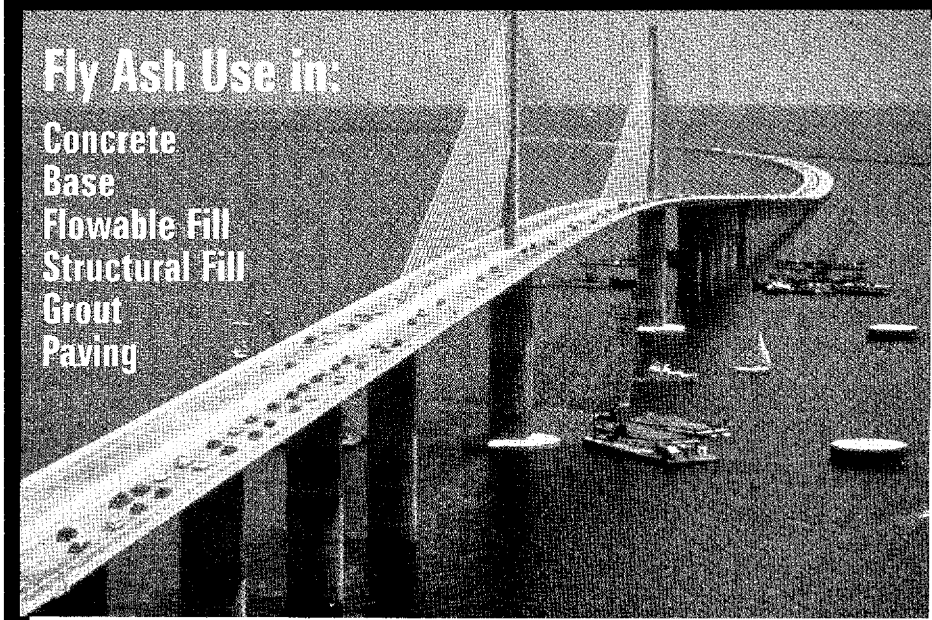
U.S. Department
of Transportation
Federal Highway
Administration

Fly Ash Facts for Highway Engineers



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Coal fly ash is a coal combustion byproduct (CCB) that has numerous applications as an engineering material; the annual production of CCBs is nearly 82 million metric tons (90 million tons). Since the first edition of *Fly Ash Facts for Highway Engineers* in 1986, substantial information has been accumulated regarding the use of fly ash. The purpose of this document is to provide technical information about engineering applications to potential users of CCBs and to advance the use of CCBs in ways that are technically sound, commercially competitive, and environmentally safe.

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PREFACE

Coal fly ash is a coal combustion byproduct (CCB) that has numerous applications as an engineering material; the annual production of CCBs is nearly 82 million metric tons (90 million tons). Since the first edition of *Fly Ash Facts for Highway Engineers* in 1986, substantial information has been accumulated regarding the use of fly ash. The purpose of this document is to provide technical information about engineering applications to potential users of CCBs and to advance the use of CCBs in ways that are technically sound, commercially competitive, and environmentally safe.

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This report was prepared by and is distributed through the Office of Technology Applications (OTA). OTA appreciates the many agency and industry representatives who provided information and technical comments necessary to compile this document.

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Fly Ash as 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.

Where does it come from? Fly ash is a byproduct of coal-fired electric generating plants. The coal is pulverized and blown into a burning chamber where it immediately ignites to heat the boiler tubes. Heavier ash particles (bottom ash or slag) fall to the bottom of the burning chamber and the lighter ash particles (fly ash) remain suspended in the exhaust gases. Before leaving the stack, these fly ash particles are removed by an electrostatic precipitator, bag house, or other method. See figure 1.

What makes it useful? Fly ash is a pozzolan, meaning it is a siliceous or siliceous and aluminous material that, in the presence of water, will combine with an activator (lime, portland cement or kiln dust) to produce a cementitous material.

What are we doing with it? Currently, approximately 9.53 million metric tons (10.5 million tons) of coal fly ash are used annually for engineering applications. The greatest volumes of ash are used in cement and concrete products, structural fills, and roadbases.

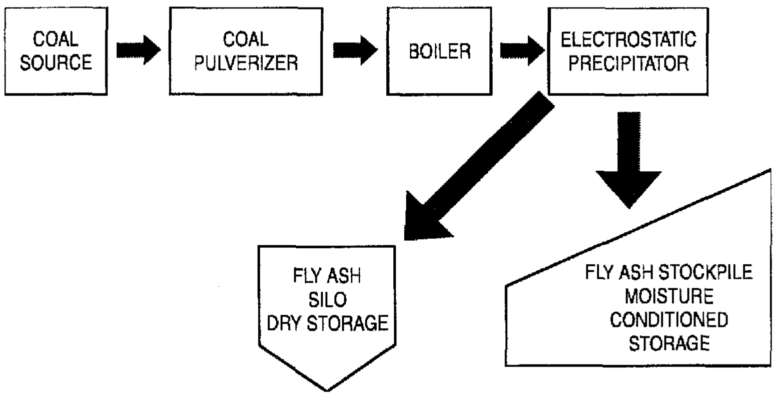


Figure 1. Fossil fuel power plant schematic.

PRODUCTION

Three basic types of burners produce fly ash. Pulverized coal burners are the most widely used. The other two types are stoker fired and cyclone burners.

Table 1. 1993 fly ash production and use.

	Million metric tons	Million short tons	Percent
• Produced	43.50	47.8	100.0
• Used	9.53	10.5	22.0

As shown in table 1, of the 43.5 million metric tons (47.8 million tons) of fly ash produced in 1993, only 9.53 million metric tons (10.5 million tons), or 22 percent of total production, was used. The following is a breakdown of fly ash uses, much of which is used in the transportation industry.

Table 2. 1993 fly ash uses.

	Million metric tons	Million short tons	Percent
Cement and concrete products	6.17	6.8	65%
Roadbase/subbase	.91	1.0	9.5%
Structural fills, embankments	.83	.91	8.7%
Flowable fills	.34	.38	3.6%
Filler in asphalt mixes	.10	.11	1.0%
Grouting	.02	.02	0.2%
Waste Stabilization	.40	.44	4.2%
Other applications	.76	.84	7.8%
	9.53	**10.5**	**100**

HANDLING

Fly ash is most often collected by electrostatic precipitators or bag houses. It is usually handled and stored in silos much like portland cement. The majority of fly ash produced is managed in one of three ways:

- Collected in closed trucks and placed in a monofill storage site.
- Conditioned (by the addition of about 20 percent water), placed and compacted at a monofill storage site.
- Mixed with large quantities of water and sluiced to a storage pond (often with bottom ash).

CHARACTERISTICS

Size and Shape. Fly ash particles are generally spherical and similar in size to portland cement and lime.

Chemistry. Fly ash particles are composed of glass with crystalline matter, carbon, and varying quantities of lime. Fly ash is divided into two classes based on the chemical composition of the ash. Ashes from subbituminous and lignite coals are Class C ashes and may contain more than 20 percent CaO. Ashes from bituminous and anthracite coal are Class F ashes and generally contain less than 10 percent CaO. Typically, Class C ashes contain 1 percent to 3 percent free lime and are reactive with water. Class F ashes generally contain no free lime.

Table 3. Typical chemical compositions.

	Fly Ash Class		Portland Cement
Compounds	Class F	Class C	
SiO_2	54.9	39.9	22.6
Al_2O_3	25.8	16.7	4.3
Fe_2O_3	6.9	5.8	2.4
CaO(Lime)	8.7	24.3	64.4
MgO	1.8	4.6	2.1
SO_3	0.6	3.3	2.3

Color. Fly ash can be tan to gray or black, depending on the source. Tan usually indicates a higher lime content, and gray to black indicates a higher carbon content. Typical samples of the two classes are shown in figure 2.

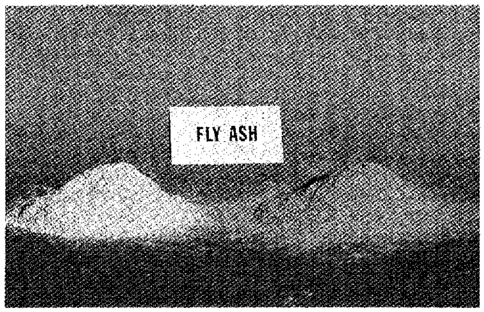
Class C  Class F

Figure 2. Examples of Class C and Class F fly ash.

QUALITY OF FLY ASH

What determines fly ash quality? Various aspects of the production process affect fly ash quality. The four most relevant characteristics of fly ash are loss on ignition, fineness, chemical composition, and uniformity. *Specification for Fly Ash in Concrete,* page 8, details these requirements.

Loss on ignition (LOI) is a measurement of unburned carbon (coal) remaining in the ash and is perhaps the single most critical characteristic of fly ash. Higher carbon contents can result in significant air-entrainment problems and can adversely affect the performance of concrete incorporating the ash.

Fineness of a particular fly ash is most closely related to the operating condition of the coal crushers and the grindability of the coal itself. It is a measure of the percent retained on the No. 325 sieve. A coarser gradation can result in a less reactive ash as well as higher carbon contents.

Chemical composition of an ash relates directly to the coal burned. Sources of coal are often blended at the production facility to achieve maximum efficiency from available fuel. Even where sources are not changed, variations in blending can affect ash chemistry, which directly affects its performance.

Uniformity of fly ash characteristics from shipment to shipment is imperative in order to produce a consistently good product. Variations in ash characteristics must be known in advance so mix designs and field procedures can be adjusted as appropriate. Be sure to conduct adequate testing prior to using a particular fly ash in an engineering design.

How can I know I'm getting good quality? The standard specifications used to determine fly ash quality are listed in table 4.

Table 4. Standard specifications for determining fly ash quality.

ACI 229R-94	Controlled Low Strength Materials (CLSM)
ASTM C 311	Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete.
ASTM C 618 (AASHTO M 295)	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 PS 23-95	Guide for the Use of Coal Combustion Fly Ash in Structural Fills

Methods of ensuring conformance with specifications vary from State to State and source to source. Some States require sealed silo 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 necessary depends on one's experience with a particular ash and its specific history of variability. When possible, purchasers prefer source approval with shipment certification to prior testing and approval of each shipment. Costs increase when silos are required for storing the material during the approval process; silo storage should be required only when necessary for acceptable control. Several States have adopted source approval/shipment certification procedures that, with minimal effort, could be adapted to a particular purchaser's needs.

