USER GUIDELINE FOR COAL FLY ASH IN GREEN INFRASTRUCTURE CONSTRUCTION

by

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In 2006 the American Coal Ash Association (ACAA) reported that 65.7 million metric tons (72.4 million tons) of coal fly ash were produced (ACAA 2007). Approximately 29.3 million metric tons (32.4 million tons) of fly ash was used predominantly in the production of concrete, concrete products, and grout.

Fly ash is useful in many applications because it is a pozzolan, meaning it is a siliceous or alumino-siliceous material that, when in a finely divided form and in the presence of water, will combine with calcium hydroxide (from lime, Portland cement, or kiln dust) to form cementitious compounds (FHWA 2003).

Nationwide, approximately 45 percent of the fly ash produced in 2006 was used leaving approximately 55 percent for disposal. Thus, there is significant room for additional use. In comparison, over 90 percent of the European Union's (EU) total coal combustion products, including fly ash, are recycled (Kalinski and Hippley 2005, Kalinski and Yerra 2006).

Although coal-burning electric utility companies produce ash, most utilities make use of commercial ash vendors to sell fly ash. There are approximately 45 commercial ash marketing firms operating throughout the United States in all states except Hawaii. In addition to commercial ash marketing organizations, some coal-burning electric utility companies have formal ash marketing programs. Most coal-burning electric utility companies currently employ an ash management specialist whose responsibility is to monitor ash generation, quality, use, or disposal, and to interface with ash marketers.

Because of variations in coals from different sources, as well as differences in the design of coal-fired boilers, not all fly ash is the same. As long as the basic operating parameters at a power plant do not change, fly ash from a known source that is supplied by a reputable ash marketing organization should be a consistent, quality-controlled product.

GENERAL BOTTOM ASH/BOILER SLAG PROPERTIES

Physical Properties

Fly ash consists of fine powdery particles that are predominantly spherical in shape, either solid or hollow, and mostly glassy (amorphous) in nature. The carbonaceous material in fly ash is composed of angular particles. Bituminous coal fly ash particle size is generally similar to that of a silt or fine sand (less than 0.075 mm). Subbituminous coal fly ashes are also silt-sized, although slightly coarser than bituminous coal fly ash (AASHTO 1999).

The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area (measured by the Blaine air permeability method) (ASTM C204-07 2007) may range from 170 to 1000 m^2/kg.

The quality of fly ash for concrete is predominately determined by fineness and consistency. Fineness establishes the reactivity of the fly ash as well as carbon content levels. Fly ash is typically finer than Portland cement and lime, and ranges between 10 and 100 micron.

Chemical Properties

The color of fly ash is a loose indicator of its chemical content. Lignite or subbituminous fly ashes are usually light tan to buff in color, indicating relatively low amounts of carbon as well as the presence of lime or calcium. Bituminous fly ashes are usually some shade of gray. Lighter shades of gray generally indicate a higher quality of ash and a dark gray to black color is generally attributed to elevated unburned carbon content (EPA 2005).

The chemical properties of fly ash are influenced to a great extent by the chemical content of the coal burned, the air pollution control strategy at the power plant, and the techniques used for handling and storage.

Table 1 summarizes the normal range of chemical constituents of fly ashes from bituminous coal, lignite coal, and subbituminous coal. Lignite and subbituminous coal fly ashes have higher calcium oxide content and lower loss on ignition (LOI) (amount of residual carbon remaining in fly ash) than fly ashes from bituminous coals. Lignite and subbituminous coal fly ashes may have a higher amount of sulfate compounds than bituminous coal fly ashes.

Table 1. Normal range of chemical composition for fly ash produced from different coal types (expressed as percent by weight).

Component	Bituminous (%)	Subbituminous (%)	Lignite (%)
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
LOI	0-15	0-3	0-5

The chief difference between Class F and Class C fly ash is the amount of calcium, silica, alumina, and iron percent in the ash (ASTM C618 -05 2005). In Class F fly ash, total calcium typically ranges from 1 to 12 percent, mostly in the form of calcium hydroxide, calcium sulfate, and glassy components in combination with silica and alumina. In contrast, Class C fly ash may have reported calcium oxide contents as high as 30 to 40 percent (McKerall et al. 1982). The amount of alkalis (combined sodium and potassium) and sulfates (SO4) are more abundant in Class C fly ashes than in Class F fly ashes.

Although the Class F and Class C designations strictly apply only to fly ash meeting the ASTM C618 specification, these terms are often used more generally to apply to fly ash on the basis of the original coal type or CaO content. Not all fly ashes are able to meet ASTM C618 requirements for concrete, yet many "off spec" fly ashes have cementing properties and can be used for base, subbase, and subgrade stabilization (Edil et al 2006).

LOI is one of the most significant chemical properties of fly ash. To be a classified fly ash, LOI can range up to 5 percent or 6 percent, per AASHTO or ASTM respectively (FWHA 2003). The LOI can indicate suitability for use as a cement replacement in concrete as variations in carbon content can affect concrete mix activity and air content (EPA 2005).

Environmental Considerations

A concern with fly ash use is the possibility of groundwater contamination by trace elements that are associated with coal combustion by-products. The possibility for trace elements to dissolve in rainwater that percolates through fly ash has caused restrictions on fly ash use by state environmental regulations.

Many leaching tests used to evaluate the environmental impact of fly ash use have the limitation of not considering the hydrogeologic setting. These tests consider the use of by-products in bulk form, but not in mixtures (Bin-Shafique et al. 2002). For example, use of fly ash in Wisconsin is regulated by Ch. NR 538 of the Wisconsin Administrative Code. This regulation requires water leaching tests (WLT) of fly ash in bulk form, but does not consider mixtures, such as fly ash stabilized soil. In addition, WLT does not necessarily model leachate produced in the field. The WLT indicates the potential for contaminant release from fly ash or mixtures, but does not evaluate how a fly ash or fly ash mixture will impact groundwater (Bin-Shafique et al. 2002).Five widely used standard leaching tests are outlined in Table 2.

Table 2. Extraction conditions for different standard leaching tests (Bin-Shafique et al. 2002).

Test Procedure	Method	Purpose	Leaching Medium	Liquid-Solid Ratio	Particle Size	Time of Extraction
Water Leach Test	ASTM D3987-06	To provide a rapid means of obtaining an aqueous extract	Deionized water	20:1	Particulate or monolith as received	18 hr
TCLP	EPA SW-846 Method 1311	To compare toxicity data with regulatory level. RCRA requirement.	Acetate buffer*	20:1	< 9.5 mm	18 hr
Extraction Procedure Toxicity (EP Tox)	EPA SW-846 Method 1310	To evaluate leachate concentrations. RCRA requirement.	0.04 M acetic acid (pH = 5.0)	16:1	< 9.5 mm	24 hr
Multiple Extraction Procedure	EPA SW-846 Method 1320	To evaluate waste leaching under acid condition	Same as EP Toxicity, then at pH = 3.0	20:1	< 9.5 mm	24 hr extraction per stage
Synthetic Precipitation Leaching Procedure (SPSL)	EPA Method 1312	To evaluate metal mobility under actual field conditions, i.e. rain or snow	DI water, pH adjusted to 4.2 to 5	20:1	< 9.5 mm	18 hr

* Either an acetate buffered solution with pH = 5 or acetic acid with pH = 3.0

The high lime content of fly ash generally results in elevated pH levels (10.1 to 12.8) and sorption controlled release of metals and metalloids. WLTs on fly ash stabilized soil show that concentrations in leachate vary non-linearly with fly ash content. This non-linearity is believed to be due to the effects of increasing pH on adsorption and means that linear dilution calculations using results from WLT are incorrect (Bin-Shafique et al. 2002). This also means that decreases in pH over time may result in higher solubility and a decrease in the adsorption of metals ((Bin-Shafique et al. 2006, Kanugo and Mohapatra 2000).

A comparison of field to laboratory leachates from fly ash stabilized soil found that column leach tests compare well with field results while water leach tests typically underestimate field concentrations (Bin-Shafique et al. 2002, Bin-Shafique et al. 2006). Concentrations in leachate collected from field lysimeters below test sections of fly ash stabilized soil were similar or slightly lower than concentrations measured in column leach tests on the same material. Thus, the column leach test appears to provide a good indication of in field conditions directly below a soil-fly ash mixture provided the test conditions mimic the field conditions. In addition, initial concentration in the field can be conservatively estimated from water leach tests providing scaling factors are applied and the infiltrating water in the field is near neutral (Bin-Shafique et al. 2006). Example results from batch tests and column leaching tests can be found in Bin-Shafique et al. (2002), Bin-Shafique et al. (2006), and Ghosh and Sobbarao (1998).

A long-term environmental monitoring program on a truck route using unstabilized Class F fly ash subbase showed that almost all trace element levels in the groundwater complied with Illinois class I and II standards. The concentration also showed a decreasing trend through time. No adverse effects on groundwater and neighboring soils were observed to have occurred (Mohanty and Chugh 2006).

In Wisconsin a test section of State Highway 60 incorporated 4 different industrial byproducts as subbase material. Analysis of leachate collected from the base of the test sections shows that the byproducts discharge contaminants of concern at very low levels (Edil et al. 2000, Sauer et al. 2005, Bin-Shafique et al. 2002b)

Bioassay tests have been conducted on algae and Dapbnia (representing plant and animal life). A mixture of pure fly ash and deionized water was produced at a ratio of 1 g of fly ash for every 4 mL of water. This solution was filtered and the leachate used in the test. Fly ashes from power-generating facilities in Ohio and Indiana were tested and the results indicated growth inhibition in the Ohio sample, but not in the Indiana sample (Harrington-Hughes 2000). The tests showed that in its pure form, fly ash could be harmful to aquatic life. However, additional studies showed that the environmental risks markedly decreased or disappeared when fly ash was mixed with other materials (Harrington-Hughes 2000).

When fly ash is used in concrete, the potential for leaching of trace elements is very low. This is due to the constituents of fly ash being encapsulated in the matrix of the concrete (EPA 1999). A field study of pavements where fly ash and bottom ash were used as a partial substitute of fine aggregate in concrete showed no increase of metal concentration in surrounding soils. Soil was collected three months after placement from underneath the pavement section that contained 6 percent fly ash-bottom ash mix by weight, and also beneath a control pavement. Concentrations of arsenic, barium, cadmium, chromium, mercury, lead, selenium, and silver showed minimal differences between the two sections (Churchill and Amirkhanian 1999).

Unencapsulated use, however, has the potential for trace element leaching. Use of fly ash in stabilized base or embankments requires good management to ensure the environment is not impacted negatively. Although studies have shown that coal fly ash is typically safe to use in unencapsulated applications, precautions must still be taken to ensure environmental impacts are acceptable (EPRI 1998, Hassett and Heebink 2001, Pflughoseft-Hassett et al. 1993, EPA 1993). An evaluation of groundwater conditions, applicable state test procedures, water quality standards, and proper construction are all necessary considerations in ensuring a safe final product (EPA 2005).

Lysimeters installed at field sites below a fly ash stabilized base showed an average annual water flux through the stabilized layer of 4 to 6 percent of average annual precipitation, which was comparable with a control section constructed without fly ash. Concentrations of trace elements in the fly ash stabilized leachate were higher than those from the control section. Additionally, concentrations of field leachate agreed well with concentrations in the effluent of laboratory column leaching tests. Further research, however, is needed in developing standards and testing governing fly ash amended soils (Bin-Shafique et al. 2002).

Use of fly ash in embankments, fill, or stabilized base requires good management and care to ensure that there is no negative impact on the environment. In particular, areas with sandy soils possessing high hydraulic conductivities and areas near shallow groundwater or drinking aquifers should be given careful consideration. An evaluation of groundwater conditions, applicable state test procedures, water quality standards, and proper construction are all necessary considerations in ensuring a safe product that does not adversely affect the environment (EPA 2005).

Leaching from fly ash flowable fill can occur due to the permeation of liquid through the fill (Naik et al. 2001). Low hydraulic conductivity of flowable fill reduces the rate at which water permeates and trace elements leach from flowable fill. Flowable fill containing fly ash is typically designed to maximize fly ash content while at the same time meeting strength requirements. Larger concentrations of fly ash correlate to a larger potential to leach trace elements (Gaddam et al. 2006). Extraction procedure toxicity test results on leachate samples from flowable fill indicate that the leachate is not hazardous (Türkel 2006). In a separate study on high fly ash content mixes, leachate from fly ash flowable fill was below the enforcement standards of the Wisconsin Department of Natural Resources ground-water quality standards and met practically all of the drinking water standards (Naik et al. 2001).

