain and permeability reduction than common AASHTO M 295 (ASTM C 618) fly ash, and will perform comparable to highly reactive pozzolans such as silica fume. Concrete durability properties such as resistance to alkali-silica reaction, sulfate attack, and corrosion are also enhanced by ultra fine fly ash.

	Portland Cement Concrete	8% Ultra Fine Fly Ash	12% Ultra Fine Fly Ash
Cement, kg/m^3 (lb/yd^3)	375 (632)	345 (582)	330 (556)
Ultra Fine Fly Ash, kg/m^3 (lb/yd^3)	-	30 (50)	45 (76)
Total Cementitious Material, kg/m^3 (lb/yd^3)	375 (632)	375 (632)	375 (632)
Water, kg/m^3 (lb/yd^3)	150 (253)	150 (253)	150 (253)
Water/Cementitious Material, kg/m^3 (lb/yd^3)	0.40	0.40	0.40
High Range Water Reducer, mL/100 kg (oz/100 lb)	625 (9.6)	438 (6.7)	364 (5.6)
Slump, mm (inches)	145 (5.75)	135 (5.25)	160 (6.25)
Rapid Chloride Permeability, coulombs			
28-day	2027	857	707
90-day	1567	418	314
2-year	1103	338	242
Direct Current Resistivity, 10^{-12} m^2/s			
28-day	14.5	31.0	40.6
90-day	24.5	79.9	93.9
2-year	25.8	81.1	107
Chloride Diffusion Coefficient, 10^{-12} m^2/s			
40-day	133	53.3	48.6
90-day	103	37.7	27.9
2-year	94.2	13.3	9.38

Table 10-1. Typical mixes using ultra fine fly ash.

Fly ash blends (Class C and Class F). Both AASHTO M 295 (ASTM C 618) Class C and Class F fly ashes have their own specific advantages when used as a cementitious material in concrete. Table 10-2 summarizes some general properties of concrete made with Class C and Class F fly ashes. It may be ideal to have a fly ash with a low to moderate LOI and that can be used to prepare a concrete that is very effective in resisting ASR, sulfate attack, and at the same time have high early strengths. One way to achieve that is to blend Class C and Class F fly ashes. The exact ratio of the blend will depend upon the specific fly ashes and their desired behavior in concrete. An example of fly ash blend mix design is shown in Table 10-3. Blended fly ashes are being marketed on a small scale in the United States.

High volume fly ash concrete (HVFAC). HVFAC refers to concrete where the fly ash comprises more than 30 percent of the total cementitious materials. HVFAC has a lower cost and is more durable than conventional concrete, and affords improved resistance to ASR and sulfate attack. Several successful field applications have been completed. Adequate early strengths and set times are obtained by using high range water reducers to achieve a very low water/cement ratio. Allowable cement substitution rates are currently limited by state transportation department specifications. An example of an HVFAC mix design

Properties	Class C Fly Ash	Class F Fly Ash
Early strengths (< 28 days)	Very effective; can replace cement 1:1	Effective; may replace cement as high as 1:2
Reduce Permeability	Effective	Very effective
Resistance to ASR	Effective but may require higher amounts	Very effective even at lower amounts
Resistance to sulfate attack	May aggravate problem	Very effective

Table 10-2. Influence of the class of fly ash on concrete performance.

is shown in Table 10-4.

Properties	Quantities	
	Metric Units	English Units
Portland Cement	154 kg/m^3	259 lb/yd^3
Class F - Fly Ash	80 kg/m^3	134 lb/yd^3
Class C - Fly Ash	61 kg/m^3	103 lb/yd^3
Water	185 kg/m^3	312 lb/yd^3
Air-Entraining Admixture	0 mL/100 kg	0 oz/100lb
Superplasticizer	2,730 mL/100 kg	42 oz/100lb
Compressive Strength		
7 Days	27 Mpa	3946 psi
28 Days	41 Mpa	5891 psi
56 Days	46 Mpa	6617 psi

Table 10-3. Example mix designs incorporating Class C and Class F blend.