Do I need to know more about this technology to use it confidently? Fly ash can produce a quality product at a competitive cost if appropriate precautions are taken in its use. This publication provides a general overview of fly ash uses from a materials, design, and construction perspective. It will familiarize generalist highway engineers and inspectors with this technology. This publication is designed to assist those individuals who have little or no previous experience using fly ash or experience in a particular application of fly ash.

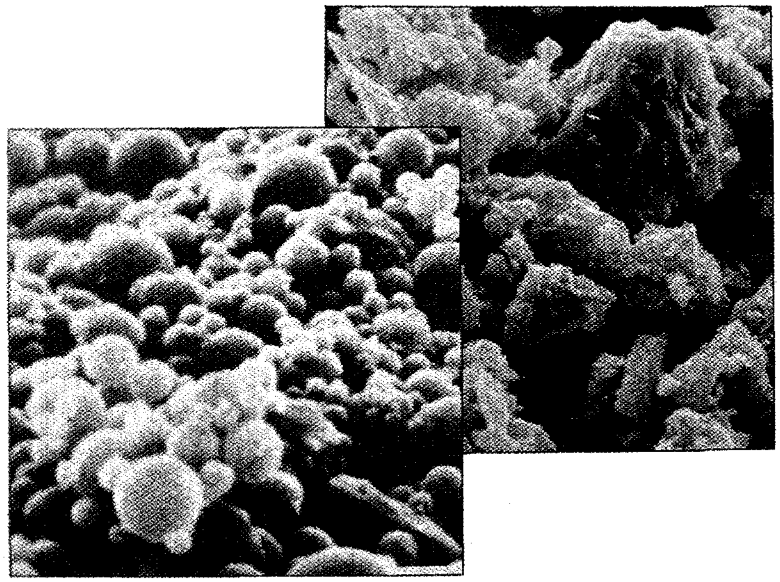


Figure 3. Fly ash (left) and portland cement (right).

SPECIFICATION FOR FLY ASH IN CONCRETE

AASHTO M 295 (ASTM C 618)	Class F & C	
Chemical Requirements		
$SiO_2 + Al_2O_3 + Fe_2O_3$	min%	70[1]
SO_3	max%	5
Moisture content	max%	3
Loss on ignition (LOI)	max%	5[2]
Optional Chemical Requirements		
MgO	max%	5[3]
Available alkalies	max%	1.5[4]
Physical Requirements		
Fineness (+ 325 Mesh)	max%	34
Pozzolanic activity/cement (7 days)	min%	75[5]
Pozzolanic activity/lime	min psi	--[6]
Water requirement	max%	100[7]
Autoclave expansion	max%	0.8
Uniformity requirements:		
Specific gravity variability	max%	5
Fineness variability	max%	5
Optional Physical Requirements		
Multiple factor (LOI x Fineness)		255[8]
Increase in drying shrinkage	max%	.03
Uniformity requirements:		
A.E. Mixture demand air entraining Agent demand	max%	20
Cement/Alkali Reaction:		
Mortar expansion (14 days)	max%	0.020

Notes:
1. Class C requirements are 50 percent
2. ASTM requirements are 6 percent
3. No ASTM requirements
4. Optional requirements per ASTM
5. ASTM requirements are 75 percent of control at 28 days
6. ASTM requirements are 5516 kPa (800 psi) minimum @ 7 days for Class F
7. ASTM requirements are 105% maximum
8. No requirement for Class C

CHAPTER 2
Frequent Applications

FLY ASH IN PORTLAND CEMENT CONCRETE

Overview: Benefits and Cautions

Is fly ash in PCC a new idea? As early as 1914, *Engineering News Record* published research results recognizing that portland cement concrete can benefit from the addition of fly ash. Since then, various organizations have conducted considerable research demonstrating the satisfactory performance of fly ash concrete under diverse conditions.

How does it work? Portland cement contains about 65 percent lime. During the hydration process, some of this lime becomes free and available. When fly ash is present in the free lime mix, it reacts with this cementitious material.

What are the benefits? Research has demonstrated the many benefits of incorporating fly ash into a portland cement concrete mix. It must be emphasized that not all benefits will be realized in every case. Fly ashes and portland cements vary, as do field conditions, but some of the benefits are:

- Significant strength gain.
- Improved workability.
- Reduced bleeding.
- Reduced heat of hydration.
- Reduced permeability.
- Increased resistance to sulfate attack.
- Increased resistance to alkali-silica reactivity.
- Lowered costs.

Some of the cautions that should be observed when using fly ash in concrete are:

- Decreased air entraining ability.
- Decreased early strength.
- Seasonal limitations.

These limitations should not discourage the use of fly ash in concrete. However, they should be considered during design and practice. Evaluate each mix to determine which benefits and cautions apply. Chapter 3 includes a discussion of the benefits and cautions. *Mixture Proportioning Concepts*, page 26, discusses sample mix designs.

FLY ASH IN STABILIZED ROADBASES

Overview: Benefits and Cautions

What is it? Fly ash and lime* can be combined with aggregate to produce a good quality stabilized roadbase. These roadbases are often referred to as pozzolanic-stabilized mixtures (PSMs). Typical fly ash contents may vary from 12 to 14 percent with corresponding lime contents of 3 to 5 percent. Portland cement may also be used in lieu of lime to increase early age strengths. The resulting material is produced, placed, and even looks like cement-stabilized aggregate base.

PSM bases have many advantages over other base materials. Some of the benefits are:

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

Some of the cautions when using a PSM are:

- Seasonal limitations.
- Traffic loading before complete curing.
- Proper sealing and protection with asphalt or other surface treatment.

**Other materials containing lime, such as portland cement and kiln dust, may also be used but may require testing or certification.*

Chapter 4 provides a basic understanding of PSM base design and construction, and mixture proportioning concepts are detailed on page 45. Additional information can also be obtained from the American Coal Ash Association's *Flexible Pavement Manual,* December 1991. See the reference list, page 67.

FLY ASH IN FLOWABLE FILL APPLICATIONS

Overview: Benefits and Cautions

What is flowable fill? 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.

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 and under structures that would be 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 because no workers are required in the trench.

- Decreases excavation costs because no space is required for compaction equipment and less material needs to be removed
- Available from practically all ready mixed concrete producers who use fly ash in their operations.
- Allows easy excavation later when properly designed.

Cautions to observe when using flowable fill include:

- Anchor lighter weight pipes to prevent floating.
- Needs confinement before initial set of the material.

Chapter 5 includes a detailed discussion of flowable fill applications. Typical mix designs are presented in tables 5 and 6, *Typical Mixture Proportioning Concepts for Flowable Fills*, on page 45.

FLY ASH IN GROUTS FOR CONCRETE PAVEMENT SUBSEALING

Overview: Benefits and Cautions

What are grouts? Grouts are proportioned with fly ash and other materials to fill voids under the pavement system without raising the slabs (subsealing) and to raise and support concrete pavements at specified grade tolerances by drilling and injecting the grout under specified areas of the pavement.

The benefits of using fly ash grouts are:

- Can be used to correct undermining without removing overlying pavement.
- Can be accomplished quickly with minimum disturbance to traffic.
- Can develop high ultimate strength.

Cautions to observe when using fly ash grouts are:

- May require curing period before extremely heavy loading because of low early strength.
- Requires confinement for grout mixture under pavement.

In Chapter 6, the section on *Mix Design*, page 49, presents more information on this topic.

FLY ASH IN FAST TRACK CONCRETE PAVEMENTS

Overview: Benefits and Cautions

Where can fast track pavements be used and what are the benefits? Increasing public and commercial use of existing airports, roadways, and urban streets has introduced major problems for airport authorities and State and municipal governments. Traditional repair or replacement solutions are aggravated by the ever-increasing traffic volumes and the public's consciousness of traffic interruption. These problems are especially acute in urban areas where congestion is most severe.

Fast track portland cement concrete (PCC) pavement construction can help resolve these problems with the following four benefits:

- Provides high-quality, long-lasting results.
- Short downtime and quick public access for airfield, highway, and municipal pavements.
- Well-suited for reconstruction or resurfacing with minimal traffic interruption.
- Can be incorporated into almost all pavement types including bonded overlays, unbounded overlays, overlays of existing asphalt, new construction, and reconstruction.

A caution is:

- Ensure proper curing time and conditions.

Taking advantage of fast track concrete construction requires minimal changes in traditional mix design procedures, construction procedures, and responsibilities. Chapter 7 provides information about fast track concrete pavement planning and construction and table 7, *Mixture Proportioning Concepts*, page 58, provides guidelines for mix design.

FLY ASH IN STRUCTURAL FILLS/EMBANKMENTS

Overview: Benefits and Cautions

What is a fly ash structural fill/embankment? Fly ash can be used as a borrow material in the construction of fills. When the fly ash is compacted in lifts, a structural fill is constructed that is capable of supporting buildings or other structures. An embankment is constructed when the fly ash is placed to support roads or to impound water. Fly ash has been used in the construction of structural fills/embankments that range from small fills for highway shoulders to large fills for interstate highway alignments.

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

- Fly ash is cost-effective in many areas because it is available in bulk quantities and reduces the expenditures for the purchase, permits, and operation of a borrow pit.
- Its low unit weight makes it ideal for placement over low bearing strength underlying soils.
- Its relatively high shear strength (compared to its unit weight) makes it ideal for placement under building foundations.
- Its ease of handling and compaction reduce construction time and equipment costs.

Some cautions are:

- Leachability and interaction with groundwater must be tested on a site-specific basis.
- Fly ash requires dust control and erosion prevention measures.

Chapter 8 includes more information, and equipment, lift thickness, and related information is presented in table 8, page 65.

CHAPTER 3
Use in Portland Cement Concrete

Fly ash in concrete contributes to improved performance in numerous ways.

- ***Resists alkali aggregate.*** Many fly ashes react with available alkalies in the concrete, which makes them less available to react with the aggregate.[1,2,3]
- ***Resists sulfate attack.*** Fly ash combines with lime, which makes it less available to react with sulfates. The resulting cementitous material also blocks concrete bleed channels that can hinder further entry of the aggressive soluble sulfates. This combination often improves a concrete's resistance to sulfate attack.
- ***Increases ultimate strength.*** Fly ash concrete gains strength over time. Mixtures designed to produce equivalent strength at early ages (fewer than 90 days) will ultimately exceed the strength of conventional portland cement concrete mixes. (See figure 4.)