Modeling

Models currently used to simulate leaching from pavement systems and potential impacts to groundwater include STUWMPP (Friend et al. 2004), IMPACT (Hesse et al. 2000), HYDRUS-2D (Simunek et al. 1999, Bin-Shafique et al. 2002b, Apul et al. 2005), WiscLEACH (Li et al. 2006), and IWEM (EPA 2002). Among these models STUWMPP, IMPACT, WiscLEACH and IWEM are in the public domain. STUWMPP employs dilution–attenuation factors obtained from the seasonal soil compartment (SESOIL) model to relate leaching concentrations from soils and byproducts to concentrations in underlying groundwater. IMPACT was specifically developed to assess environmental impacts from highway construction. Two dimensional flow and solute transport are simulated by solving the advection dispersion reaction equation using the finite difference method (Li et al. 2006).

WiscLEACH combines three analytical solutions to the advection–dispersion–reaction equation to assess impacts to groundwater caused by leaching of trace elements from CCPs used in highway subgrade, subbase and base layers. WiscLEACH employs a user friendly interface and readily available input data along with an analytical solution to produce conservative estimates of groundwater impact (Li et al. 2006). Factors found to have the greatest influence on concentrations in groundwater are depth to the groundwater table, thickness of the fly ash layer, hydraulic conductivity of the least conductive layer in the vadose (unsaturated) zone, hydraulic conductivity of the aquifer, and initial trace element concentrations in the fly ash layer (Li et al. 2006).

The U.S. EPA's Industrial Waste Management Evaluation Model (IWEM), although developed to evaluate impacts from landfills and stock piles, can help in determining whether fly ash leachate will negatively affect groundwater. IWEM inputs include site geology/hydrogeology, initial leachate concentration, metal parameters, and regional climate data. Given a length of time, the program will produce a leachate concentration at a control point (such as a pump or drinking well) that is a known distance from the source. In addition, Monte Carlo simulations can provide worst-case scenarios for situations where a parameter is unknown or unclear. In comparing IWEM to field lysimeter information, IWEM over predicted the leachate concentrations and could be considered conservative. Overall, however, IWEM performed satisfactorily in predicting groundwater and solute flow at points downstream from a source (Melton et al. 2006).

Fly ash can cause a dust problem during storage and processing or through wind erosion during placement in unencapsulated use. Workers involved with dry ash handling can take precautions by requesting Material Safety Data Sheets (MSDS) from fly ash suppliers, by wearing safety goggles to protect their eyes from dust, and by wearing a suitable particulate respirator (i.e., approved by the National Institute for Occupational Safety and Health for particulates). Dust problems can be partially alleviated by compaction and covering of the fly ash, moistening fly ash during placement, and using mechanical ventilation or extraction in areas where dust could escape into the workplace (EPA 2005). Special lay-down trucks exist that reduce dusting issues.

A source of information on assessing risk and protecting groundwater is U.S. EPA's "Guide for Industrial Waste Management" which can be found at:
http://www.epa.gov/industrialwaste/guide.asp

Finally, due to the variability in fly ash composition between coal plants, industry-wide generalizations about the environmental impact of fly ash cannot be made. Also, because of the variety of leachate testing methods and the variety of standards and regulations to compare these test results to, state regulations should be identified and followed when determining the environmental suitability of fly ash from a particular source.

State Regulations and Specifications

The U.S. Environmental Protection Agency (EPA) has delegated responsibility to the states to ensure that coal combustion by-products are properly used. Each state, therefore, has its own specifications and environmental regulations. A map from the National Energy Technology Laboratory that links to a database of state regulations on the utilization and disposal of coal combustion by-products can be found at: http://www.netl.doe.gov/technologies/coalpower/ewr/coal_utilization_byproducts/states/select_state.aspl

The state regulations database contains summary information on current regulations in each state and contact information for individuals with regulatory responsibility. Some states allow free use of fly ash while others allow limited application. States are generally most concerned with unencapsulated use of fly ash, such as in structural fills, mine applications, and embankments. Some states consider these applications to be waste disposal rather than reuse or recycling (Dockter and Jagiella 2005).

In general, the specifications used by all states for use of fly ash are provided by the American Society of Testing and Materials (ASTM) or the American Association of State Highway and Transportation Officials (AASHTO) and are listed in Table 3.

Table 3. Specifications that apply to reuse of fly ash.

Specification	Title	Application
ASTM D242-04	Mineral Filler for Bituminous Paving Mixtures	Asphaltic concrete
AASHTO M 172	Mineral Filler for Bituminous Paving Mixtures	Asphaltic concrete
ASTM C593-06	Fly Ash and Other Pozzolans for Use with Lime>	Soil stabilization
ASTM D 5239-04	Practice for Characterizing Fly Ash for Use in Soil Stabilization	Soil stabilization
ASTM E2277-03	Guide for Design and Construction of Coal Ash Structural Fills	Structural fill
ACI 232.2R	Use of Fly Ash in Concrete	Portland cement concrete
ASTM C311-05	Sampling and Testing Fly Ash or Natural Pozzolans in for Use in Portland-Cement Concrete	Portland cement concrete
AASHTO M 295 ASTM C618	Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete	Portland cement concrete
ASTM C6103-04	Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)	Flowable fill
ACI 229R	Controlled Low Strength Materials (CLSM)	Flowable fill
ASTM D6024-02	Ball Drop on Controlled Low Strength Material to Determine Suitability for Load Application	Flowable Fill

A site maintained by the Federal Highway Administration (FHWA) contains a searchable library for all highway specifications across the country. This can be found at: http://fhwapap04.fhwa.dot.gov/nhswp/index.jsp

DESIGN CONSIDERATIONS AND GUIDELINES

Portland Cement Concrete – Supplementary Cementitious Material

By 2010, the net cement production in the world is expected to be nearly two billion metric tons (2.2 billion tons), emitting two billion metric tons of carbon dioxide annually (Bilodeau and Malhotra 2000). The replacement of fly ash for Portland cement is therefore one way to reduce greenhouse gas emissions while also advancing sustainable development.

Fly ash has been used as a cement and mineral admixture in Portland cement concrete (PCC) for nearly 70 years. Approximately 50 percent of recycled fly ash is used in the production of concrete and concrete products, making it the largest single use of fly ash (ACAA 2007). Fly ash can also be used as a feed material for producing Portland cement and as a component of a Portland-pozzolan blended cement.

Coal fly ash has been used in Portland cement concrete (PCC) as a mineral admixture, and more recently as a component of blended cement. As an admixture, fly ash functions as either a partial replacement for, or an addition to, Portland cement and is added directly into ready-mix concrete at the batch plant. Fly ash can also be interground with cement clinker or blended with Portland cement to produce blended cements. ASTM C595 defines two blended cement products in which fly ash is a component: 1) Portland-pozzolan cement (Type IP), containing 15 to 40 percent pozzolan, and 2) Pozzolan modified Portland cement (Type I-PM), containing less than 15 percent pozzolan (ASTM C595-07 2007).

ASTM C618 defines two classes of fly ash for use in concrete: 1) low-calcium or Class F fly ash, usually derived from the burning of anthracite or bituminous coal, and 2) high-calcium or Class C fly ash, usually derived from the burning of lignite or subbituminous coal (ASTM C618-05 2005, Papadakis 1999). ASTM C618 also delineates requirements for the physical, chemical, and mechanical properties for these two classes of fly ash. Class F fly ash is pozzolanic, with little or no cementing value alone. Class C fly ash has self-cementing properties as well as pozzolanic properties.

Fly ash of both classes reacts chemically with lime to form cementitious materials. Since Portland cement contains about 65 percent lime, some of which becomes free and available during hydration, the inclusion of fly ash in Portland cement forms additional cementitious materials and improves many properties of the resulting concrete (FHWA 2003).

Virtually all state transportation agencies indicate that they have used fly ash as a mineral admixture in concrete, as a partial replacement for Portland cement, or in blended Portland-pozzolan cement. Fly ash has been used in concrete pavements and shoulders for years, and most states have specifications for the use of fly ash as a partial replacement for Portland cement in concrete (Collins and Ciesielski 1994, Dockter and Jagiella 2005).

The principal benefits of fly ash in concrete include enhanced workability, reduced bleeding and less water demand, increased ultimate strength, reduced hydraulic conductivity and chloride ion penetration, lower heat of hydration, greater resistance to sulfate attack, greater resistance to alkali-aggregate reactivity, and reduced drying shrinkage (FHWA 2003).

The main precautions associated with the use of fly ash in concrete can include slower early strength development, extended initial setting time, difficulty in controlling air content, seasonal limitations during winter months, and quality control of fly ash sources (FHWA 2003). The use of Class F fly ash usually results in slower early strength development, but the use of Class C fly ash does not and may enhance early strength development.

Material Processing:
To ensure the quality of fly ash for use in PCC, the following sources of ash should be avoided:

- Ash from a peaking plant instead of a base loaded plant;
- Ash from plants burning different coals or blends of coal;
- Ash from plants burning other fuels (wood chips, tires, trash) blended with coal;
- Ash from plants using oil as a supplementary fuel;
- Ash from plants using precipitator additives, such as ammonia;
- Ash from start-up or shut-down phases of operation;
- Ash from plants not operating at a "steady state";
- Ash that is handled and stored using a wet system.

When fly ash is used in blended cement or as a partial replacement for Portland cement in ready-mix concrete, the ash must be in a dry form and requires no processing. When used as a raw feed material for the production of Portland cement, either dry or conditioned ash can be used.

Fly ash used in concrete should be as consistent and uniform as possible. The fly ash should be monitored by a quality assurance/quality control (QA/QC) program that complies with the recommended procedures in ASTM C311 (ASTM C311-05 2005). These procedures establish standards for methods of sampling and frequency of performing tests for fineness, loss on ignition (LOI), specific gravity, and pozzolanic activity such that the consistency of a fly ash source can be certified. The most important quality control consideration concerning the use of fly ash in PCC mixes is to ensure that the air content of the freshly mixed concrete is within specified limits. Air content testing of fly ash concrete mixes may need to be performed at a greater frequency than with normal PCC mixes. Another quality control consideration in freshly mixed PCC is workability, as determined by slump tests. Slump testing of fly ash concrete should be done at the same frequency as for normal PCC mixes.

Many state transportation agencies, through their own program of sampling and testing, have been able to prequalify sources of fly ash within their own state (or from nearby states) for acceptance in ready-mixed concrete. Prequalification of fly ashes from different sources provides an agency with a certain level of confidence in the event fly ashes from different sources are to be used in the same project.

When fly ash is used as a mineral admixture, the ready-mix producer typically handles fly ash in the same manner as Portland cement, except that fly ash must be stored in a separate silo from the Portland cement.

Certain fly ashes will reduce the effectiveness of air entraining agents, requiring a higher dosage of air entraining agents to meet specifications. Therefore, the concrete producer must ensure that the proper amount of air entraining admixture is added during mixing, so that the air content meets specifications. The air content of concrete should be carefully checked and adjusted during production to ensure that the air content remains within specified limits. As with any concrete, excessive vibration should be avoided to maintain the air content of the in-place concrete (FHWA 2003).

Placement and handling of fly ash concrete is similar to that of normal concrete. Fly ash concrete using Class F fly ash has a slower setting time than normal concrete. As a result, finishing operations may have to be delayed, possibly by 1 to 2 hours, depending on the temperature. Also, fly ash concrete surfaces may tend to be more sticky than normal concrete during placement and finishing, although properly proportioned concrete mixes containing fly ash should improve workability and finishing (FHWA 2003). Normal procedures for screeding, finishing, edging, and jointing of conventional PCC are also applicable to fly ash concrete.

The slower strength development of concrete containing Class F fly ash may require moisture be retained in the concrete for a longer period of time than is required for conventional concrete. The proper application of a curing compound should retain moisture in the concrete for a sufficient period of time to permit strength development. Beyond the application of a curing compound, typical curing practices should be adequate for concrete containing Class F fly ash. Moist curing should be carried out for a minimum duration of 14 days to ensure good strength and durability (Hani and Nakin 2002).

Construction should be scheduling to allow adequate time for strength gain prior to: traffic loads, freeze-thaw cycles, or the application of deicing salts. Some states have a construction cut-off date beyond which fly ash is not permitted to be used in concrete until the following spring. There is less of a concern with the use of Class C fly ash in cold weather than Class F fly ash.