Properties	Quantities	
	Metric Units	English Units
Cement	155 kg/m^3	261 lb/yd^3
Fly Ash	215 kg/m^3	362 lb/yd^3
Water	120 kg/m^3	202 lb/yd^3
Air Entraining Admixture	54 kg/m^3	0.8 lb/yd^3
Superplasticizer	1,216 kg/m^3	18.7 lb/yd^3
Compressive Strength		
1 Day	8 Mpa	1,160 psi
7 Days	20 Mpa	2,900 psi
28 Days	35 Mpa	5,075 psi
91 Days	43 Mpa	6,235 psi
365 Days	55 Mpa	7,975 psi
Flexural Strength		
14 Days	4.5 Mpa	650 psi
91 Days	6.0 Mpa	870 psi
Splitting-Tensile Strength		
28 Days	3.5 Mpa	510 psi
Young's Modulus Elasticity		
28 Days	35 Gpa	5.08 mpsi
91 Days	38 Gpa	5.51 mpsi
Drying Shrinkage Strain at 448 Days	500 ± 50 x 10^{-6}	
Specific Creep Strain at 365 Days (per Mpa of stress)	28 ± 4 x 10^{6}	
Rapid Chloride Permeability, coulombs		
28-Day	500 - 2,000	
90-Day	200 - 700	
1-Year	≈ 150	

Table 10-4. Example mix design for HVFAC.

APPENDIX.A

CONVERSION FACTORS

1 inch	2.54 cm
1 foot	0.305 m
1 pound	0.436 kg
1 ton	0.907 tons (metric)
1 psi	6.895 kPa
1 psf	0.479 kPa
1 gal/sy	4.527 liters/m3
° C	5/9 (° F - 32°)
° F	9/5 (° C + 32°)

APPENDIX.B

SPECIFICATIONS AND RECOMMENDED PRACTICE GUIDELINES

American Association of State Highway and Transportation Officials (AASHTO)

AASHTO M 85	Specification for Portland Cements
AASHTO M 172	Standard Specification for Mineral Filler for Bituminous Paving Mixtures
AASHTO M 240	Specification for Blended Cements
AASHTO M 295	Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete
AASHTO T 26	Standard Method of Test for Quality of Water to be Used in Concrete
AASHTO T 99	Standard Method of Test for Moisture-Density Relation of Soils Using a 2.5 kg (5.5 pound) Rammer and 305 mm (12 inch) Drop
AASHTO T 106	Standard Method of Test for Compressive Strength of Hydraulic Cement Mortar (Using 50 mm or 2 inch) Cube Specimens
AASHTO T 197	Standard Method of Test for Time of Settling of Concrete Mixtures by Penetration Resistance
AASHTO T 232	Standard Method of Test for Cement Content of Freshly Mixed Soil-Cement

American Society for Testing and Materials (ASTM)

ASTM C 29	Test Method for Unit Weight and Voids in Aggregates
ASTM C 33	Specification for Concrete Aggregates
ASTM C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM C 78	Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
ASTM C 94	Specification for Ready Mixed Concrete
ASTM C 109	Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)

ASTM C 150	Specification for Portland Cement
ASTM C 403	Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
ASTM C 494	Specification for Chemical Admixtures for Concrete
ASTM C593	Fly Ash and Other Pozzolans for Use with Lime
ASTM C 595	Specification for Blended Hydraulic Cements
ASTM C 596	Test Method for Drying Shrinkage of Mortar Containing Portland Cement
ASTM C 618	Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
ASTM C 666	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
ASTM C 672	Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
ASTM C 685	Specification for Concrete Made by Volumetric Batching and Continuous Mixing
ASTM C 917	Test Method for Evaluation of Cement Strength Uniformity From a Single Source
ASTM C 928	Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs
ASTM C 939	Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method)
ASTM C 1157	Performance Specification for Hydraulic Cement
ASTM D 698	Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft3 (600 kN-m/m3))
ASTM D 1883	Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils
ASTM D 2901	Test Method for Cement Content of Freshly Mixed Soil-Cement
ASTM D 4318	Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
ASTM D 4829	Test Method for Expansion Index of Soils
ASTM D 5239	Practice for Characterizing Fly Ash for Use in Soil Stabilization
ASTM E 1861	Guide for Use of Coal Combustion By-Products in Structural Fills