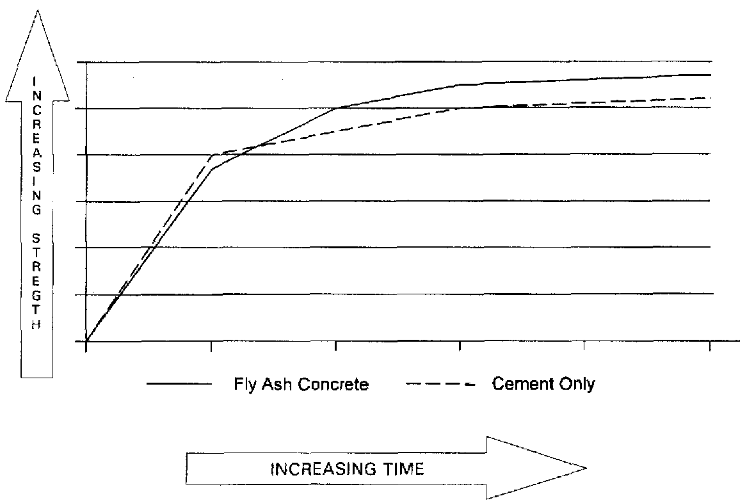


Figure 4. Strength gain of fly ash concrete.

- ***Improved workability.*** The spherical shape and small size of fly ash particles combine to lubricate the mix. (See figure 5.)

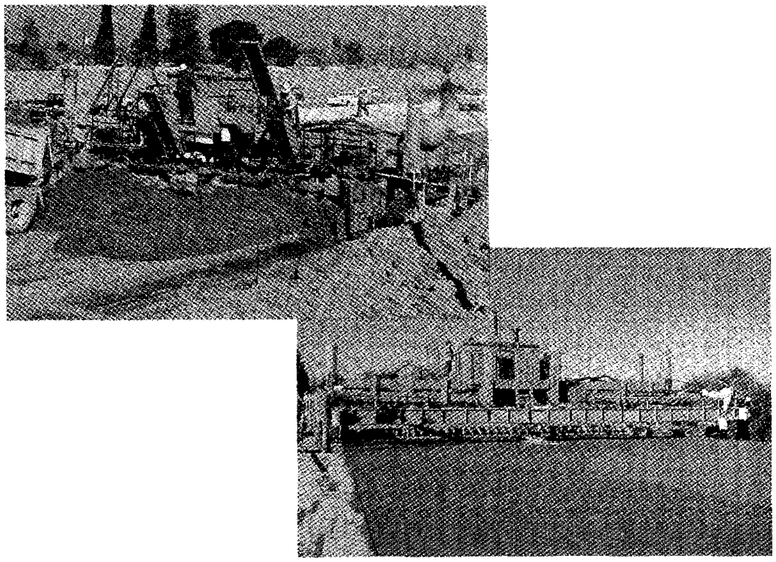


Figure 5. The addition of fly ash to concrete enhances workability even in very stiff mixes.

- ***Reduced bleeding.*** The improved workability leads to lower water requirements, which results in less bleeding and consequently more durable surfaces. (See figure 6.)

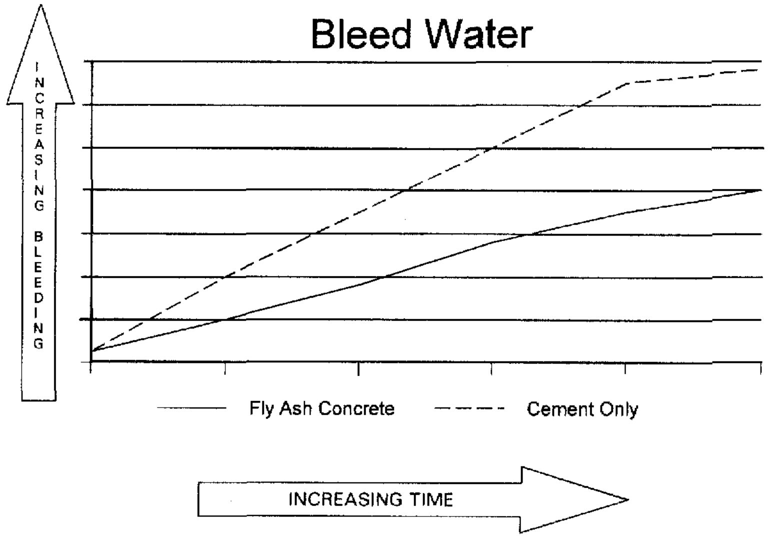


Figure 6. Typical concrete bleed water curves.

- ***Reduced heat of hydration.*** Fly ash reaction generates heat more slowly than the faster reacting portland cement. Some researchers claim that substitution also can slow the hydration of portland cement itself. This combination can lessen heat problems in mass concrete placements.

- ***Reduced permeability.*** Fly ash reaction with available lime and alkalies generates additional cementitous compounds that block bleed channels. (See figure 7.)

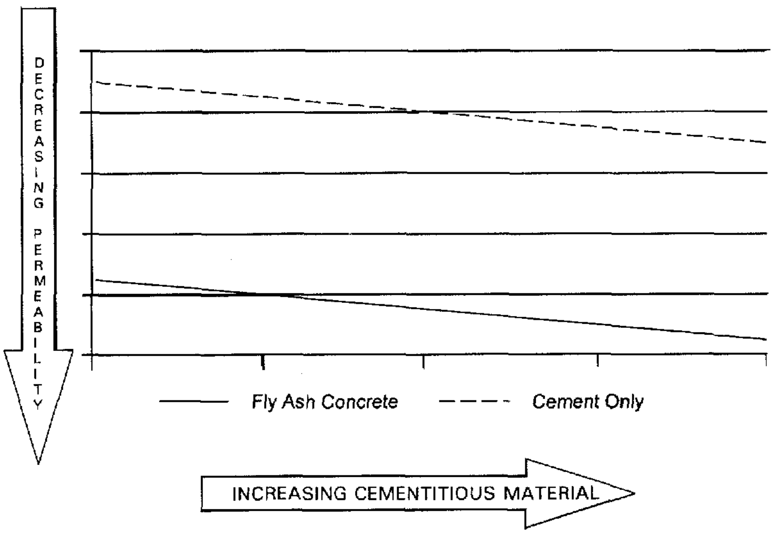


Figure 7. Permeability.

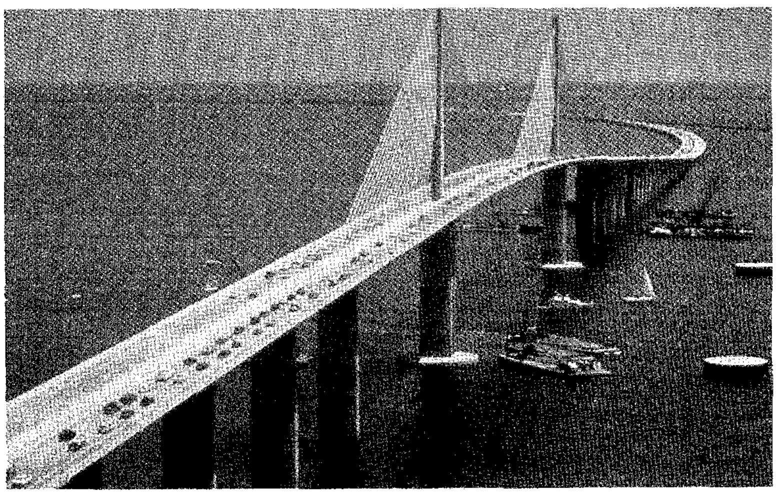


Figure 8. Fly ash concrete improved both the fresh and hardened concrete properties in the decks and piers of Tampa Bay's Sunshine Skyway Bridge.

- ***Lowered costs.*** If the substitution mix design method (discussed in chapter 3) is employed, actual cement costs can be reduced. After considering the cost of incorporating fly ash into a mix, the real savings may be significant.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Procedures for proportioning fly ash concrete (FAC) mixes necessarily differ slightly from those for conventional PCC. Basic guidelines are contained in the American Concrete Institute (ACI) Recommended Practice 211.1. Highway agencies generally use variations to this procedure, but the basic concepts recommended by ACI are widely acknowledged and accepted. Conceptual procedures for proportioning of fly ash concrete are outlined in *Mixture Proportioning Concepts*, page 26.

There are two basic approaches to developing an FAC mix design. One method removes portland cement and adds fly ash to provide equivalent performance. The second method adds fly ash to a mix design to provide improved performance. Portland cement replacement percentages may vary from 15 percent to 25 percent with some even higher percentages substituted for mass concrete placements. It is recommended that an equivalent or greater weight of fly ash replace the cement removed. Substitution ratios of fly ash to portland cement normally vary from 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, develop curves for various replacement ratios and select the optimum replacement percentage and ratio. This mix design development should be performed using the proposed construction materials.

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

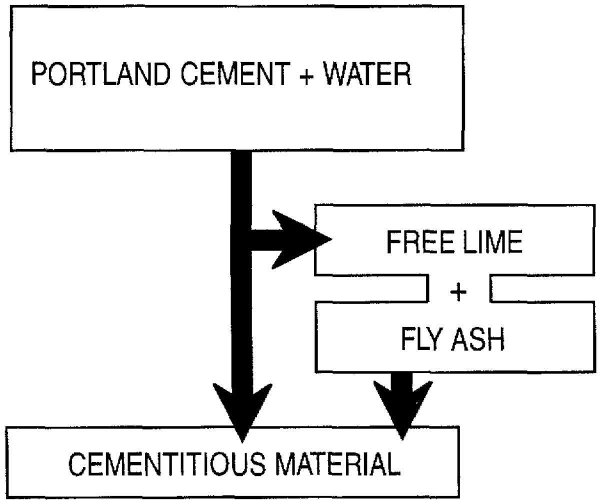


Figure 9. Hydration Reaction

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

EFFECTS OF MATERIAL CHARACTERISTICS ON FLY ASH CONCRETE QUALITY

Various characteristics of fly ash and other constituents with which it is used can significantly affect the quality of concrete produced. Those material characteristics of greatest importance and their effects on the product are discussed below.

Fly Ash Physical Properties

Particles. Fly ash consists largely of solid and hollow spherical particles with some irregularly shaped carbon and other particles. The carbon and hollow particles tend to float to the top during the concrete finishing process and may produce dark-colored surface streaks. Larger concentrations of these particles are not desirable.

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 No. 325 sieve. Significantly finer ashes (90 to 95 percent + passing No. 325) may increase water requirements and increase the demand for air entraining admixture.