Alternative approaches to a cutoff date include: reducing the percentage of fly ash used during colder weather, increasing the amount of Portland cement, using high-early strength cement, or including a chemical accelerator. Normal construction practices for cold weather concreting (such as heated aggregates and mixing water, reducing the slump of the concrete, covering the poured concrete with insulation material, and using space heaters for inside pours) are also applicable for concrete containing fly ash (PCA 1980).

Design Considerations for Concrete/Cement:
Some of the engineering properties of fly ash that are of particular interest when fly ash is used as an admixture or a cement addition to PCC mixes include fineness, LOI, chemical composition, moisture content, and pozzolanic activity. Most specifying agencies refer to ASTM C618 when citing acceptance criteria for the use of fly ash in concrete.

Fineness is the primary physical characteristic of fly ash that relates to pozzolanic activity. As the fineness increases, the pozzolanic activity can be expected to increase. Current specifications include a requirement for the maximum allowable percentage retained on a 0.045 mm (No. 325) sieve when wet sieved. ASTM C618 specifies a maximum of 34 percent retained on a 0.045 mm (No. 325) sieve. Methods of specific surface area estimation can also assess fineness, such as the Blaine air permeability test commonly used for Portland cement (ASTM C204-07 2007).

Pozzolanic activity refers to the ability of the silica and alumina components of fly ash to react with available calcium and/or magnesium from the hydration products of Portland cement. ASTM C618 requires that the pozzolanic activity index with Portland cement, as determined in accordance with ASTM C311 be a minimum of 75 percent of the average 28-day compressive strength of control mixes made with Portland cement.

Many state transportation departments specify a maximum LOI value that does not exceed 3 or 4 percent, although ASTM criteria allow a maximum LOI content of 6 percent (ASTM C618-05 2005). This is because carbon contents (reflected by LOI) higher than 3 to 4 percent have an adverse effect on air entrainment.

Fly ashes must have a low enough LOI (usually less than 3.0 percent) to satisfy ready-mix concrete producers that are concerned about product quality and the control of air-entraining admixtures. Furthermore, consistent LOI values are almost as important as low LOI values to ready-mix producers that strive for consistent and predictable quality.

Concrete mixes containing fly ash with a very high LOI can produce dark-colored surface streaks as carbon particles float to the top during concrete finishing (FHWA 2003).

ASTM C618 specifies a maximum allowable moisture content of 3.0 percent.

At a given water-cement ratio, the spherical shape of most fly ash particles permits greater workability than with conventional concrete mixes. The fly ash particles act as miniature "ball bearings" within the concrete mix, providing the mix with a lubricant effect ((FHWA 2003). When fly ash is used, the absolute volume of cement plus fly ash usually exceeds that of cement in conventional concrete mixes. The increased ratio of solids volume to water volume produces a paste with improved plasticity and more cohesiveness (Halstead 1986).

Pumpability is increased by the same characteristics affecting workability, specifically, the lubricating effect of the spherical fly ash particles and the increased ratio of solids to liquid that makes the concrete less prone to segregation (Halstead 1986).

When replacing up to 25 percent of the Portland cement in concrete, all Class F fly ashes increase the time of setting. Some Class C fly ashes may increase or decrease the time of setting. Delays in setting time are more pronounced, compared with conventional concrete mixes, during the cooler months (Halstead 1986).

Bleeding is usually reduced when fly ash is used in concrete mix because of the greater volume of fines and lower required water content for a given degree of workability (Halstead 1986).

Previous studies of fly ash concrete mixes have generally confirmed that most mixes that contain Class F fly ash that replaces Portland cement at a 1:1 (equal weight) ratio gain compressive strength, as well as tensile strength, more slowly than conventional concrete mixes for as long as 60 to 90 days. Beyond 60 to 90 days, Class F fly ash concrete mixes will ultimately exceed the strength of conventional PCC mixes (FHWA 2003). For mixes with replacement ratios from 1:1

to 1.5:1 by weight of Class F fly ash to the Portland cement that is being replaced, 28-day strength development is approximately equal to that of conventional concrete.

Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes. Some Class C fly ashes are as effective as Portland cement in developing 28-day strength (Cook 1981). Both Class F and Class C fly ashes are beneficial in the production of high-strength concrete. However, the American Concrete Institute (ACI) recommends that Class F fly ash replace from 15 to 25 percent of the Portland cement and Class C fly ash replace from 20 to 35 percent (ACI 211.4R 1993).

The initial impetus for using fly ash in concrete stemmed from the fact that the more slowly reacting fly ash generates less heat per unit of time than the hydration of the faster reacting Portland cement. Thus, the temperature rise in large masses of concrete (such as dams) can be significantly reduced if fly ash is substituted for cement, since more of the heat can be dissipated as it develops. Not only is the risk of thermal cracking reduced, but greater ultimate strength is attained in concrete with fly ash because of the pozzolanic reaction (Halstead 1986). Class F fly ashes are generally more effective than Class C fly ashes in reducing the heat of hydration.

Fly ash reacting with available lime and alkalies generates additional cementitious compounds that act to block bleed channels, filling pore space, and reducing the hydraulic conductivity of hardened concrete (Meyers et al. 1976). The pozzolanic reaction consumes calcium hydroxide ($Ca(OH)^2$), which is leachable, replacing it with insoluble calcium silicate hydrates (CSH) (Halstead 1986). The increased volume of fines and reduced water content also play a role in reducing hydraulic conductivity.

As with all concretes, the resistance of fly ash concrete to damage from freezing and thawing depends on the adequacy of the air void system, as well as other factors, such as strength development, climate, and the use of deicer salts. Special attention must be given to attaining the proper amount of entrained air and air void distribution because fly ash may reduce the effectiveness of air entraining agents (Freeman et al. 1997). Once fly ash concrete has developed adequate strength, no significant differences in concrete durability have usually been observed (Halstead 1986). There should be no more tendencies for fly ash concrete to scale in freezing and thawing exposures than conventional concrete, provided the fly ash concrete has achieved its design strength and has the proper air void system.

Class F fly ash in concrete generally improves the sulfate resistance. However, replacement of low-calcium fly ash has reduced the resistance of Portland cement to acid rain attack (Hester 1967, Jia and Zhou 2006). Some Class C fly ashes may improve sulfate resistance, while others may actually reduce sulfate resistance and accelerate deterioration (Dunstan 1980, Helmuth 1987). Class C fly ashes should be individually tested before use in a sulfate environment. The relative resistance of fly ash to sulfate deterioration is reportedly a function of the ratio of calcium oxide to iron oxide (Dunstan 1980).

Class F fly ash has been effective in inhibiting or reducing expansive reactions resulting from the alkali-silica reaction. In theory, the reaction between the very small particles of amorphous silica glass in the fly ash and the alkalis in the Portland cement, as well as the fly ash, ties up the alkalis in a non-expansive calcium-alkali-silica gel. This prevents the alkali from reacting with silica within aggregates that would have resulted in expansive reactions. However, because some fly ashes (including some Class C fly ashes) have appreciable amounts of soluble alkalis, testing of mixes is recommended to ensure that expansion due to alkali-silica reactivity will be at acceptable levels (Halstead 1986).

A modified ASTM C1260 accelerated mortar-bar test can be employed to identify potential alkali-silica reactivity as well as assess the effectiveness of supplementary cementitious materials in decreasing alkali-silica reactivity effects. The original ASTM C1260 that is generally performed quickly (within 14 days) and under harsh conditions (high temperature and highly alkaline solution). This test can produce high alkali-silica reactivity in fly ash mixes even when field performance is adequate. A modified ASTM C1260 for fly ash extends testing times to 28 days and considers various test solutions resulting in more representative levels of alkali-silica reactivity. Further research into other factors such as temperature and constituents of sample mixtures need to be performed (Chang-Seon et al. 2003).

Fly ash, especially Class F fly ash, is effective in three ways in substantially reducing alkali-silica expansion: 1) fly ash produces a denser, less permeable concrete, 2) when used as a cement replacement fly ash reduces total alkali content by reducing the Portland cement; and 3) alkalis react with fly ash instead of reactive silica aggregates. Class F fly ashes are probably more effective than Class C fly ashes because of higher silica content, which can react with alkalis. Users of Class C fly ash are encouraged to evaluate the long-term volume stability of concrete mixes in the laboratory prior to field use, with ASTM C441 as a suggested method of test.

Structural design procedures for concrete pavements containing fly ash are no different than design procedures for conventional concrete pavements. The procedures are based on the design strength of the concrete mix, usually determined by testing after moist curing for 28 days. Design strength for pavement concrete may be either the tensile or flexural strength, or possibly the unconfined compressive strength. Design strength of structural concrete is usually the unconfined compressive strength as determined by ASTM C39.

Mix Design:

Concrete mixes are designed by selecting the proportions of the mix components that will develop the required strength, produce a workable consistency concrete that can be handled and placed easily, attain sufficient durability under exposure to in-service environmental conditions, and be economical. Procedures for proportioning fly ash concrete mixes differ slightly from those for conventional concrete mixes. Basic mix design guidelines for normal concrete (ACI 211.1 2002) and high-strength concrete are provided by ACI (ACI 211.4R 1993).

One mix design approach used in proportioning fly ash concrete is to design a mix with all Portland cement, remove a portion of the Portland cement, and then add fly ash to compensate for the cement removed. Class C fly ash is typically substituted at a 1:1 ratio, while Class F fly ash may also be substituted at a 1:1 ratio, but is sometimes specified at a 1.25:1 to 1.5:1 ratio (FHWA 2003). Some states require that for certain mixes, fly ash be added to a mix without a reduction in cement content.

The percentage of Class F fly ash used as a percent of total cementitious material in typical highway pavement or structural concrete mixes usually ranges from 15 to 25 percent by weight (FHWA 2003). This percentage usually ranges from 20 to 35 percent for Class C fly ash (ACI 211.4R 1993).

Mix design procedures for normal, as well as high-strength, concrete involve a determination of the total weight of cementitious materials (cement plus fly ash) for each trial mix. The ACI mix proportioning guidelines recommend a separate trial mix for each 5 percent increment in the replacement of Portland cement by fly ash. If fly ash replaces Portland cement on an equal weight basis (1:1), then the total weight of cementitious material in each trial mix remains the same. However, because of the differences in the specific gravity values of Portland cement and fly ash, the volume of cementitious material will vary with each trial mixture (ACI 211.4R 1993).

When Type IP (Portland-pozzolan) or Type I-PM blended (Pozzolan modified Portland) cement is used in a concrete mix, fly ash is already part of the cementing material; therefore, there it is recommended not to add additional fly ash. The blended cement can be used in the mix design process in the same way as a Type I Portland cement.

To select a mix proportion that satisfies the design requirements for a particular project, trial mixes must be made. In a concrete mix design, the water-cement (w/c) ratio is a key design parameter, typically ranging from 0.37 to 0.50. When using a blended cement, the water demand typically is reduced because of the presence of fly ash. When fly ash is used as a separately batched material, trial mixes should be made using a water-cement plus fly ash (w/c+f) ratio, sometimes referred to as the water-cementitious ratio.

The design of any fly ash concrete mix is based on proportioning the mix at varying water-cementitious ratios to meet or exceed requirements for compressive strength (at various ages), entrained air content, and slump or workability needs. The mix design procedures stipulated in ACI 211.1 provide a step-by-step process regarding trial mix proportioning of the water, cement (or cement plus fly ash), and aggregate materials. However, fly ash has a lower specific gravity than Portland cement, which should be taken into consideration in the mix proportioning process.

Asphalt Concrete – Mineral Filler

Asphalt concrete is a composite material consisting of an asphalt binder and mineral aggregate that is laid down in lifts and compacted to a sufficient density to allow dynamic loading by traffic. For highway and airfield applications, hot mix asphalt concrete (HMA) is most commonly used and is generated by heating the aggregate to around 300° F and the asphalt cement to 200° F before mixing. Flexible pavement comprises more than 93 percent of all roadways in the U.S. The American Coal Ash Association has reported that approximately 26,720 metric tons (29,450 tons) of ash were used as asphalt mineral filler in 2006 (ACAA 2007). Past surveys of state transportation agencies indicated that the majority of states use fly ash as a mineral filler. Increased use of fly ash in this application would dramatically decrease the amount of landfilled fly ash while potentially decreasing costs (Churchill and Amirkhanian 1999).