American Concrete Institute (ACI)

ACI 211.1	Standard Practice for Selecting Proportions of Normal, Heavyweight, and Mass Concrete
ACI 211.4R	Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash
ACI 212.3R	Chemical Admixtures for Concrete
ACI 214	Recommended Practice for Evaluation of Strength Results of Concrete Strength Testing
ACI 226.1R	Ground Granulated Blast Furnace Slag as A Cementitious Constituent in Concrete
ACI 229R	Controlled Low Strength Materials (CLSM)
ACI 232.2R	Use of Fly Ash in Concrete
ACI 301	Specifications for Structural Concrete for Buildings
ACI 305R	Hot Weather Concreting
ACI 306R	Cold Weather Concreting
ACI 318	Building Code Requirements for Reinforced Concrete
ACI 363R	State-of-the-Art Report on High-Strength Concrete
ACI 363.2R	Guide to Quality Control and Testing of High Strength Concrete

Other Test Methods

ANSI/AWWA C105/A21.5	American National Standard for Polyethylene Encasement for Ductile-Iron Pipe Systems

APPENDIX.C

DESIGN AND CONSTRUCTION REFERENCES

PORTLAND CEMENT CONCRETE

ACI Manual of Concrete Practice, American Concrete Institute, Farmington Hills, Michigan.

Fast Track Concrete Pavements, Technical Bulletin 004P, American Concrete Pavement Association, Skokie, Illinois, 1994.

STABILIZED BASE COURSE

Coal Fly Ash in Pozzolanic Stabilized Mixtures for Flexible Pavement Systems (Flexible Pavement Manual), American Coal Ash Association, Washington, DC.

Guidelines and Guide Specifications for Using Pozzolanic Stabilized Mixture (Base Course or Subbase) and Fly Ash for In-Place Subgrade Soil Modifications, AASHTO Task Force Report 28, Washington, DC.

Soil and Pavement Base Stabilization with Self-Cementing Coal Fly Ash, American Coal Ash Association, Alexandria, Virginia, May 1999.

FLOWABLE FILL

ACI 229R, *Controlled Low Strength Materials, American Concrete Institute,* Farmington Hills, Michigan.

NRMCA Flowable Fill Pamphlet, National Ready Mixed Concrete Association.

GROUTS FOR PAVEMENT SUBSEALING

Slab Stabilization Guidelines for Concrete Pavements, Technical Bulletin 018P, American Concrete Pavement Association, Skokie, Illinois, 1994.

SOIL IMPROVEMENT

Soil and Pavement Base Stabilization with Self-Cementing Coal Fly Ash, American Coal Ash Association, Alexandria, Virginia, May 1999.

Fly Ash for Soil Improvement, Geotechnical Special Publication No. 36, American Society of Civil Engineers, New York, New York, 1993.

Guidelines and Guide Specifications for Using Pozzolanic Stabilized Mixture (Base Course or Subbase) and Fly Ash for In-Place Subgrade Soil Modifications, AASHTO Task Force Report 28, Washington, DC.

STRUCTURAL FILLS/EMBANKMENTS

ASTM E 1861, Structural Guide for the Use of Coal Combustion By-Products in Structural Fills, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

Technical Advisory T 5080.9, Use of Coal Ash in Embankments and Bases, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, May 1988.

ASPHALT PAVEMENTS

American Association of State Highway Transportation Officials. Standard Method of Test, *Mineral Filler for Bituminous Paving Mixtures,* AASHTO Designation M17-83, Part 1 Specifications, 14th Edition, 1986.

L. Allen Cooley, Jr. and Michael H. Huner. *Evaluation of Fly Ash Sources for Use as Mineral Filler in Hot Mix Asphalt*, Proceedings: 14th International Symposium on Management and Use of Coal Combustion Products, Volume 2, Palo Alto, California, January 2001.

Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt, National Asphalt Pavement Association, Information Series 118, August 1994.