Specific gravity. Although specific gravity does not directly affect concrete quality, it is of definite 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 properties. Silicon dioxide, aluminum oxide, and iron oxide are active components in fly ash. These components react with calcium ions to produce cementitious material. Ashes tend to contribute to concrete strength at a faster rate when these components are mostly present in finer fractions of the ash. The converse is also true.

AASHTO limits magnesium oxide to a maximum of 5 percent to prevent deleterious expansion caused by the formation of magnesium hydroxide.

Sulfur trioxide content is limited to 5 percent as greater amounts have been shown to increase mortar bar expansion. Within specification limits, higher SO_3 contents may in some cases result in higher early concrete strength.

Available alkalies in most ashes are less than the specification limit of 1.5 percent. Concentrations greater than this may adversely affect alkali-aggregate expansion problems. Generally speaking, however, most fly ashes will assist in eliminating potential problems in this area. For more information on alkali-silica reactivity, the Mid-Atlantic Regional Technical Committee has published *Guide to Alkali-Aggregate Reactivity* and *Guide Specifications for Concrete Subject to Alkali-Silica Reactions.*

Loss on ignition (LOI), as stated, is a measurement of unburned carbon remaining in the ash. It can range up to 5 percent per AASHTO and 6 percent per ASTM. This remaining unburned carbon will adsorb air entraining admixtures (AEA) and increase water requirements. Values greater than 3 to 4 percent will probably necessitate significant increases in AEA dosage while lower values may require only minor adjustments. Also, some of the carbon in fly ash may be encapsulated in glass or otherwise be less active and therefore not affect the mix. Variations in this characteristic can contribute to fluctuations in air content and call for more careful field monitoring of entrained air in the concrete.

OTHER CONSTITUENTS

Aggregates. Conduct appropriate sampling and testing to ensure the aggregate to be used in mix design development is of good quality and accurately represents materials that will be used on the project. Some aggregates of marginal quality have been observed to adversely affect the air void matrix in hardened concrete. If durability of an FAC trial batch is below expectations, examine aggregate quality as a possible contributor.

Cement. Fly ash can be used effectively in combination with all types of portland cement, but it is not recommended for routine use with high early strength or pozzolanic cements. Cements 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 merits and also evaluated in combination with the specific fly ash to be used.

Chemical admixtures. Air Entraining Admixtures (AEAs): neutralized vinsol resins are frequently used in FAC and generally produce good results. Unfortunately, they are readily adsorbed by carbon in the ash and thus are quite sensitive to fluctuations in LOI and carbon adsorbency. They will normally produce satisfactory results if the LOI is less than about 4 percent and the ash characteristics do not fluctuate.

Increasing use of fly ash has prompted many companies to develop AEAs specifically for use in FAC. Some of these can produce good results, but it is strongly recommended that the AEA selected for use be evaluated on its own merits. The size, distribution, and durability of bubbles produced, along with the gross amount of air entrained, significantly affect concrete durability. All of these parameters should be evaluated whenever possible because changes in other aspects of FAC mix design can inhibit the effectiveness of AEA.

Retarders. Adding fly ash should not appreciably alter the effectiveness of an otherwise acceptable retarder. However, fly ash in the mix usually delays the time of set and may reduce the need for retarder. In many cases, retarder dosage should be reduced or eliminated to avoid unacceptable delays in concrete set time.

Water reducers. Fly ash concrete normally requires less water, but it can be further improved with the use of water-reducing admixtures. The effectiveness of these admixtures may vary with the addition of fly ash. It is recommended that normal water-reducing admixtures be used in lieu of the retarding types unless it is specifically determined that a retarder is needed.

CONSTRUCTION PRACTICES

General Considerations

The effects to construction practices of using FAC in lieu of conventional PCC depend on the specific characteristics of the mix design being used. FAC mix designs can be developed that will perform essentially the same as PCC mix designs with only minor detectable differences in handling and finishing. 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 and holding bin. Because the volume of fly ash used is usually significantly less than the volume of portland cement required, it might be cost-effective to store the fly ash in a tanker truck or other container in lieu of a second silo. Take care to clearly mark the loading pipe for fly ash to guard against confusion when deliveries are made.

If a separate holding bin cannot be provided economically, it may be possible to divide the portland cement holding bin. However, use a double-walled divider to ensure there are no small holes. Fly ash particles will flow through even the smallest hole and over time make it much larger.

Fly ash should be weighed on top of the cement. It is not normally good practice to place it into the weigh bin first because it can leak through openings that will hold portland cement.

Take care to keep concrete mixing, agitation time, and conditions as uniform as possible from delivery to delivery. A worn mixer, a little water in a truck, or a driver stopping for a soft drink are examples of seemingly small variables whose effects to the mix could be magnified with the use of fly ash.

Field Practices

Beginning with the first concrete delivery to the job site, check every load for entrained air until project personnel are confident a good consistent air content is being obtained. After that, regular and closely spaced checks should continue to ensure consistency.

Place the concrete as quickly as possible to reduce air loss in the mix during agitation. FAC mix handling characteristics allow it to be placed easily. The need for vibration during placement should be minimal. Definitely avoid excessive vibration because it will lower the in-place air content of the concrete. Adjust automated equipment to ensure that only the minimum vibration necessary to properly place the concrete is provided.

FAC has more cement paste and less bleed water than conventional PCC, thus the surface will be a bit more sticky during the finishing process.

Finishers might be frustrated by the seemingly dry sticky surface, but they should be cautioned against overworking. The unnecessary surface manipulation results in a loss of air in the exposed area of the concrete, which increases the potential for scaling.

The slower strength development of FAC might require that the concrete retain moisture for a longer period of time. Proper application of curing compound will normally retain moisture as long as economically feasible. Other curing methods are certainly acceptable as long as the specified acceptance strength can be achieved.

The improved workability of FAC is likely to result in an overall easier placement. Many contractors report improved smoothness of FAC pavements over those constructed with conventional PCC.

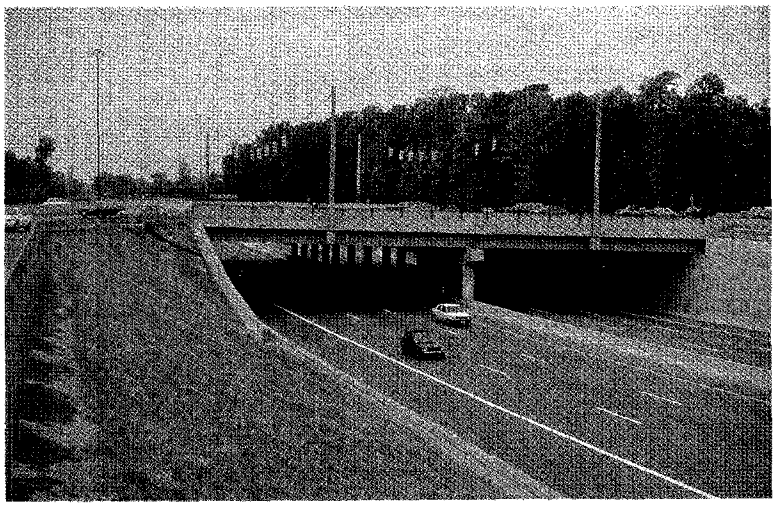


Figure 10. Fly ash concrete for bridge construction.

Has the solution to all our concrete problems finally arrived? If the answer was *yes*, this publication probably wouldn't be needed. Fly ash is simply another material that can be used in the design of a quality concrete mix.

What advice do you have for the first-time user? Even with the benefits listed, the potential effects of fly ash in concrete aren't all wonderful. The user should pay close attention to the following guidelines:

- ***Mix design evaluation.*** Evaluate the performance of proposed mix designs before construction. Good quality constituents do not always produce a mix that will perform as desired.
- ***Air content problems.*** The fineness of fly ash makes it naturally more difficult to develop and hold entrained air. Remaining carbon in the ash also adsorbs some of the AEA. Higher carbon ashes naturally require higher AEA contents. Longer mixing times or other variations from truck to truck can result in larger than normal fluctuations in air content. Testing requirements must ensure that the fly ash used maintains a uniform carbon content (LOI) to mitigate

unacceptable fluctuations in entrained air. Also pay careful attention to air content at the point of placement to ensure against low air content and the problems that can result.

- ***Lower early strength.*** The substitution mix design method will result in lower strengths at early ages. Mix design should consider form removal sequence and anticipated early loading. Lower early strengths can be overcome by using appropriate admixtures or other adjustments to the mix design.

- ***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 °C (40 °F), strength gain may continue at a slower rate resulting from continued cement hydration.

MIXTURE PROPORTIONING CONCEPTS

Fly Ash/Portland Cement Concrete

Note: This procedure presents basic concepts only and is not intended to serve as a complete guide to mixture proportioning of fly ash concrete.

Given: The following target values should be identified prior to proportioning the mix.

- Strength (at designated ages).
- Aggregate size.
- Target water/cement plus pozzolan (w/c+p) ratio.
- Air content.
- Slump.

This publication discusses considerations in selecting these values.

Step 1. Estimate water content.

With the aggregate size and target slump, enter the appropriate table of ACI 211.1 and determine the approximate water required per cubic meter (cubic yard). When fly ash is to be used, this estimated water requirement may be reduced 5 to 10 percent for the initial trial batch.

Step 2. Estimate fly ash and portland cement requirements.

The target w/c+p ratio and the estimated water content in step 1 are used to compute the total cementitious material required.

With the percent of total cementitious material represented as fly ash already selected, we can now compute the actual weights of fly ash and cement.

Step 3. Estimate coarse aggregate content.

The appropriate table in ACI 211.1 provides volumes of dry-rodded coarse aggregate. With the coarse aggregate size and the fineness modulus of the sand, a volume of course aggregate per cubic meter (cubic foot) of concrete can be selected. This volume is then multiplied by the dry-rodded unit weight of the aggregate to obtain the coarse aggregate weight per cubic meter (cubic foot) of concrete.

Step 4. Estimate fine aggregate content.

Estimate fine aggregate requirements by subtracting the total estimated weight of other constituents from the estimated weight of the fresh concrete on a cubic meter (cubic yard) basis. The appropriate table of ACI 211.1 provides first estimates of concrete weight and can be adjusted to meet mix parameters.

Step 5. Adjust trial batch.