Use of fly ash as a mineral filler is governed by ASTM D242 and AASHTO M-17, which outline specifications for mineral filler. Asphalt mixtures containing low levels of fly ash, approximately 5 percent by dry weight of aggregate, exhibit mix design properties that are usually comparable to asphalt mixtures containing natural fillers such as hydrated lime or stone dust. Gradation, organic impurities, and plasticity characteristics ordinarily associated with mineral filler specification requirements can normally be met without difficulty. The characteristics of mineral fillers that are most related to asphalt paving mixture performance are particle sizes in microns corresponding to D60 and D10 of the P200 material and the methylene blue test (Kandhal et al. 1998).

Fly ash can also be used as an asphalt cement extender. Testing has shown 10 and 30 percent replacement of asphalt cement with fly ash does not significantly negatively affect mix properties like strength and durability (Simms 1998). Replacement of a portion of asphalt cement with fly ash in paving mixtures could provide an economical alternative to using costly asphalt as well as provide longer pavement service life due to improved pavement properties (Simms 1998). Although testing has shown the possible benefits of this application, further testing, especially in the field, is required to prove the legitimacy using fly ash as a partial asphalt cement replacement. In general, states reported fair to good performance on the survey (AASHTO 1994).

Material Processing:

Fly ash must be in a dry form when used as a mineral filler. This means that moisture-conditioned fly ash and reclaimed ponded fly ash are unsuitable for use in asphalt concrete.

Fly ash is collected at the power plant and stored in watertight silos in a dry form. As a result, fly ash can readily be loaded into pneumatic trucks and delivered to a hot mix asphalt plant.

Fly ash can be a dusty material and may result in more dust generation than normally experienced with conventional mineral fillers.

At a hot mix plant, the fly ash can be discharged directly into a storage silo, like conventional mineral fillers, prior to input into the mixing plant.

Typical placement and compacting equipment can be used with asphalt mixes containing fly ash.

Design Considerations for Asphalt Concrete:

The physical requirements for mineral filler in bituminous paving mixtures are defined in AASHTO M-17 and are shown in Table 4. These requirements include gradation, organic impurities, and plasticity characteristics. Other properties of interest include fineness and specific gravity.

Table 4. AASHTO M-17 specification requirements for mineral filler use in asphalt paving mixtures.

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

The AASHTO specification limits for mineral filler range from 70 to 100 percent passing the 0.075 mm (No. 200) sieve. Most fly ashes typically fall within a size range of from 60 to 90 percent passing the 0.075 mm (No. 200) sieve (Di Gioia and Nuzzo 1972).

Although most sources of fly ash are capable of meeting the AASHTO gradation requirements for mineral filler, consistency of gradation is important, especially the size and shape of the particles finer than a 0.075 mm (No. 200) sieve. Theoretically, higher fineness may indicate a more effective mineral filler, although the higher fineness also means a greater surface area of particles that must be coated, resulting in an increase in asphalt content of the mix. Fly ash fineness is often specified by the percentage by weight retained on the 0.045 mm (No. 325) sieve, especially when used in Portland cement concrete;(16) however, this is not a standard for fly ash used as a mineral filler.

The specific gravity of fly ash varies from source to source. Specific gravity may be as low as 1.7 to as high as 3.0, but is more often within a range of 2.0 to 2.8. Most conventional mineral fillers have a specific gravity in the 2.6 to 2.8 range. The bulk unit weight of fly ash is typically less than conventional mineral filler; therefore, a given weight percentage of fly ash will usually occupy a greater volume than that of a conventional filler material.

As determined by the modified Rigden's void test, asphalt binder tends to become over stiffened when composed of mineral fillers with more than 50 percent voids. This is generally not a concern when using fly ash as a mineral filler as most fly ashes have a Rigden measured percentage of voids of less than 50 percent (FHWA 2003).

Some fly ash from boilers that burn oil during start-up periods may contain residual oil in the fly ash. Although no standard for carbon content or loss on ignition (LOI) is specified for fly ash used as a mineral filler, it is more practical to use a fly ash with a relatively low LOI (less than 5 or 6 percent) to minimize the potential absorption of asphalt by carbonaceous particles. The LOI of fly ash may not be a significant factor affecting performance as a mineral filler, especially for fly ash with a low calcium content. Laboratory tests performed to evaluate the effectiveness of

LOI have shown that asphalt mixes incorporating fly ash with LOI up to 10 percent perform satisfactorily (FHWA 2003).

Fly ash is a nonplastic material. Thus, plasticity is not an issue when using fly ash as a mineral filler.

Conventional AASHTO pavement structural design methods are applicable to hot mix asphalt incorporating fly ash as mineral filler in the mix.

Mix Design

The same mix design methods that are commonly used for hot mix asphalt paving mixtures are also applicable to mixes in which coal fly ash is used as a mineral filler. The percentage of fly ash filler to be incorporated into the design mix is the lowest percentage that will enable the mix to satisfy all the required design criteria.

A small amount of hydrated lime (usually ½ to 2 percent by weight) improves the anti-stripping characteristics of an asphalt paving mix. Because Class C fly ash contains 30 percent or more calcium, the use of Class C fly ash may improve asphalt stripping. In addition, fly ash is hydrophobic in nature and is believed to reduce asphalt stripping (FHWA 2003), although further testing is needed to confirm that fly ash improves asphalt stripping characteristics.

Stabilized Base – Supplementary Cementitious Material

Stabilized bases or subbases are mixtures of aggregates and binders, such as Portland cement, which increase the strength, bearing capacity, and durability of a pavement substructure. Because fly ash may exhibit pozzolanic properties and self-cementing properties, fly ash is successfully used as all or part of the binder in stabilized base construction applications. Both bituminous (pozzolanic) and subbituminous or lignite (self-cementing) fly ashes can be used. Results from both laboratory and field studies have shown that fly ash can be used in stabilized bases or subbases and those stabilized layers can be included in flexible pavement designs (Arora and Aydilak 2005, Bin-Shafique et al. 2004, Edil et al. 2000, Wen et al. 2004).

The use of fly ash in stabilized base and subbase mixtures dates back to the 1950s, when a patented base course product known as Poz-o-Pac (consisting of a blend of lime, fly ash, and aggregate) was originally developed. Since the Poz-o-Pac patents expired during the early 1970s, numerous variations of the basic lime-fly ash-aggregate formulations have evolved. There have also been stabilized base mixtures containing Portland cement that have evolved from soil-cement. All of these mixtures contain fly ash and can be described under the general heading of pozzolan-stabilized base (PSB).

The major component of most stabilized base mixtures is the aggregate. Early Poz-o-Pac mixes within high traffic volume roadways used locally available high-quality crushed rock (such as limestone, trap rock, or granite), sand and gravel, or blast furnace slag. PSB mixes have been placed within haul roads, residential streets, and local roadways using power plant aggregates (bottom ash or boiler slag), marginal aggregates (including some off-spec materials), coal refuse, and reclaimed paving materials. Such alternative aggregates are often available and economical in areas where high-quality aggregate materials may be in short supply.

A similar base course application for fly ash is stabilized cold in-place recycling (CIR). Typically the stabilized CIR process consists of milling existing pavement and mixing the recycled pavement with an asphalt emulsion for stabilization. CIR provides a high-quality base for new asphalt surface courses while permitting the in-place recycling of existing asphalt pavement materials. Similar benefits of asphalt emulsion stabilized CIR have been realized by replacing the asphalt emulsion with fly ash (Thomas et al. 2000, Crovetti 2000, Ramme and Tharaniyil 2004,Wen et al. 2003, Wen et al. 2004, Li et al 2007).

According to a 2005 survey, 12 states have some type of specifications for using fly ash in transportation soil stabilization applications (Dockter and Jagiella 2005). At least 22 states have used fly ash in stabilized base or subbase material (Collins and Ciesielski 1994). Many of the stabilized base and subbase installations have been placed in low traffic areas such as local streets or parking lots. These installations have not usually been well documented. There are, however, a number of PSB projects that have been well reported and have provided excellent performance. At least seven states installed PSB base courses as part of the Federal Highway Administration Demonstration Project No. 59, Fly Ash Use in Highway Construction.

PSB pavements have provided good to excellent performance over many years in numerous locations. In general, these mixtures have been more economical than alternative base materials. Nonetheless, a concern of highway engineers using stabilized-based materials, including soil-cement, is the development of cracks within the base course that may reflect up to the pavement surface (so called "reflection cracks"). A Kansas DOT study comparing partial-depth CIR stabilized with either Class C fly ash or an emulsion with lime slurry showed that the fly ash test sections were more susceptible to both transverse and longitudinal cracking (Thomas et al. 2000). A similar comparative study in Wisconsin between a control section, asphalt emulsion stabilized section, and a fly ash section showed no observed surface cracking after six years of use (Ramme and Tharaniyil 2004, Crovetti 2000).

Material Processing:
Aside from possible adjustments to moisture content, there is little to no processing required for using fly ash in PSB mixtures. For Class F fly ash, the moisture content is dictated by the type of equipment used to produce the base course material. If a central-mix concrete plant is used, the fly ash will most likely be fed from a silo in dry form. If a pugmill mixing plant is used, the fly ash will probably be fed from a storage bin in conditioned form. If PSB materials are to be mixed in place at the jobsite, Class F fly ash will be placed and mixed in a conditioned form. Conditioned ash contains a minimal amount of water (usually 10 to 15 percent) to prevent dusting.

Activators (e.g., lime, Portland cement, kiln dust) are nearly always added to the mixture in a dry form. This means that the activators require no processing and will be delivered to the job site and stored in silos or tankers.

Class C fly ash is likely to be self-cementing. There are two ways to offset the rapid hardening of base materials using self-cementing ashes. One is to initially condition the ash with relatively low amounts (10 to 15 percent) of water, stockpile the partially hardened material for several weeks, and then run the ash through a crusher to break down any agglomerations prior to use.

The second is to use a commercial retarder (such as gypsum or borax) blended at a low percentage with the fly ash as a means of delaying the initial set (ACAA 1991).

The aggregate used in PSB mixtures should be in a saturated surface-dry condition during stockpiling. The moisture content of the aggregate should be checked prior to mixing to ensure that excess moisture has not been acquired during stockpiling.

If fly ash used in a PSB mixture is mixed in a dry form, the fly ash should be stored in a silo or pneumatic tanker. If conditioned fly ash (usually Class F fly ash) is used, then the conditioned fly ash can be stockpiled. When fly ash is stockpiled for an extended period of time in dry or windy weather, the stockpile may need to be periodically moistened to prevent unwanted dusting.

The primary concerns related to construction and placement of self-cementing fly ash include:

- Uniform distribution of the fly ash
- Proper pulverization and thorough mixing of the fly ash with subgrade material
- Control of moisture content to achieve maximum density and strength
- Final compaction within the prescribed time frame (ACAA 2006).

The blending or mixing of PSB materials can be accomplished either in a mixing plant or in-place.

Plant mixing provides greater control over the quantities of materials batched, which results in a uniform PSB mixture. Blending of PSB ingredients in a mixing plant can occur in discrete batches or by continuous mixing. Pugmill mixing plants blend accurately controlled amounts of aggregate, fly ash, activator, and water in batches in a mixing chamber, usually for periods of 30 to 45 seconds. Pugmill mixing plants can be used with properly calibrated field conveyors from bins or silos for a continuous mixing operation. Rotating drum mixers have been used for blending PSB materials in batches (Barenberg and Thompson 1976). Plant-mixed materials should be delivered to the job site as soon as possible after mixing.

Alternatively, in-place mixing can be used for cold in-place recycling (CIR) of asphalt pavement. On site mixing does not require the establishment of a mixing plant and also takes advantage of the rapid set time of self-cementing fly ash (White et al. 2005). Although mix-in-place typically does not result in an accurately proportioned mix, mix-in-place still produces high-quality PSB material. The various components of the PSB mixture are delivered, spread on the road site, and mixed in place using a pulvamixer or construction disc.

Delivery of PSB material is typically handled by covered end-dump vehicles. The same equipment used for spreading plant-mixed PSB material can be used for mix-in-place material. Once the PSB material is dumped, spreading is usually accomplished by a bulldozer or a motor grader. However, plant-mixed material can also be spread to a more uniform and accurate loose thickness by a spreader box or a paving machine. PSB material should be as close as possible to optimum moisture content when placed.