Trial batches should be prepared and tested in accordance with ASTM C 192 or full-sized field batches. They should be checked for unit weight and yield (ASTM C 138, C 173, or C 231). They should also be monitored for workability and finishing properties. Make appropriate adjustments and prepare new trial batches. Carefully evaluate concrete from the final mix design before construction to ensure its field performance will be as desired.

CHAPTER 4
Use in Stabilized Road Bases

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Mix Proportioning

When a decision is made to use lime/fly ash/aggregate [pozzolanic-stabilized mixture (PSM)] roadbase, a mixture design must be developed that will:

- Possess adequate strength and durability for its designated use.
- Be easily placed and compacted.
- Be economical.

Quality mixtures have been produced with lime contents ranging from 2 to 8 percent. Fly ash contents may range from 8 to 15 percent. Typical proportions range from 3 to 4 percent lime and 10 to 15 percent fly ash. When conditions warrant, 0.5 to 1.5 percent of Type 1 portland cement can be used to accelerate initial strength gain. More information is presented in the section on *Mixture Proportioning Concepts*, page 35.

Strength development of a PSM is highly dependent on curing time and temperature. A specified minimum curing time as a function of temperature can be designated using the degree-day concept. In this approach the curing degree days necessary is the product of days cured and the curing temperature in excess of 4.4 °C (40 °F).

Evaluate various curing times and temperatures to assess the curing degree-days required to produce the specified strength. More often, minimum curing times are specified along with an allowable curing temperature range that will produce the required strength. Target strengths for mix design development should allow for the fact that PSM bases will continue to develop notable strength after completion of the initial curing period. Higher specified early strengths can result in a PSM base exhibiting future characteristics more like those of a rigid pavement.

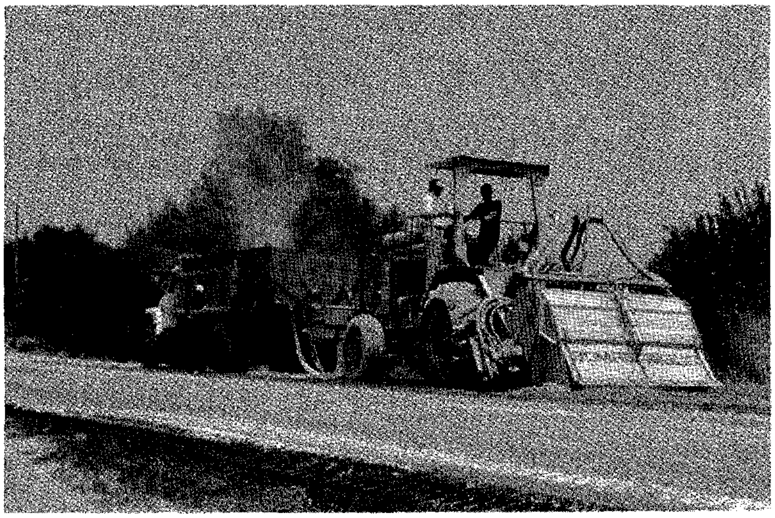


Figure 11. In-place mixing of fly ash-stabilized roadbase.

In designating the required strength, employ the design values used in developing layer thickness. PSM bases were not evaluated at the AASHO Road Test, but subsequent guidance in the selection of layer coefficients has been developed. Agencies should evaluate their own mixes and establish pavement design layer coefficients and corresponding strengths for use in mix design development.[4]

Mix Design Evaluation

Compaction. The density of PSM mixtures significantly affects cured strength. Specimens are normally compacted at moisture content and density as determined by AASHTO T 180.

Strength. Closely controlled curing conditions are important as both time and temperature significantly affect POZZ strength. Use standard proctor-sized specimens; normal curing is at +38 °C (100 °F) for 7 days. As time permits, use other conditions to assess strength development, degree days required, etc. Some agencies are using 14-day curing periods at 22 °C (72 °F).

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.

Control of Materials

Lime. Hydrated lime is the most popular form used though 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 compactible.

Construction Practices

Blending of materials. Central plant mixing provides the best quality although in-place mixing is 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 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 fly ash can be routinely added through an aggregate hopper.

Calibrate plants before beginning an operation and make daily checks to ensure product consistency. Determine and adhere to necessary retention time in the pugmill to achieve proper mixing throughout the operation.

Hauling. The blended mixtures can be hauled to the site in open trucks, but trucks should be covered if there is drying and dusting or long haul distances are required.

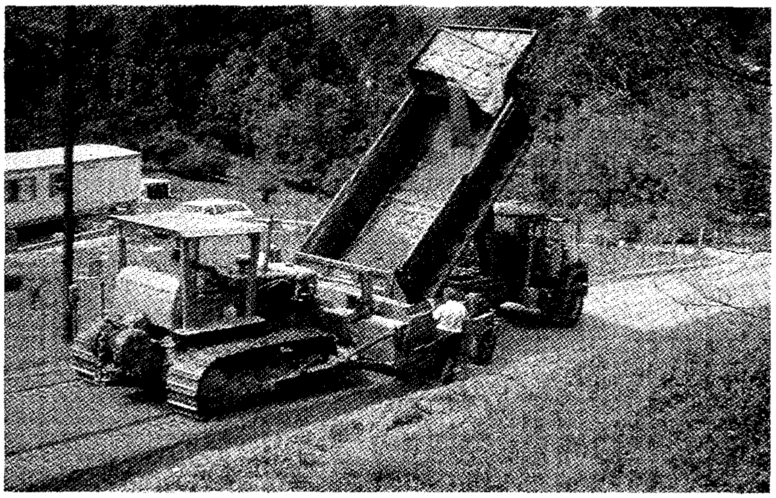


Figure 12. Spreading fly ash-stabilized roadbase after central plant mixing.

Spreading. 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 203 to 254 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. 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. The final surface should be clipped to proper grade with a motor grader before final rolling with a steel-wheeled roller. In clipping, 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.

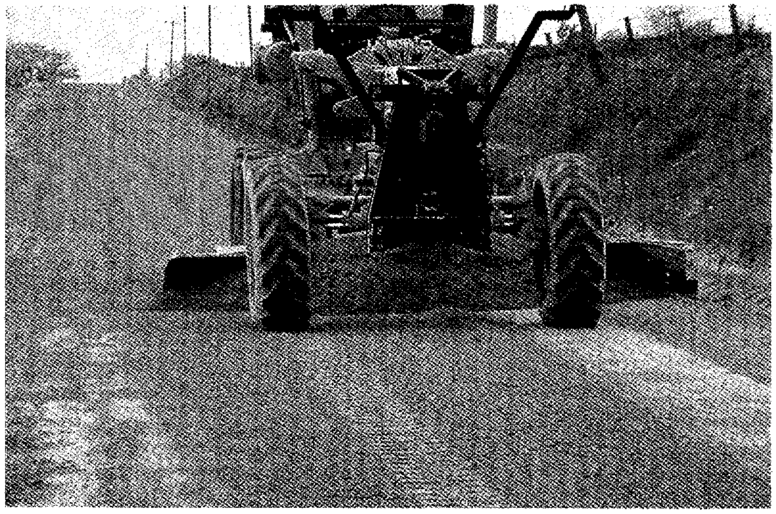


Figure 13. Achieving final grade with a motor grader before final compaction.

Curing. Compacted layers should be quickly sealed to prevent drying. Apply a prime coat of 0.45 to 0.91 liters per square meter (0.1 to 0.2 gal/ yd^2) 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.

Many mixes provide enough mechanical strength to support construction traffic when compaction is completed, but it is recommended that there be minimal early loadings. Opening to traffic should follow at least 7 curing days and only after a suitable riding surface has been placed.

- ***Lower costs.*** The cost of PSM varies notably from area to area but is often less than alternative base materials. Allowing its use can also increase competition.
- ***Autogenous healing.*** Whenever fractured surfaces remain in intimate contact, PSMs have the inherent ability to heal or recement

across cracks if moisture is present and unreacted lime and fly ash are available. This phenomenon is known as autogenous healing.

- ***Energy efficient.*** PSMs use a byproduct that requires no energy to produce and, because PSMs need not be heated, it requires less energy to place than asphaltic bases.

What if I can't afford to buy specialized construction equipment? There is no need to with PSMs! Most plants can be readily adapted to produce the pugmilled mix. Depending on the desired control, it can be spread with an asphalt paver or jersey spreader, the latter being the most popular method. A motor grader can be used to spread dumped material, but it is not recommended because of the inability to maintain good control.

When placing PSM bases under relatively thin asphalt pavements, expect transverse cracks to appear within 1 to 3 years. Sawing and sealing of joints is one method used to reduce the adverse effects on appearance and to provide for better future sealing. Joint spacing may vary from 6.1 to 12.2 m (20 to 40 ft) depending on local experience. This approach is still being evaluated.

What advice do you have for the first-time user? PSMs can produce strong durable bases only if attention is paid to the following precautions:

- ***Mix design evaluation***. Proposed mix designs should be evaluated for performance before construction. Good quality constituents do not always produce a mix that will perform as desired. Many high calcium ashes will require admixture or prior field "conditioning" to produce a mix with acceptable set times.

- ***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.

- ***Curing.*** Moisture must be maintained in the mix to ensure continued strength development. Quickly and properly applied bituminous curing will maintain required moisture as long as economically feasible and should provide satisfactory curing conditions.

MIXTURE PROPORTIONING CONCEPTS

Lime/Fly Ash/Aggregate Bases

Note: This procedure presents basic concepts and is not intended to serve as a complete guide to mixture proportioning.

Step 1. Determine the total quantity of lime activator plus fly ash required to produce the maximum dry density when combined with the proposed project aggregate (optimum fines content). Generally, the recommended fines content is approximately 2 percent above the quantity of matrix material (consisting of fly ash, water, activator and minus No. 4 size aggregate fines) required for maximum dry density.

Step 2. Select the proportion of activator to fly ash. This ratio varies from one constituent source to another. Initial proportions should be based on experience where possible. For best results, prepare trial batches with several ratios and select the most economical one that produces a mix exceeding performance requirements per ASTM C 593. At the recommended fines content determined in step 1, strength development is influenced by adjusting the ratio of the weight of activator to weight of fly ash.

Step 3. Adjust the mix to compensate for construction variability by increasing the designated activator content by about 1/2 percent and the fly ash content by about 1-1/2 percent.

CHAPTER 5
Use in Flowable Fill Applications

GENERAL

Flowable fill has several names, but each is essentially the same material:

- 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 14. Flowable fill used as backfill material for a utility trench allows rapid return of traffic to the roadway.

Flowable 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.[5] Consequently, flowable mixtures 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 ASTM C 618 specification requirements as a concrete admixture to be suitable for use in flowable fill mixes. Because low strength development is usually desirable in flowable fill, even fly ash with high LOI or carbon content is suitable. 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 also been used successfully. Flowable fill mixes using high-calcium fly ash may not require any cement.

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.

(Photo courtesy of National Ready Mixed Concrete Association)

Figure 15. Flowable fill eliminates the need for workers to enter the trench to compact.

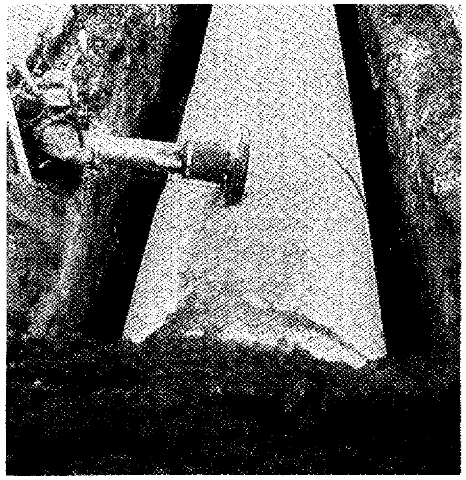


Figure 16. With flowable fill, the width of the trench need not accommodate compaction equipment, resulting in additional savings.

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. (See figure 15.) With flowable fill, workers need not be in the excavation, resulting in cost savings from less excavation and no shoring. (See figure 16.)

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Flowable fills typically contain fly ash and water and may contain portland cement and filler materials in the form of bottom ash, sand or other aggregates. 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 the major ingredient in flowable fills. However, when available 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 247.7 to 396.3 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 59 kilograms per cubic meter (50 to 100 pounds per cubic yard) to provide a weak cementitious matrix. More information on mix design is provided in *Typical Proportioning Concepts for Flowable Fills*, page 45.

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.

The American Concrete Institute (ACI) Committee 229 has designated low fly ash content mixes that contain high percentages of fine aggregate as Controlled Low Strength Material (CLSM).

According to the ACI definition, CLSM has an upper compressive strength limit of 8.274 kPa (1200 psi), however, strengths can be designed as low as 344.7 kPa (50 psi). Most flowable fill mixes are designed to achieve a maximum strength of 1034 to 1379 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 344.7 to 482.7 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, using a dry weight basis. The high fly ash content mixes normally contain 95 percent fly ash and 5 percent portland cement. 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 and 6, page 45.

The most important physical characteristics of flowable fill mixtures are:

- Strength development.
- Flowability.
- Time of set.
- Bleeding and shrinkage.

These characteristics are discussed in detail on the following pages.

Strength development in flowable fill mixtures is directly related to cement content and water content. Most high fly ash content mixes only require from 3 to 5 percent portland cement by dry weight of the fly ash to develop 28-day compressive strengths in the 344.7 to 1034.3 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.

Flowability is basically a function of the water content. The higher the water 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.

Time of set is directly related to the cement content. Typical high fly ash flowable fill mixes containing 5 percent cement achieve a sufficient set to support the weight of an average person in about 3 to 4 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 1 to 2 hours after placement. For most mixes, especially the high fly ash mixes, increasing cement content or decreasing water content or both should reduce the setting time somewhat.

Bleeding and shrinkage 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 often results in a shrinkage of approximately 10.42 mm/m (1/8-in/ft) of depth of the fill. The 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, tremie, 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.

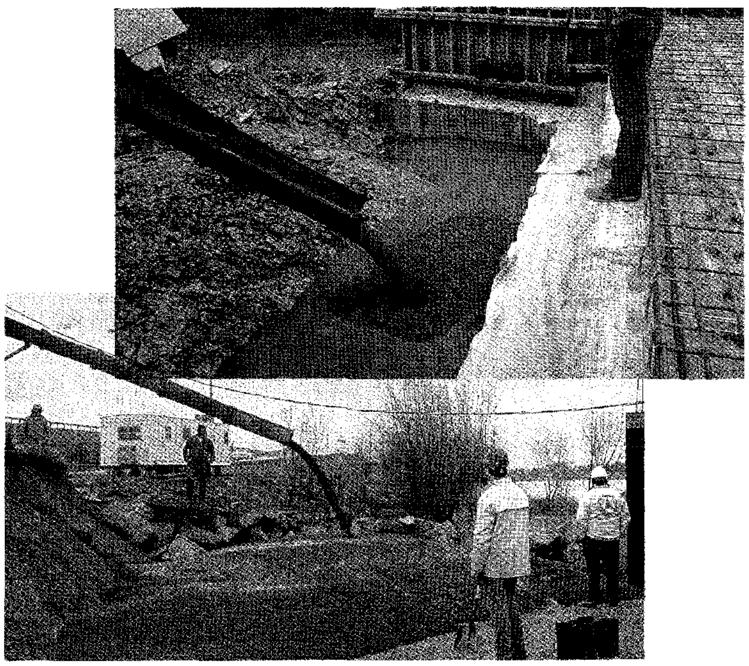


Figure 17. Bridge abutment backfill with flowable fill.

An important requirement for flowable fills in many geotechnical applications is that they can be removed with ordinary excavation equipment. From the perspective of concrete technology, this means that compressive strength should be limited to 689.5 to 1379 kPa (100 to 200 psi). 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 or a mortar flow cone and unit weight, as well as measures of compressive strength, bearing capacity, or penetration resistance.

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.

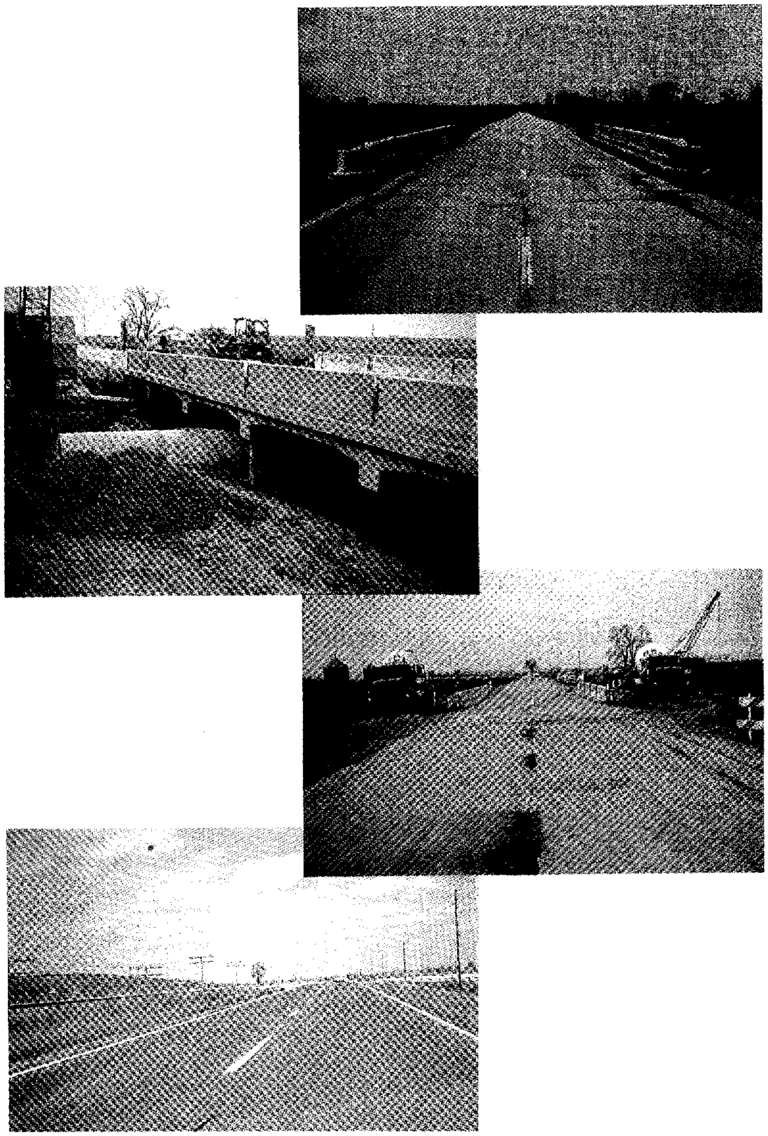


Figure 18. Bridge replaced by culverts and flowable fill.

TYPICAL MIXTURE PROPORTIONING CONCEPTS FOR FLOWABLE FILLS

Table 5. High fly ash content mixes—typical proportions.

Component	Range kg/m³ (lb/yd³)	Mix Design kg/m³ (lb/yd³)
Fly ash (95%)	949 to 1542 (1600 to 2600)	1234 (2080)
Cement (5%)	47 to 74 (80 to 125)	62 (104)
Added Water	222 to 371 (375 to 625)	247 (416)*
		1543 (2600)

*Equal to 189 liters (50 gallons)

Table 6. Low fly ash content mixes—typical proportions.

Component	Range kg/m³ (lb/yd³)	Mix Design kg/m³ (lb/yd³)
Fly ash †	119 to 297 (200 to 500)	178 (300)
Cement	30 to 119 (50 to 200)	59 (100)
Sand	1483 to 1780 (2500 to 3000)	1542 (2600)
Added Water	198 to 494 (333 to 833)	297 (500)‡
		2076 (3500)

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

CHAPTER 6

Use in Grouts for Concrete Pavement Subsealing

The principal requirement for a slab stabilization material is that it can flow or expand to fill very small voids and still have adequate strength to support the slab. A good stabilization material should remain insoluble, incompressible, and nonerodable after is 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 soupy, 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. Fly ash grout meets all of these requirements.[6]

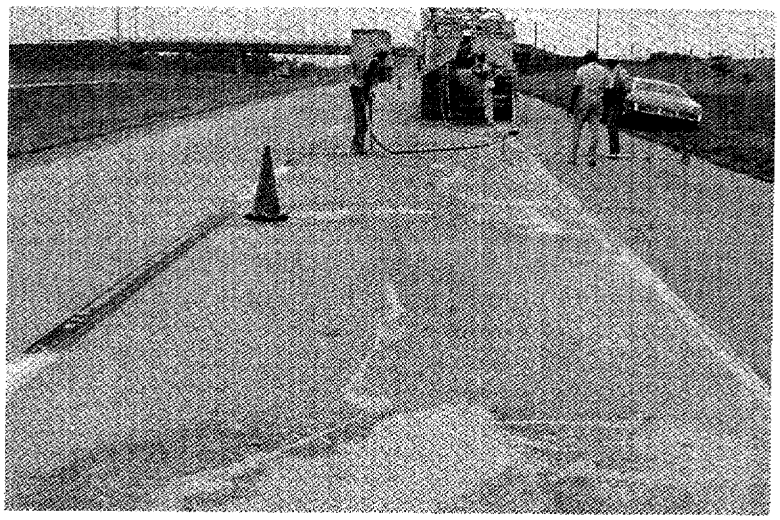


Figure 19. Fly ash grouts for pavement subsealing.