During the in-place mixing operation, fly ash should be placed on the roadway first, either directly on a prepared subgrade, or above a layer of aggregate, if the PSB mixture contains aggregate. Fly ash is usually applied in a conditioned form to minimize dusting. The activator is then placed on top of the fly ash, usually in a dry condition, although lime can also be applied in a slurry form. The materials are then mixed together by means of a rotary mixer.

Controlling the water content of the fly ash treated materials is one of the most important steps in the construction procedure. Moisture contents should be between 0 and 4 percent above optimum moisture content (ACAA 2006). If water is added after blending with the stabilized material, hydration can occur before compaction. Adding water to the pulverized material may make the untreated material unstable for construction equipment. Furthermore, applying water to the fly ash directly distributed on the surface of the subgrade is ill-advised due to premature hydration. Introducing water in the drum of the rotary mixer is the recommended option and proven to be most efficient means of uniformly distributing water (ACAA 2006).

Compaction of PSB materials should be completed as quickly as possible after placement, especially with mixtures containing Class C (self-cementing) fly ash. The stabilized material can lose strength capacity if the fly ash hydrates in an uncompacted state. The pozzolanic reactions between Class F fly ash and lime is a relatively slow reaction, and a maximum delay of 4-hours should be followed whereas a maximum delay of 2-hours has been recommended for Class C fly ash (White et al. 2005, Little et al. 2000).

Equipment used for compaction is the same, regardless of whether PSB material is plant-mixed or mix-in-place. For granular or more coarsely graded PSB materials, compaction requires the use of steel-wheeled, vibratory, or pneumatic rollers. For more fine-grained PSB materials, initial compaction often requires the use of a sheepsfoot roller, followed by a pneumatic roller (ACAA 1991).

PSB materials should not be placed in layers that are less than 100 mm (4 in) or greater than 200 to 225 mm (8 to 9 in) in compacted thickness. The material should be spread in loose layers that are approximately 50 mm (2 in) greater in thickness prior to compaction than the desired compacted thickness. The top surface of an underlying layer should be scarified prior to placing the next layer.

After placement and compaction of the PSB material, the material should be properly protected against drying to assist in the development of in-place strength. Water can be periodically applied between lifts or before application of a wearing surface. If an asphalt concrete pavement is to be placed as an overlay, an asphalt emulsion seal coat should be applied to the top surface of the base or subbase within 24 hours of pavement placement. The exact type of emulsion, rate of application, and temperature of the asphalt must be in compliance with applicable specifications.

The performance of pavement systems incorporating PSB material depends on the development of in-place strength following placement, compaction, and curing. Depending on the anticipated traffic loadings, an analysis of when traffic can be permitted to travel on the base material may be necessary to avoid potential fatigue damage due to early overloading.

Unless an asphalt surface or binder course has been placed over the PSB material, vehicles should not be permitted on the PSB layer until achieving an in place compressive strength of at least 2410 kPa (350 lb/in^2). Based on laboratory testing for strength development, the time to achieve this strength can be determined. Ordinarily, placement of asphalt paving over the PSB material is recommended within 7 days after the PSB material has been placed (ACAA 1991). If a Portland cement concrete pavement is constructed over the PSB layer, a waiting period of 7 days is also recommended.

Unless pozzolan stabilized materials are able to develop a certain level of strength prior to the first freeze-thaw cycle, these materials may be unable to withstand repeated freezing and thawing. Since strength development is time- and temperature-dependent, PSB material placed when the air temperature is too cold may not be able to develop the strength and durability needed for adequate freeze-thaw resistance. Minimum temperatures of 4.5°C (40°F) to 10°C (50°F) are commonly used for lime and Portland cement stabilization (ACAA 2006).

Another concern with late season construction includes mixing operations in clays of high plasticity. Experience has shown that high plasticity clays may require more than one pass at lower temperatures ACAA 2006).

Snow has been shown to introduce extra water during the compaction of fly ash without causing the workability problems encountered when attempting to compact fly ash at wetter than optimum states. Addition of snow can cause a 30 percent increase in void ratio, 14 percent decrease in unit weight, and a 70 percent increase in long-term shear strength. The higher strength is believed to be due to the availability of more water for cementation reactions (Baykal et al. 2004).

Self-cementing fly ash mixed with water alone usually results in a very rapid time of set. Delays between placement and compacting of PSB material containing self-cementing fly ash are accompanied by a significant decrease in the strength of the compacted base material, unless a retarder is used. Accordingly, PSB mixtures containing self-cementing fly ash should be compacted as soon as possible after mixing, with a recommended maximum elapsed time of no more than 2 hours between mixing and completion of compaction (Thornton and Parker 1980).

A low percentage of water, in the range of 10 to 25 percent by weight of ash, is sufficient to reduce dusting and can be added at the mixing plant. The additional water that is required for proper compaction of the PSB material can be applied in place at the construction site before compaction.

A commercial retarder (such as gypsum, borax, or concrete retarding admixture) may be added in low percentages to the PSB material at the mixing plant. Tests have shown that the addition of 1 percent gypsum did not adversely affect the overall strength development of PSB material, but was effective in retarding rapid setting (Thornton and Parker 1980, Ferguson 1993).

Stabilized base layers constructed with fly ash are less likely to produce reflection cracking in overlying pavement as is sometimes the case with Portland cement stabilized base layers. This is most likely due to a less stiff bond within the fly ash stabilized base. Approaches for controlling or minimizing the potential effects of reflective cracking associated with PSB layers have been recommended by ACAA (1991). A field and laboratory study showed that lime and fly ash stabilized soil is less prone to shrinkage and cracking than cement-stabilized soil base course (Shirazi 1999).

A cement-stabilized Class F fly ash mixture that was used beneath a highway shoulder demonstrated localized cracking due to low density and strength. Severe heave and cracking also developed adjacent to grooves and joints that were cut in the asphalt pavement between the shoulder and traveled way. These joints intercepted and diverted runoff into the underlying fly ash which caused cracking (Gray et al. 1994).

A Kansas DOT study comparing partial-depth CIR stabilized with either Class C fly ash or an emulsion with lime slurry showed that the fly ash test sections were more susceptible to both transverse and longitudinal cracking (Thomas et al. 2000). A similar comparative study in Wisconsin between a control section, asphalt emulsion stabilized section, and a fly ash section showed no observed surface cracking after six years of use (Ramme and Tharaniyil 2004, Crovetti 2000).

Design Considerations for Stabilized Base:
Some of the properties of fly ash that are of particular interest when fly ash is used in stabilized base applications include water solubility, moisture content, pozzolanic activity, fineness, and organic content. Consult ASTM D5239 and C593 for specifications on characterizing fly ash for use in soil stabilization. Other properties of interest include compressive strength, flexural strength, resilient modulus, bearing strength, autogeneous healing, fatigue, freeze-thaw durability, and hydraulic conductivity.

The physical requirements most frequently cited for the use of fly ash (Class F) in PSB mixtures are provided in ASTM C593 which specifies a maximum water soluble fraction of 10 percent.

If conditioned fly ash is used, the moisture content of the conditioned ash should be determined prior to mixing to confirm the moisture content is in the same range as the ash used during mix design.

One of the most important properties of fly ash used in PSB mixtures is pozzolanic activity or reactivity. The pozzolanic reactivity is an indicator of the ability of a given source of fly ash to combine with calcium to form cementitious compounds. The pozzolanic reactivity of fly ash is influenced by the fineness, silica and alumina content, LOI, and alkali content. Besides the gradation of the aggregate used, the pozzolanic reactivity of the fly ash is the major contributor to the strength of the base mix. Pozzolanic activity of fly ash with either lime or Portland cement can be determined using the test methods described in ASTM C311.

Fineness requirements for stabilization of soil with Class F fly ash, which requires mixing with lime, are given in ASTM C593. ASTM C593 specifies that 98 percent of the fly ash should be finer than 0.6 mm (No. 30 sieve) and 70 percent finer than 0.075 mm (No. 200 sieve). Most fly ash is capable of meeting these specifications.

Fly ash used in PSB mixtures does not have to meet the ASTM C618 requirements of fly ash that is used in Portland cement concrete. Although LOI is not a criterion for the use of fly ash in PSB mixtures, organic soils have traditionally been more difficult to stabilize chemically due to lower solids content, higher water content, lower pH, and chemical interference with cementing reactions (Edil et al. 2006).

Compressive strength is the most widely used criterion for the acceptability of PSB materials. Compressive strength testing of PSB mixtures is usually performed on Proctor-size specimens 10.2 cm (4 in) in diameter by 11.7 cm (4.6 in) in height, molded at or very close to the optimum moisture content of the mixture. In general, higher compressive strength indicates higher quality of the stabilized material. For cement-stabilized base mixtures, the Portland Cement Association recommends a minimum 7-day compressive strength after curing at 23°C (73°F) of 3,100 kPa (450 lb/in2) (PCA 1992). Where lime or kiln dust is used as the activator, ASTM C593 specifies a minimum compressive strength after 7 days of curing at 38°C (100°F) as 2760 kPa (400 lb/in2). The ultimate strength of PSB mixtures containing Class F fly ash may be two to three times higher than the 7-day strength. The rate of strength increase for Class F mixtures diminish rapidly after 56 days (Arora et al. 2005).

Actual compressive strength development of PSB mixtures in the field is time- and temperature-dependent. As the temperature increases, the rate of strength gain also increases. At or below 4°C (40°F), the pozzolanic reaction virtually ceases and the mixture no longer gains strength. However, once temperatures exceed 4°C (40°F), the pozzolanic reaction resumes and further strength gains occur. For this reason, PSB mixtures can continue to show incremental gains in strength over many years (Arora et al. 2005).

Because hardened PSB material is a semi-rigid pavement layer, the flexural strength of PSB mixtures may be a better indicator of the material's effective strength. Although flexural strength can be determined directly by testing, most transportation agencies estimate the flexural strength as a fraction of compressive strength. An average value of 20 percent of the unconfined compressive strength is considered to be a fairly accurate estimate of the flexural strength of PSB mixtures (Meyers et al. 1976).

The California bearing ratio (CBR) test (ASTM D1883-05 2005) is often used as a way of measuring the bearing strength of soils used in subgrades for highway and airfield pavements. Due to the relatively high strength of compacted PSB mixtures, high CBR values (in excess of 100 percent) are not unusual. Use of the CBR test is more applicable to subgrade soil stabilization with fly ash than in evaluating PSB mixtures.

In addition to reducing the swell potential of soft soils (Ferguson 1993), an increase in CBR has been observed with the addition of fly ash to fine-grained soils with plasticity indices in the range of 15 and 40. At an in situ water content of 7 percent wet of optimum, these soils generally had CBRs between 1 and 5, indicating their poor value as subgrades. Addition of 10 percent fly ash caused the CBRs to increase by a factor of 4; while the addition of 18 percent fly ash increased the CBR by a factor of 8. Soil type also affected the observed CBR increase. The largest CBR gain was found with soft, highly plastic clays, and the smallest CBR gain was with more well-graded, silty clay (Edil et al. 2006). Field CBRs can be two-thirds the value measured during laboratory design. This is likely due to clumping of clay particles in the field, reducing the uniformity of cementing (Bin-Shafique et al. 2004).

Resilient modulus is a measure of the modulus of elasticity during rapidly applied loadings. Resilient modulus is related to the long-term performance of materials under service loads. Soft soils treated with fly ash can experience relatively large increases in resilient modulus measured by AASHTO T 292 (Little et al. 2000). Poor subgrade material can have appreciable gains in Mr (near 100 MPa) with the addition of 10 to 12 percent fly ash (Bin-Shafique et al. 2004). The relationship, $M_r = 3 \times \text{CBR}$ (MPa), corresponds well to laboratory results on fly ash stabilized soil (Sawangsuriva and Edil 2005, Edil et al. 2006).

One of the unique characteristics of PSB compositions is the ability to heal or re-cement cracks within the material by means of a self-activating mechanism. This mechanism is referred to as autogenous healing and results from the continuation of the pozzolanic reaction between the activator and the fly ash in the PSB mixture. The extent to which autogenous healing occurs depends on the age of the pavement when cracking develops, the degree of contact of the fractured surfaces, curing conditions, the strength of the pozzolanic reaction, and available moisture (Meyers et al. 1976).