MIX DESIGN AND SPECIFICATION REQUIREMENTS

Stabilization Materials

Fly ash-cement mixtures are recommended highly for several reasons. They are generally available within reasonable distance of most projects and are usually inexpensive. The fineness and spherical shape of the pozzolan results in a ball-bearing effect that enhances the flow properties and allows the grout to fill very thin voids. Although most of the pozzolan particles are silt-sized, they also contain a small but effective amount of clay-sized particles that provide sufficient grading to reduce segregation during pumping and injection. This results in increased durability when placed. Finally, because the hydration of cement produces lime, additional cementation occurs when the pozzolans react with the lime, which enhances the stability and produces a more effective grout.

Additives

It may be necessary to use additives or admixtures in fly ash-cement grouts to achieve the required goals. The current trend, however, is to use no additives whenever possible because of the unpredictable reactions. Laboratory tests have shown widely differing reactions from combinations of the same additive and pozzolans from different sources, and from combinations of the same pozzolan and different brands of the same additives.

Because of inconsistent reactions when using additives, the contractor should submit independent test results of chemical and physical properties as well as 1-day, 3-day, and 7-day comprehensive strength tests, flow cone times, time of initial set, and shrinkage and expansion results.

Types of additives may include accelerators such as calcium chloride to reduce set times; retarders to increase set time; expanding materials such as powdered alumina 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 water content. The contracting agency should allow the contractor to choose additives based on experience.

Mix Design

A typical cement-pozzolan mix design calls for 1 part cement (Type I, II, or III), 3 parts pozzolan (natural or artificial), and enough water for fluidity, usually about 1.5 to 3.0 parts water. This combination should develop sufficient strength to preclude grout erosion that could result from hydraulic action under a heavily trafficked pavement. It may be possible to reduce the cement component in some of the western, Class C ashes because they have sufficient reactivity by themselves. When this is done, the grout must still pass all the physical and chemical tests of the cement-pozzolan mix. When the ambient air temperature is between 1.7 °C to 10 °C (35 °F and 50 °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. Dry ingredients must be added in a specific ratio to increase the consistency of the grout. Do not permit stabilization using cement-pozzolan grouts when the ambient temperature is below 1.7 °C (35 °F) or when the subgrade is frozen.

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-pozzolan grout slurries.

For limestone dust slurries, the time of efflux should be 16 to 22 seconds. To ensure uniformity, the specifications should require that the consistency of the grout be checked twice daily.

The quantity of necessary water for grout flowability far exceeds the amount of water needed for hydration. Together, the roundness of the fly ash particles and the uniform gradation combine to give the grout a high permeability for its average grain size. This high permeability lets the excess water to be driven off or squeezed out during injection with a relatively low pumping pressure, which immediately makes the grout more viscous. After injection, the combination of confinement and additional excess water draining from the grout helps increase the in-place strength.

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) is used. Typical set times with these tests are 1-1/2 to 2 hours. However, none of the test methods considers that cement-pozzolan grouts at normal temperatures lose their fluidity within approximately 20 to 30 minutes after injection. Furthermore, because the grout is virtually always in total confinement under the slab, it is capable of supporting substantial loads before the set time indicated by these tests. Laboratory tests and field performance have shown no known pumping or displacement of the in situ grout when the traffic lane is opened within 1 hour of stabilization.

Strength

A minimum strength requirement is normally used to ensure the durability of the grout. A typical value is 4137 kPa (600 psi) at 7 days measured by the standard mortar cube test, ASTM 109. Recommendations for a pozzolan-cement grout typically suggest a 7-day compressive strength of 4137 to 5516 kPa (600 to 800 psi). The ultimate strength of the grout will be much higher (10.3 to 27.6 mPa/1500 to 4000 psi). The California Department of Transportation (CalTrans) evaluated the performance of several grouts using various cement-pozzolan ratios and determined that a 1:3 cement-pozzolan mixture with a minimum compressive strength of 5171 kPa (750 psi) at 7 days is needed to preclude erosion caused by hydraulic activity under a heavily trafficked pavement.

Finally, the contractor should submit mill certifications for the cement; chemical and physical analysis for the pozzolans; grain structure analysis for the limestone dust; and independent laboratory tests of the grout slurry. The test results should include 1-, 3-, and 7-day strengths, flow cone times, shrinkage and expansion results, time of initial set, and water retentivity.

Equipment

In the past, most 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. As stabilization procedures get more sophisticated, the trend is to automate bulk transport and metering plants because they can reduce labor and material costs by as much as 30 to 50 percent.

The small particle size and resulting increased surface area make it difficult to thoroughly wet the cement and fly ash particles with normal mixing equipment. Because of this, the contractor should use a colloidal mixer to mix cement-pozzolan 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 remove air from the solid particles, which allows them to be wetted and make a more homogeneous mixture.

If limestone dust grouts are to be used, a paddle-type drum mixer may be substituted for the high-speed colloidal mixer. Though not recommended, paddle-type drum mixers also can be used for cement-pozzolan grouts. However, cement-pozzolan grouts made from paddle-type mixers require more water than the colloidal mixers to produce a grout with the same flowability. Grout should *never* be mixed by a conveyor, with a mortar mixer, or in a ready mix truck. Mixes made with these will require more water and the solids will agglomerate or ball up. The balled-up, partially wet clumps of grout will plug the voids at the injection hole and prevent lateral penetration.

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 reduce over 1 to 3 hours. This is because of the hardening of the grout, which is dependent on the temperature, degree of confinement, and grout properties. It is possible to measure this change in deflection for the given job site and select a minimum opening time.

Typical specifications recommend time ranges from 30 minutes to 3 hours depending on the mix composition and the degree of confinement of the grout. Because the grout is laterally confined, experience has shown no pumping or displacement of grout when traffic has returned within an hour of stabilization. In cold weather, use accelerators in the grout to speed the initial set time.

PRODUCTION AND PLACEMENT

Material Proposal

The contractor should submit a proposal for all materials, including any additives that may be used. The proposal should include mill certifications for the cement, physical and chemical analysis for the fly ash or other pozzolans, and tests of the grout by an approved laboratory showing 1-, 3-, and 7-day strengths, flow cone times, shrinkage and/or expansion measurements, and time of initial set. The 7-day strength typically is required to be no less than 4137 kPa (600 psi) as measured using AASHTO Test Method T-106 and ASTM C 109. The test specimens must use the materials (including water and admixtures) that are to be used in the project.

Grout Plant

The grout plant usually will have a positive displacement cement injection pump and a high-speed colloidal mixing machine or paddle-type mixer. The typical colloidal mixing machine operates within a speed range of 800 to 2000 rpm to create a high shearing action for producing homogeneous mixtures.

The dry materials must be accurately measured by weight or volume if delivered and stored in bulk containers. Alternatively, the materials can be packaged in sacks containing an accurately measured amount of material for uniform batching. The water is batched through a meter or scale.

Drilling 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 51 mm (2 in) in diameter, drilled vertically and round, 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 within the pavement system.

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 1379 kPa (200 psi) are typical, with pressures to 2068.5 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 4137 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.

Cautions

Pavement movements above the specified tolerances may require grinding or even removal and replacement of the pavement. Also, 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.

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

Materials Specifications

Portland cement shall meet the requirements for Types I, II, or III, per AASHTO M 85 (ASTM C 150).

Fly ash and other pozzolans. Shall meet the requirements of ASTM C 618. However, the contractor may use other pozzolans if test data meeting project specification requirements are available and the material has been used previously for this purpose on other public works projects.

Fluidity of the grout may be measured by the Corps of Engineers flow cone method or ASTM C 939. Time of efflux for pozzolanic grouts for subsealing should be 10 to 16 seconds. Use a more fluid mixture with a flow cone time of efflux of 9 to 16 seconds during the initial injection at each hole. Fluidity measurements typically are made not fewer than two times on each shift.

CHAPTER 7
Use in Fast Track Concrete Pavement

LABORATORY TESTING

It is highly recommended that laboratory testing be used to evaluate the use of fly ash. Also, evaluate the effects of temperature on the rate of hydration in the range of expected mix temperatures. As the mix temperature drops, the rate of reaction drops and could seriously alter the setting time of the concrete. Experience has shown that essentially all fly ash sources will contribute to lower water demand, improved workability, and increased long-term strength gain. Although most fast track concrete mixes have employed Class C fly ash, Class F also may produce acceptable results and may be considered after evaluation. Ground granular slag (used in the U.S. mainly along the east coast) is another feasible additive, although it has not been used in fast track concrete to date. It has been used, however, in general construction and increases early and long-term strength. This material is extremely temperature sensitive, especially at higher dosage rates. It is highly recommended that mixes employing ground granular slag be tested at the expected mix temperature ranges.

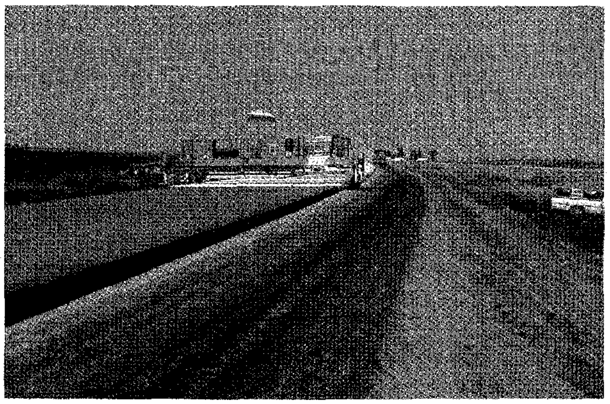


Figure 20. Fast track concrete pavements with fly ash concrete.

What are the guidelines for potential applications? The main objective in any pavement reconstruction operation is to provide a new, high-quality pavement to the public for the least cost and inconvenience. Standard specifications used by most agencies for conventional concrete mixes require opening to traffic based on strength and/or curing intervals from 5 to 14 days. Using fast track technology, concrete mixes can be designed and curing techniques used that will promote development of required opening strengths at intervals ranging from 6 to 24 hours. The result is that concrete alternatives can now be provided for projects that in the past were not considered feasible with concrete because of lengthy cure times.