All engineering materials are subject to potential failure caused by progressive fracture under the action of repeated wheel loadings. In pavement design analysis, the flexural fatigue properties of PSB materials are a very important consideration. The flexural strength of PSB mixtures, like the compressive strength, increases with time, while the stress level (the ratio of applied stress to the modulus of rupture) gradually decreases. Because of autogenous healing, PSB mixtures are even less susceptible to fatigue failure than other conventional paving materials (Ahlberg and Barenberg 1965).

Durability testing of PSB materials is performed using one of two established test procedures. For lime and lime-based activators (including kiln dusts), the durability test procedure specified in ASTM C593 is used. This is a vacuum saturation procedure that has been correlated to weight loss after 12 freeze-thaw cycles. The acceptance criterion for ASTM C593 durability testing is that test specimens must have at least 2750 kPa (400 psi) unconfined compressive strength following vacuum saturation testing. For cement-based activators, the durability test procedure specified in ASTM D560 is used. The acceptance criterion is a maximum of 14 percent weight loss after 12 freeze-thaw cycles.

The minimum strength required prior to the first freezing cycle to provide sufficient durability against freeze-thaw damage depends on the severity of the climate. The American Coal Ash Association (ACAA) recommends minimum compressive strengths of 6900, 5500, and 4100 kPa (1000, 800, and 600 lb/in^2), respectively, for severe, moderate, and mild freeze-thaw conditions (ACAA 1991).

Initial hydraulic conductivity for hardened PSB mixtures can be expected to range between 10^{-5} and 10^{-6} cm/sec. As the pozzolanic reaction proceeds, PSB materials may have hydraulic conductivity values between 10^{-6} and 10^{-7} cm/sec (Ahlberg and Barenburg 1965).

The design method for pavements including PSB mixtures can follow AASHTO flexible pavement methods provided in Guide for Design of Pavement Structures (AASHTO 1993). This method accounts for the predicted loading (the predicted number of 80 kN equivalent single axle loads that the pavement will experience), required reliability (degree of certainty that a design will function properly during the design life), serviceable life (ability to lose quality during the pavement life), the pavement structure (characterized by the structural number), and subgrade support (related to the resilient modulus of the subgrade) (AASHTO 1993).

The structural number of a pavement design accounts for the relative strength of the constructed materials. The total structural support from the surface course, base course, and any subbase course equals the required structural number. Layer thicknesses are calculated using layer coefficients that define the structural support. The layer coefficients can be obtained from the relationship provided by AASHTO based on CBR or Mr.(28) When available, assigning layer coefficients for fly ash stabilized soils based on correlations for granular subbase materials is reasonable (Bin-Shafique et al. 2004).

By stabilizing the subgrade, the stabilized layer effectively acts as a subbase course that is directly between the base course and the subgrade. A stabilized layer replaces the conventional subbase layer and should be included in the structural number. In this manner, a pavement incorporating a stabilized subbase can be designed with a structural number just as a conventional cut-and-fill pavement (Bin-Shafique et al. 2004).

Mix Design:

A wide range of aggregate sizes can be accommodated in stabilized base and subbase mixtures. After determining the particle size distribution of the aggregate in a PSB mixture, the initial step in determining the mix proportions is to find the optimum fines content. This is done by progressively increasing the quantity of fines (consisting of fly ash plus activator) and making density determinations for the blends of aggregate and fines. Estimated optimum moisture content is selected and held constant for each blend. Each blend of aggregate and fines is compacted into a Proctor mold using standard compaction procedures. At least three such blends are required and five blends are recommended. Dry density versus fines content is plotted and this procedure is used to identify the percentage of fines (expressed as a percentage by dry weight of the total mixture) that results in the highest compacted dry density.

The optimum fines content selected by this procedure should be 2 percent higher than the fines content at the maximum dry density. The optimum moisture content must then be determined for this mix design proportions.

Once the fines content and optimum moisture have been determined, the ratio of activator to fly ash must also be determined. Using a series of trial mixtures, final mix proportions are selected on the basis of the results of both strength and durability testing according to ASTM C593 procedures.

To determine the most suitable proportion of activator to fly ash, five different mix combinations should be evaluated at the optimum moisture content. The typical range of activator to fly ash ratios is 1:3 to 1:5 when using lime or Portland cement. The typical range of kiln dust to fly ash ratios is in the range of 1:1 to 1:2.

The ratio of fines (activator plus fly ash) to aggregate determines the amount of matrix available to fill the void spaces between aggregate particles. Normally, activator plus fly ash contents range from 12 to 30 percent by dry weight of the total mix, although fine-graded aggregates require a higher percentage for satisfactory strength development than well-graded aggregates.

In general, the trial mixture with the lowest ratio of activator to fly ash that satisfies both the strength and durability criteria is considered the most economical mixture. To ensure an adequate factor of safety for field placement, the PSB mixture used in the field should have an activator content that is at least 0.5 percent higher (1.0 percent higher if kiln dust) than that of the most economical mixture identified in the laboratory tests (ACAA 1991).

Laboratory tests conducted on Class F fly ash-soil mixtures prepared with cement and lime as activators showed that the cement mixes performed better than the mixes using lime as an activator. The CBR, unconfined compressive strength, and resilient modulus increased with increasing cement content; up to 5 percent cement. Conversely, lime treatment had a detrimental effect and an increase in lime content decreased the unconfined compressive strength of both 7 and 28 day specimens (Arora and Aydilek 2005).

Case studies indicate that Class C fly ash is typically used in the range of 7 to 10 percent dry weight for stabilized CIR (Li et al. 2007, Cross and Young 1997, Crovetti 2000, Thomas et al. 2000, Wen et al. 2004).

Flowable Fill – Aggregate or Supplementary Cementitious Material

The use of flowable fill as a highway construction material is becoming more widespread throughout the United States. Most state transportation agencies have used flowable fill mainly as a trench backfill for storm drainage and utility lines on street and highway projects. Other applications for flowable fill include filling behind retaining walls, building excavations, underground storage tanks, abandoned sewers and utility lines, and slab jacking.

Coal fly ash can be used as a component in the production of flowable fill (also called controlled low strength material or CLSM), which is used as a self-leveling, self-compacting backfill material in lieu of compacted earth or granular fill. Flowable fill mixtures include filler material, cementitious material, and can contain mineral admixtures. Filler material usually consists of fine aggregate such as sand, but some flowable fill mixes may contain equal portions of coarse and fine aggregates (Smith 1991). Fly ash has been used as a replacement of partial replacement for all three constituents in flowable fill.

Since flowable fill is normally a comparatively low-strength material, there are no strict quality requirements for fly ash used in flowable fill mixtures. Fly ash is well suited for use in flowable fill mixtures. The fine particle size (nonplastic silt) and spherical particle shape enhances mix flowability. The pozzolanic or cementitious properties of fly ash allow for lower cement content than would normally be required to achieve equivalent strengths.

There are two basic types of flowable fill mixes that contain fly ash: high fly ash content mixes and low fly ash content mixes. The high fly ash content mixes typically contain nearly all fly ash, with a small percentage of Portland cement and enough water to make the mix flowable. Low fly ash content mixes typically contain a high percentage of fine aggregate or filler material (usually sand), a low percentage of fly ash and Portland cement, and enough water to also make the mix flowable (Collins and Tyson 1993, FHWA 2003). Class F fly ash is well suited for use in high fly ash content mixes, but can also be used in low fly ash content mixes. Class C fly ash is almost always used only in low fly ash content flowable fill mixes because of the cementitious properties of Class C fly ash (Hennis and Fishette 1993). There are also flowable fill mix designs in which both Class F and Class C fly ash are used in varying proportions (Hennis and Fishette 1993).

Material Processing:
Fly ash used in flowable fill does not have to meet strict specification requirements, such as ASTM C618 for use in concrete (FHWA 2003). A high-quality source of ash is not required and fly ash with high LOI or carbon content is suitable (FHWA 2003). High carbon content can be a concern with concretes containing air-entrainment where entraining admixtures are more susceptible to absorption. Since CLSM does not often have requirements for air content, carbon content does not affect the properties (FHWA 2003). Dry or conditioned fly ash as well as reclaimed ash from settling ponds may also be suitable for flowable fill. No special processing is necessary prior to use.

Pozzolanic-type fly ash can be introduced into flowable fill mixes in either a dry or moistened condition. Self-cementing fly ash should be introduced into flowable fill mixes in a dry condition to avoid presetting.

If fly ash is to be added in a dry form (usually in low fly ash content mixes) the fly ash should be stored in a silo or pneumatic tanker. Fly ash (usually Class F fly ash) in a conditioned form in high fly ash content mixes can be stockpiled. If fly ash is stockpiled for an extended period in dry or windy weather conditions, the stockpile may need to be periodically moistened to prevent dusting.

Flowable fills can be batched and mixed in pugmills, turbine mixers and central-mix concrete plants. High fly ash content flowable fill mixes have been mixed in rotary-mix concrete trucks or in mobile-mix vehicles. Batching and mixing in individual mobile-mix vehicles is usually done only when small quantities of flowable fill are required at a particular location. Under such circumstances, attaining a uniform distribution of cement throughout the mix may be difficult.

Central-mix concrete plants work especially well with low fly ash content mixes, in which a high percentage of sand is used. The flowable fill mix is batched as a regular concrete mix without any coarse aggregate. Pugmills are well suited for mixes prepared with ponded or conditioned ash. A second feed bin can be added to a pugmill if sand (or other filler) is used.

Portable batch plants, such as those used for grouting, are often employed for on-site mixing of flowable fill. On-site mixing using self-cementing fly ash has been done successfully with slurry jet mixers. Dry ash is stored in large tanks on site and is pneumatically discharged through Y-shaped nozzles with metered amounts of water (Newman et al. 1992).

Flowable fill materials are most commonly transported to the site and discharged using rotary-mix concrete trucks. However, flowable fill may also be placed by pumps, conveyors, chutes, boxes, buckets, tremie, or in any way that concrete can be placed. Flowable fill requires no compaction or vibration following placement.

For placement of relatively deep backfills behind abutments or retaining walls, several lifts or layers are recommended. This limits the amount of lateral pressure exerted by the flowable fill and also prevents excessive heat of hydration, especially if self-cementing fly ash is used (Newman et al. 1992). When flowable fill is used to backfill pipe trenches, some lighter-weight pipes, such as corrugated metal pipes, will have to be restrained to prevent floating as the flowable fill is placed. Flowable fill can be placed in flowing or ponded water because the fill will displace the water, thus eliminating the need for pumping prior to placement.

There are normally no requirements for the curing of flowable fill, although during periods of hot weather, covering the exposed surfaces of flowable fills is advised to minimize evaporation and shrinkage cracking. Temperatures within the flowable fill in excess of 90° to 100°F (32° to 38°C) are considered excessive.

A quality assurance program is recommended to monitor the consistency, properties, and performance of flowable fill. As a minimum, such a program should consist of initial mix design testing, determination of key mix properties (such as strength development, flowability, setting time and density), and field testing of these properties, with flowability considered the most important quality control parameter to be monitored in the field prior to placement of the material.

Flowable fills do develop heat when placed, especially mixes containing self-cementing fly ash. Consequently, flowable fill can be placed at, or even below, freezing temperature. However, heated water should be used and bleed water at the fill surface should be removed. Also, a protective layer should be placed above the top surface of the flowable fill to minimize or prevent freeze-thaw damage. Ice or frozen surface material should be removed before placing additional layers of either flowable fill or pavement material (Collins and Ciesielski 1994).

Design Considerations for Flowable Fill:

Engineering properties of flowable fill mixes that are of interest include compressive strength, flowability, stability, bearing capacity, modulus of subgrade reaction, lateral pressure, time of set, bleeding and shrinkage, density, and hydraulic conductivity. The properties of fly ash that are the most influential to the performance of flowable fill mixtures are the spherical particle shape and pozzolanic activity with Portland cement.

Strength development in flowable fill mixtures is directly related to cement content and water content, particularly when Class F fly ash is used. Most high fly ash content mixes only require from 3 to 5 percent of the cementitious material be Portland cement to develop 28-day compressive strengths in the 345 to 1000 kPa (50 to 150 lb/in^2) range (FHWA 2003). For low fly ash content mixes with Class C fly ash, the fly ash contributes to the strength development and can also be a complete replacement for Portland cement. Ultimate strengths may gradually increase well beyond the 28-day strength, perhaps even beyond 90 days, especially in high fly ash content mixes. As the water content is increased to produce a more flowable mix, compressive strength development decreases (Collins and Tyson 1993, FHWA 2003).

Flowability or fluidity is a measure of how well a mixture will flow when being placed. Mixes with higher water content are more flowable (FHWA 2003). Flowability can vary from stiff to fluid depending on the job requirements. Flowability can be measured using a standard concrete slump cone, a flow cone, or a modified flow test using an open ended 75 mm (3 in) diameter by 150 mm (6 in) high cylinder (ASTM C143/C143M-05a, ASTM C939-02, Balsamo 1987). Flowability ranges associated with the standard concrete slump cone (ASTM C143) generally vary from 150 mm (6 in) to 200 mm (8 in) (ASTM C143/C143M-05a) . Admixtures (such as water reducing agents) are not normally used in flowable fill. For high fly ash content mixes, the slump ranges can be expected to be at least 25 to 50 mm (1 to 2 in) higher than low fly ash content mixes at comparable moisture contents.

The flow cone test (ASTM C939) is a standard procedure for determining the flow rate of grout. A desirable rate of flow for most applications of flowable fill is a time of 30 to 45 seconds through a standard flow cone (Balsamo 1987).

The modified flow test conducted according to ASTM D6103 involves filling a 75 mm (3 in) diameter by a 150 mm (6 in) cylinder mold with flowable fill, emptying the contents of the cylinder on a flat surface, and measuring the diameter of the flowable fill. This test is best suited to mixtures that contain primarily fine aggregates (low fly ash content mixtures). For good flowability, the diameter of the spread material should be at least 200 mm (8 in) (Balsamo1987, ASTM D6103-04).

For low fly ash content flowable fill materials, designated as Type 1 CLSM by the Ohio DOT, triaxial tests indicate a drained friction angle of 28° and a cohesion of 33 kPa (685 lb/ft^2) for 7 day strength. For high fly ash content flowable fill materials, designated as Type 3 CLSM by the Ohio DOT, triaxial tests indicate a drained friction angle of 33° and a cohesion of 34 kPa (705 lb/ft^2) for 7 day strength (Masada and Sargand 2001).

The unconfined compressive strength of flowable fill increases with time; therefore, the bearing capacity increases with time. Small scale penetration tests to measure ultimate bearing capacity tests on Ohio DOT fly ash flowable fill showed an almost 6 fold increase in capacity from 2 hours to 2 days, from 900 kPa (19,000 lb/ft^2) to 5250 kPa (110,000 lb/ft^2) (Masada and Sargand 2001). With an unconfined compressive strength of 685 kPa (14,400 lb/ft^2) flowable fill has two to three times the capacity of most well-compacted granular soil fill materials (Ramme and Tharaniyil 2004).

Flowable fill has shown CBR ranging from 40 to 90 percent (American Stone 2000, Brewer and Associates 1991). CBR testing of typical 690 kPa (100 lb/in2) flowable fill resulted in a CBR value of 50 within 24 hours of placement. As the compressive strength of the flowable fill material increases, the CBR can be expected to increase.

The modulus of subgrade reaction (k), used for the design of rigid pavement systems, is usually in the range of 8.2 to 49.2 MPa/m (50 to 300 lb/in^3) for most soils and 82 MPa/m (500 lb/in^3) for a good granular subbase material. For flowable fill, k is usually 820 MPa/m (5000 lb/in^3) or higher, meaning flowable fill is superior to any earthen backfill (Krell 1989).

Lateral Pressure: Because of lateral fluid pressure at the time of placement, flowable fill installations at depths in excess of 1.8 m (6 ft) are normally placed in separate lifts, with each lift not exceeding 1.2 to 1.5 m (4 to 5 ft) (Newman et al. 1992). Once flowable fill has hardened, the lateral pressure is reduced.

For most flowable fill mixes, especially those with high fly ash content, an increase in the cement content or a decrease in the water content, or both, should result in a reduction in hardening time. Typical high fly ash content flowable fill mixes (containing 5 percent cement) harden sufficiently 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 operate on the surface without damage. Some low fly ash content flowable fill mixes, especially those containing self-cementing fly ashes, have harden sufficiently to allow street patching within 1 to 2 hours following placement (FWHA 2003).

A setting time of 15 hours for mixes of fly ash and crushed sand, regardless of cement content, have been observed with test method ASTM D6024, which takes into account field parameters. As the cement is the main component that dominates the setting time for flowable fill mixes, reduced setting time is expected as the cement content increases. However, when fly ash in large quantities (500 kg/m^3) is used, the fly ash contributes to the setting process by shortening the setting time, and the change in the cement content is less dominant (Katz and Kovler 2004).

High fly ash content flowable fill mixes with relatively high water contents (250 mm (10 in) slump) tend to bleed water prior to initial set. Evaporation of the bleed water often results in shrinkage of approximately one percent of flowable fill depth. The shrinkage may occur laterally as well as vertically. No additional shrinkage or long-term settlement of flowable fill occurs once the material has reached an initial set (FWHA 2003). Low fly ash content mixes, because of their high fine aggregate content and ability to more readily drain water through the flowable fill, tend to exhibit less bleeding and shrinkage than high fly ash content mixes.

The density of standard flowable fill is similar to that of well-compacted soil in the range of 1850 to 2300 kg/m^3 (115 to 145 lb/ft^3), with the material being heaviest when first placed. High fly ash content flowable fill mixes are usually lighter than low fly ash content fills and can have densities as low as 1450 kg/m^3 (90 lb/ft^3). With the addition of lightweight aggregate, such as crumb rubber, flowable fill can have a relatively low density 1170 to 1570 kg/m^3 (73 to 98 lb/ft^3) and be considered a lightweight fill (Pierce and Blackwell 2003). Densities as low as 400 kg/m^3 (25 lb/ft^3) have been achieved in mixes by using foaming agents (Chugh et al. 1998).

Hydraulic conductivity of high fly ash content flowable fill mixtures decrease with increasing cement content and are in the range of 10^{-6} to 10^{-7} cm/sec (Glogowski et al. 1988, Gabr and Bowders 2000). The hydraulic conductivity of low fly ash content flowable fill mixtures is greater than that of high fly ash content mixtures, and typically are in the 10^{-4} to 10^{-6} cm/sec range (Balsamo1987). In general, hydraulic conductivity increases as the slump increases (Doven and Pekrioglu 2005). hydraulic conductivity may be reduced by adding bentonite to the mixture (Gabr and Bowders 2000).

Structural design procedures for flowable fill materials are no different than geotechnical design procedures used for conventional earth backfill materials. The procedures are based on using the unit weight and shear strength of the flowable fill to calculate the bearing capacity and lateral pressure of the material under given site conditions.

Mix Design:
Flowable fill mixtures traditionally have been proportioned by trial and error. Most specifications for flowable fill provide quantities of constituents that produce an acceptable product, although some specifications are performance-based (usually based on a maximum compressive strength) and leave the proportioning up to the material supplier. ACI provides guidance for the mix proportioning of flowable fill mixtures (ACI 1999).

High fly ash content flowable fill mixes are proportioned on the basis of the percentage of Portland cement (usually Type I cement) per dry weight of fly ash. A 5 percent Portland cement mix is fairly typical with a 95 percent dry weight proportion of fly ash, although in some areas self-cementing fly ash accounts for 100 percent of the cementitious material (FHWA 2003). The amount of water added to the mix is a variable that is determined by the desired degree of fluidity or flowability in the mix and depends on the surface characteristics of the solids in the mixture. For most material combinations, 250 to 400 liters of water per cubic meter of flowable fill is sufficient (50 to 80 gallons per cubic yard of fill) (FHWA 2003). When conditioned fly ash is used, the amount of water in the fly ash must be included with the amount of added water in the mix to determine the moisture content (Collins and Tyson 1993).

A broader range of mix designs exist for low fly ash content mixes (FHWA 2003). Since fly ash is not the principal component in these mixes, the cement content is not based on a percentage of the dry weight of the fly ash in the mix, but as a percentage of the filler material and fly ash. Because of the rapid setting nature of Class C fly ash it is used in lesser amounts in low fly ash mixes. Flowable fill mixes are designed to develop a desired range of compressive strength. In the case of trench backfilling, a specified maximum ultimate strength in the range 690 kPa to 1035 kPa (100 to 150 lb/in^2) may be the basis for design (Collins and Tyson 1993).Unconfined compressive strength testing in accordance with ASTM D 4832-02 is recommended .

Embankment and Fill Material

According to the American Coal Ash Association, structural fill or embankment material is the second largest use of fly ash after concrete production (ACAA 2007). Nearly all of the fly ash used for embankment construction is anthracite or bituminous coal fly ash. Fly ash has been used for several decades as an embankment or structural fill material, particularly in Europe. As an embankment or fill material, fly ash is used as a substitute for natural soils.

The *Standard Guide for Design and Construction of Coal Ash Structural Fills*, ASTM E2277-03, addresses fly ash in embankment or fill applications. The standard includes guidelines on site characterization considerations such as geologic and hydrologic investigations, laboratory test procedures, design considerations and methods, and construction considerations (EPA 2005).

When used in structural fills or embankments, fly ash offers several advantages over natural soil or rock. The relatively low unit weight of fly ash makes it well suited for placement over soft or low bearing strength soils. The high shear strength results in good bearing support and minimal settlement. The ease with which fly ash can be placed and compacted at the proper moisture contents, can reduce construction time and equipment costs. In areas where fly ash is readily available in bulk quantities, the cost of fly ash can be less expensive than borrow soil.

Material Processing:
Fly ash for embankment construction should be delivered to the job site within 3 to 4 percent of its optimum moisture content, preferably on the dry side of optimum (Collins and Srivastava 1989). A moisture content 1 or 2 percent above optimum can make fly as difficult to compact (Baykal et al. 1989). Dry fly ash from a silo must be water conditioned to the desired moisture content. Conditioned fly ash from a landfill should be excavated from the landfill, stockpiled, and additional water added, if needed, prior to delivery. Ponded fly ash must be removed from a lagoon, stockpiled until the moisture content has been sufficiently reduced for placement and then delivered to the job site.

Since most lignite or subbituminous fly ashes are self-cementing, the addition of moisture in amounts approaching the optimum moisture content may result in flash setting or sudden hardening of the ash. To prepare this type of fly ash for use as embankment material, the ash may need to be lightly conditioned with water (10 to 15 percent), stockpiled for several weeks, and passed through a crusher to remove agglomerations prior to its use as fill. Additional water, if needed, should be added only after the lignite or subbituminous fly ash has been placed and just prior to compaction.

Bituminous (pozzolanic) fly ash is usually conditioned with water at the power plant and hauled in covered dump trucks with sealed tailgates. Subbituminous or lignite (self-cementing) fly ash may be partially conditioned at the plant and hauled in covered dump trucks to the project site, or hauled dry in pneumatic tank trucks from the plant to the project site, where it is placed in a silo and conditioned with water when ready for placement. Temporary stockpiling should be performed to reduce lagoon ash water prior to transportation to prevent road spillage during transportation (FHWA 2003).

If a temporary stockpile of fly ash is built at the project site, the surface of the stockpile must be kept damp enough to prevent dusting. The stockpile should be placed in a well-drained area so the ash is not inundated with water following a rainfall (Di Gioia et al. 1972).

Prior to fly ash placement, the site should undergo preparations consistent with preparation requirements for soil fill materials. The site must be cleared and grubbed and topsoil should be kept for final cover. Before and during construction, special attention should be given to site drainage and to preventing seeps, pools, or springs from contacting fly ash stockpiles (FHWA 2003).

Construction equipment needed to properly place and compact fly ash in an embankment or structural backfill includes a bulldozer for spreading the material, a compactor, either a vibrating or pneumatic tired roller, a water truck to provide water for compaction (if needed) and to control dusting, and a motor grader where final grade control is critical.

Fly ash is usually spread and leveled with a dozer, grader, or other equipment in lifts no thicker than 0.3 m (12 in) when loose. Using a disk harrow or a rotary tiller may be necessary if the fly ash contains lumps (Di Gioia et al. 1979). Fly ash lifts should be compacted as soon as the material has been spread and is at proper moisture content. Experience has shown that steel-wheel vibratory compactors and/or pneumatic tired rollers provide the best compaction. If a vibratory roller is used, the first pass should be made with the roller in the static mode (without any vibration), followed by two passes with the roller in the vibratory mode and traveling relatively fast. Additional passes should be in the vibratory mode at slow speed (Baykal et al. 2004, ASTM E2277-03 2003).