In the future, fast track concrete pavement alternatives could be considered for almost all proposed projects. The merit of fast track alternatives will be determined in feasibility studies and in development of construction and traffic control staging plans. This will be true particularly where traffic patterns and access requirements along a project warrant special consideration.[7]

MATERIALS SPECIFICATIONS

Fast track concrete mixes should not require special materials or techniques. However, material selection does require more attention than for historical PCC. Local cements, additives, admixtures, and aggregates can be adapted to produce the high early strengths needed. No set mix design is required for this work.

The early strength of any mix is controlled by the water-cement ratio, cement content, cement fineness, and chemical reaction of the cementitious particles. The heat of hydration, aggregate particle distribution, entrained air, water temperature, ambient air temperature, and curing provisions must be considered for both early and long-term strength gain. The quality of fast track concrete is conducive to good durability because of the low water-cement ratio required to attain high early strengths also reduces concrete permeability.

It is recommended that a thorough laboratory analysis be conducted to determine the properties of the concrete developed with local materials before specifying a fast track (high early strength) mix design. This testing will also verify the compatibility of all chemically active ingredients.

ADDITIVES

Fly ash and ground granular slag are often used as partial replacements for portland cement in concrete mixtures. These materials draw their benefit from the ability to react with the products of the cement/water hydration process, which helps extend the strength gain period. It should be cautioned that the effects of these materials are temperature and time dependent. Fly ash has been used in fast track concrete mixtures, although generally as an additive rather than a substitute for portland cement.

Historically, fly ash has been used to reduce the amount of cement in conventional mixes up to about 20 percent. Fly ash substitution can also be made in fast track concrete mixes using standard cements. However, to maintain early strength-gain rates, a maximum substitution rate for each source of portland cement and fly ash must be evaluated on a case-by-case basis. The fly ash is normally included with the cement in determining the water/cementitious materials ratio of the mix.

Table 7. Mixture proportioning concepts.

MIX DESIGN	CEMENT TYPE	CEMENT QUANTITY	TARGET W/C RATIO	FLY ASH	COARSE AGGREGATE	FINE AGGREGATE	ADMIXTURES AE*	WR†	AC‡
A	I	380 (641)	n.a.	73 (123)	843 (1420)	843 (1420)	YES	YES	NO
B	II	390 (658)	0.39	0 (0)	1008 (1698)	679 (1145)	YES	YES	NO
C	II	390 (658)	0.39	99 (167)	935 (1575)	630 (1062)	YES	YES	YES
D	III	421 (710)	0.373	0 (0)	907 (1528)	806 (1358)	YES	YES	NO
E	III	380 (640)	0.425	70 (118)	838 (1413)	838 (1413)	YES	YES	NO
F	III	380 (640)	0.425	70 (118)	838 (1413)	838 (1413)	YES	YES	NO
G	III	380 (641)	0.425	73 (123)	839 (1414)	836 (1409)	YES	YES	NO
H	III	441 (743)	0.40	82 (138)	776 (1308)	779 (1313)	YES	YES	NO

*AEA = Air entraining admixtures
†WR = Water reducer
‡AC = Nonchloride accelerator

n.a. = not available
kg/m^3 (lbs/yd^3) = kilograms per cubic meter (pounds per cubic yard)

CHAPTER 8
Use in Structural Fills/Embankments

SPECIFICATION REQUIREMENTS

General

Specifications are required to ensure that the fly ash embankment will possess the strength and compressibility requirements that were assumed during design. Either method or performance specifications can be written for the compaction of fly ash.[8,9]

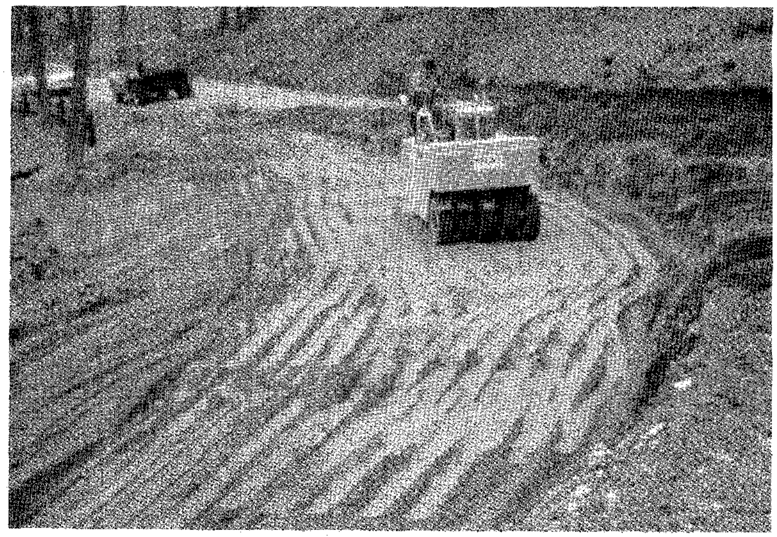


Figure 21. Highway embankment with fly ash structural fill.

Ash sources. Fly ash can be hopper, silo, lagoon, or stockpiled ash. Hopper or silo fly ash can be delivered with close limitations on moisture content and grain size distribution. Conversely, the moisture content or grain size distribution of lagoon or stockpiled ash can vary considerably depending upon its location within the lagoon or stockpile.

Therefore, using lagoon 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 in silos and hauled to the construction site in pneumatic tank trucks. 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.

Compaction/quality control. The two types of specifications written for fly ash embankments are performance specifications and method specifications. Performance specifications state the required degree of compaction and 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 Method T99-81. Determine the allowable range for the moisture content by plotting the laboratory moisture-density relationship as shown in table 8, page 65. Fly ash may be variable enough that several curves are required. It is preferable to place the ash at less than optimum moisture because the compactive effort applied by construction equipment may exceed the compactive effort applied in the laboratory.

On some projects, method specifications are preferable to performance specifications. The method specification is based on the results of field compaction tests on trial strips. The lift thickness, weight of compaction equipment, speed of compaction equipment, and the number of passes must be evaluated so that the fly ash achieves the necessary degree of compaction. If vibratory compaction equipment is being used, the resonant frequency of each compactor in use must be established in the field. The method specification allows for simpler quality control because the compaction procedures can be monitored visually.

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 will 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. Give special attention to draining the site and to preventing seeps, pools, or springs from contacting the fly ash.

Delivery and on-site storage. Fly ash is usually hauled to the site in covered dump trucks, pneumatic tanker trucks, or ready mix 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 transport and to allow proper placement. Because of the self-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 in loose lifts 152 to 305 mm (6 to 12 in) thick. The lift is then tracked with the dozer for initial compaction.

Figure 22. Spreading fly ash structural fill.

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. Table 8, page 65, is a list of the types of compaction equipment that have been tested for use with fly ash.

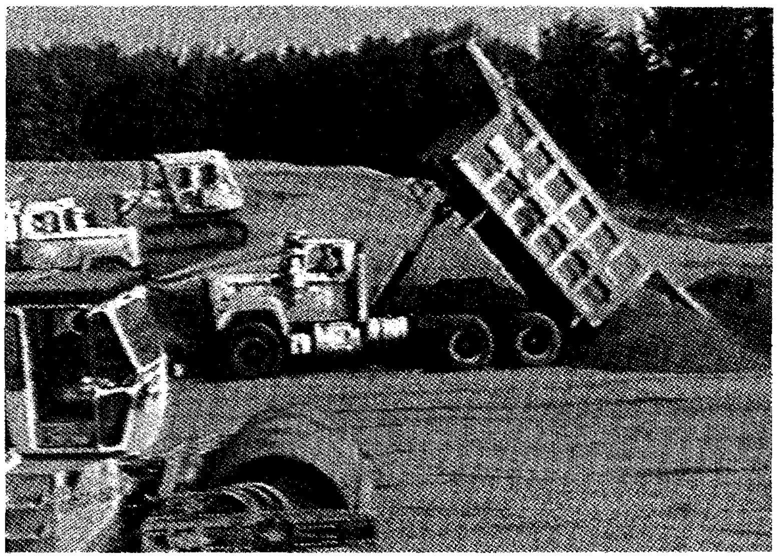


Figure 23. Compaction of fly ash structural fill is crucial, as with any backfill material.

Moisture control. Control of the required range of moistures is an important consideration in the compaction procedure. 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 recompacted 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, it 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.

What do I have to do?

1. ***Assess availability.*** Contact the local electric utility or ash broker to determine whether an adequate supply of fly ash can be provided in the time frame required.
2. ***Investigate site conditions.*** As with any embankment project, use standard geotechnical techniques 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.
3. ***Evaluate the 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 apply equally well 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.

What other factors should be considered? The mechanical behavior and compaction characteristics of fly ash are generally similar to those of silt. Conversely, fly ash also shares some of the difficulties that are characteristic of silt such as dusting, erosion, piping, 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 borrow material below the groundwater table or when the embankment design cannot provide adequate drainage.

What about 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 water quality standards. This is 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 itself is 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.

Where can I go for more guidance? The Federal Highway Administration has participated in several demonstration projects to document the behavior of fly ash structural fills and embankments. The American Coal Ash Association is an excellent source for information on other projects, as well as on fly ash characteristics and behavior. The Electric Power Research Institute has published several design and construction manuals on fly ash use in highway construction. Finally, the American Society for Testing and Materials (ASTM) has published a guide for the use of coal combustion fly ash in structural fills.

Table 8. Combinations required for 95 percent of the standard proctor maximum dry density, AASHTO Method T 99-81.[10]

Equipment	Thickness	Passes	Comments
Vibratory Smooth Drum Roller (1 to 1-1/2 tons) (900 to 1350 kg)	150 mm (6 in)	≤8	May slightly overstress surface; compaction may only reach 90 percent
Vibratory Smooth Drum Roller (6 to 10 tons) (5400 to 9100 kg)	150-300 mm (6-12 in)	≤8	9100 kg (10 ton) roller may need as few as 3 passes at lower lift thicknesses; may overstress surface
Vibratory Smooth Drum Roller (10 to 20 tons) (9100 to 11,000 kg)	200-300 mm (8-12 in)	4-6	May seriously overstress surface; ballast reduction and frequency change will reduce this problem
Pneumatic-tired Roller (10 to 12 tons) (9100 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) (5400 to 9100 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

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TECHNOLOGY APPLICATIONS

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