In general, six passes of the roller are usually needed to meet compaction requirements. In most cases, 90 to 95 percent of a standard Proctor maximum dry density is the minimum specified density to be achieved. This is almost always achievable when the moisture content of the fly ash is within 2 or 3 percent of optimum, preferably on the dry side of optimum (Kinder and Morrison1979).

For each project, the type of compactor, the moisture content of the fly ash at placement, the lift thickness, and the number of passes of the compaction equipment should be evaluated using a test strip. A vibratory compactor should use a test strip to evaluate the speed at which the compactor should be operated, the static weight, dynamic force and frequency of vibration of the compactor, and the number of passes required to achieve the specified density (Di Gioia et al. 1979).

Quality control programs for fly ash embankments or structural backfills are similar to such programs for conventional earthwork projects. These programs typically include visual observations of lift thickness, number of compactor passes per lift, and behavior of fly ash under the weight of the compaction equipment, supplemented by laboratory and field testing to confirm that the compacted fly ash has been constructed in accordance with design specifications.(12) More information on performance specifications and procedures and method specifications and procedures can be found in ASTM E2277.

Fly ash surfaces must be graded or sloped at the end of each day to provide positive drainage and prevent the ponding of water or the formation of runoff channels that could erode slopes and produce sediment in nearby surface waters. Compacted fly ash slopes should be protected as soon as possible after finished grades to reduce erosion. Erosion control on side slopes is usually provided by placing from 150 mm (6 in) to 600 mm (2 ft) of soil cover on the slopes. An alternative approach is to build outside dikes of soil to contain the fly ash as the embankment is being constructed (Di Gioia et al. 1979).

Design Considerations for Embankment and Fill:
Engineering properties of fly ash that are of particular interest when fly ash is used as an embankment or fill material are moisture density relationship (compaction curve), particle size distribution, shear strength, consolidation characteristics, bearing strength, and hydraulic conductivity.

Fly ash has a relatively low compacted density, thereby reducing the applied loading and settlement of the supporting subgrade. Conditioned fly ash tailgated over the slope of an embankment can have a loose dry density as low as 6.3 to 7.9 kN/m^3 (40 to 50 lb/ft^3). However, when well compacted at optimum moisture content (usually between 20 and 35 percent), the dry unit weight of fly ash may be greater than 13.4 kN/m^3 (85 lb/ft^3), as high as 15.7 kN/m^3 (100 lb/ft^3).

Fly ash is predominantly a silt-sized nonplastic material. Between 60 and 90 percent of fly ash particles are finer than a 0.075 mm (No. 200) sieve. As such, fly ash can be considered to be frost-susceptible (Gray and Lin 1971). The potential reduction in strength from freeze-thaw cycles is a concern. Laboratory test results show that unconfined compressive strength of compacted fly ash was not affected by freeze-thaw cycles, because the degree of saturation was not 100 percent, which allowed for volumetric expansion of freezing water to occur without affecting the fly ash strength. (Cocka 1997) Therefore, fly ash fills should be free draining.

The shear strength of freshly compacted fly ash samples is primarily from internal friction, although some apparent cohesion has been observed in bituminous (pozzolanic) fly ashes (Di Gioia and Nuzzo 1972). The shear strength of fly ash is affected by the density and moisture content with maximum shear strength occurring at optimum moisture content (Mclaren and Di Gioia 1987). Bituminous fly ash has a friction angle that is usually in the range of 26° to 42°. A test program involving shear strength testing for 51 different ash samples resulted in a mean friction angle of 34°, and a standard deviation of 3.3° (Mclaren and Di Gioia 1987). Therefore, a friction angle of 30° would be a reasonable estimate for design.

An embankment or structural backfill should possess low compressibility to minimize roadway settlements or differential settlements between structures and adjacent approaches. Consolidation has been shown to occur more rapidly in compacted fly ash than fine-grained soil because fly ash has a higher void ratio and greater hydraulic conductivity than most fine-grained soils. For fly ashes with age-hardening properties, including most Class C fly ashes, the magnitude of the compressibility is reduced.

California bearing ratios (CBR) for Class F fly ash from the burning of anthracite or bituminous coals have been found to be similar to fine grained soil, 5 to 15 percent. For naturally occurring soils, CBR values normally range from 3 to 15 percent for fine-grained materials (silts and clays), from 5 to 40 percent for sand and sandy soils, and from 20 to 100 percent for gravels and gravelly soils.

The hydraulic conductivity of well-compacted fly ash ranges from 10^{-4} to 10^{-6} cm/s, which is roughly equivalent to the hydraulic conductivity of a silty sand to silty clay soil. The hydraulic conductivity of fly ash is affected by the degree of compaction, grain size distribution, and internal pore structure. Since fly ash consists almost entirely of spherical shaped particles, the particles are able to be densely packed during compaction, resulting in comparatively low hydraulic conductivity that minimizes the seepage of water through a fly ash embankment.

Virtually any fly ash can be used as an embankment or structural backfill material, including ponded ash that has been reclaimed from an ash lagoon. The principal technical considerations related to the design of a fly ash embankment or structural backfill are essentially the same as the considerations for the design of an earthen embankment or backfill. There are certain special design considerations, however, that should be considered when fly ash is used in embankment or fill applications. If designed properly, fly ash has comparable strength and compressibility to most soil fill materials, while possessing lower dry unit weight (Kim et al. 2005).

Fly ash, because of its predominance of silt-size particles, tends to wick water, making it possible that the lower extremities of a fly ash embankment could become saturated. The base of a fly ash embankment should not be exposed to free moisture, wetlands, or the presence of a high water table condition. An effective way to prevent capillary rise or the effects of seepage in fly ash embankments and backfills is the placement of a drainage layer of well-draining granular material at the base of the embankment (ASTM E2277-03 2003).

To determine a safe design slope, slope stability analysis of a design cross-section of the fly ash embankment must be performed. The basic principle of slope stability analysis is to compare the factors contributing to instability with those resisting failure. The principal resistance to failure is the shear strength of the embankment material. A long term and seismic slope stability analysis should be preformed. For long-term stability of fly ash embankments, a factor of safety of 1.5 against slope instability is recommended, while for seismic loadings a factor of safety of 1.2 is recommended (ASTM E2277-03 2003). Unless the fly ash is self-hardening, the cohesion (c) value should be zero for these calculations. Duncan and Wright (2005) provides state-of-the-art guidance on slope-stability analysis.

Erodibility of compacted fly ash is affected by the slope angle. Slopes should be protected as soon as possible after attaining final grade to minimize erosion by runoff or even high winds. One way to prevent such erosion is to construct a fly ash embankment within dikes of granular soil, which serve to protect the slopes throughout construction. Another way is to cover the slopes with topsoil as the embankment is being constructed. Overfilling slopes and trimming excess fly ash back to the appropriate grade once the final height is achieved is another approach. Finally, short-term erosion control may be accomplished by stabilizing the surface fly ash on the slopes with a low percentage of Portland cement or lime (Di Gioia et al. 1979), or covering with a blanket of coarse bottom ash.

The ability of the top portion of a fly ash embankment to support a pavement structure can be predicted by the California Bearing Ratio (CBR) for a flexible asphalt pavement system or by a modulus of subgrade reaction (K-value) for a rigid or concrete pavement system. These bearing values can then be used to design pavement layer thicknesses in accordance with the AASHTO design guide for pavement structures.(15) Methods for determining the CBR can be found in ASTM D1883-05 and the modulus of subgrade reaction in D 1195 or D 1196, or bearing ratio by test methods D 1883 or D 4429, as appropriate.

During times of heavy or prolonged precipitation, the delivered moisture content of the fly ash may have to be reduced to compensate for the effects of the precipitation.

Fly ash, unlike most soils, can be compacted in the winter, although spreading and compacting fly ash when the ambient air temperature is below -4°C (25°F) is not recommended (Di Gioia et al. 1979). In addition, placing frozen fly ash is also not recommended. Because fly ash obtained directly from silos or hoppers dissipates heat slowly, fly ash may be placed during cold weather. If frost does penetrate into the top surface of the fly ash, the ash can be removed from the surface by a bulldozer, or recompacted after thawing and drying (ASTM E2277-03 2003).Construction should be suspended during severe weather conditions, such as heavy rainfall, snowstorms, or prolonged and/or excessively cold temperatures.

Strength reduction of fly ash during periods of cyclic freezing and thawing may occur (Cocka 1997). The frost susceptibility of fly ash can be measured according to ASTM D5918. This test method applies two freeze-thaw cycles to a compacted specimen 146 mm (5.75 in) in diameter and 150 mm (6 in) in height. The heave rate and California bearing ratio (CBR) after thaw give an indication of frost susceptibility. Frost susceptible materials have a heave rate greater than 4 mm/day and a CBR after thaw less than 10 (ASTM D5918-06 2006). Frost heaving of the top portion of a fly ash embankment can be substantially decreased by the addition of moderate amounts of cement or lime.

Laboratory test results have shown that unconfined compressive strength of compacted fly ash was not affected by freeze-thaw cycles, because the degree of saturation was not 100 percent, which allowed for volumetric expansion of freezing water to occur without affecting the fly ash strength (Cocka 1997). Therefore, fly ash fills should be free draining. When frost susceptibility remains a concern, substituting a soil that is not susceptible to frost for fly ash within the frost zone will elevate the potential problem.

Chemical and/or electrical resistivity tests (e.g. ASTM G187-05) of some fly ashes have indicated that certain ash sources may be potentially corrosive to metal pipes placed within an embankment. Each source of fly ash should be individually evaluated for corrosivity potential. If protection of metal pipes is deemed necessary, the exterior of the pipes may be coated with tar or asphalt cement, the pipes may be wrapped with polyethylene sheeting, or the pipe can be backfilled with sand or an inert material (AASHTO 1993).

The sulfate content of fly ash, particularly self-cementing ash, has caused some concern about the possibility of sulfate attack on adjacent concrete foundations or walls. Precautions that can be taken against potential sulfate attack of concrete include painting concrete faces with tar or an asphalt cement, using a waterproof membrane (such as polyethylene sheeting or tar paper), or using Type V sulfate-resistant cement in the adjacent concrete.

Bituminous (pozzolanic) fly ash is more frequently used to construct embankments and structural backfills than subbituminous or lignite (self-cementing) fly ash. This is due in part to difficulties in placing and compacting self-cementing fly ash, which can harden almost immediately after the addition of water. Current practice is to lightly condition self-cementing fly ashes with water, allow them to stockpile for a period of time, then run the partially hardened fly ash through a primary crusher before taking it to the project site. There is a need to develop more well-defined handling and preconditioning procedures for using self-cementing fly ash as a fill material.

END USER RESOURCES

Several resources are available to end users interested in incorporating coal fly ash into construction applications. Additional information on coal ash production and use in the United States can be obtained from:

American Coal Ash Association (ACAA)
15200 E. Girard Ave., Ste. 3050
Aurora, Colorado 80014-3955
http://www.acaa-usa.org/

Coal Combustion Products Partnership (C2P2)
Office of Solid Waste (5305P)
1200 Pennsylvania Avenue, NW
Washington, DC 20460
http://www.epa.gov/epaoswer/osw/conserve/c2p2/index.asp

Electric Power Research Institute (EPRI)
3412 Hillview Road
Palo Alto, California 94304
http://my.epri.com

Edison Electric Institute (EEI)
1701 Pennsylvania Avenue, N.W.
Washington, D.C. 20004-2696
http://www.eei.org/

Green Highways Partnership
http://www.greenhighwayspartnership.org/

AASHTO Center for Environmental Excellence
444 North Capitol Street, NW Suite 249

Washington, D.C., 20001
202-624-5800
http://environment.transportation.org/

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ASTM C204-07 standard test methods for fineness of hydraulic cement by air-permeability apparatus. In: Annual book of ASTM standards, ASTM, West Conshohocken, Pennsylvania: 2007.

ASTM C311-05 standard test methods for sampling and testing fly ash or natural pozzolans for use in Portland-cement concrete. In: Annual book of ASTM standards. ASTM, West Conshohocken, Pennsylvania: 2005.

ASTM C39/C39M-05e1 standard test method for compressive strength of cylindrical concrete specimens. In: Annual book of ASTM standards. ASTM, West Conshohocken, Pennsylvania; 2005.

ASTM C441-05 standard test method for effectiveness of pozzolans or ground blast-furnace slag in preventing excessive expansion of concrete due to the alkali-silica reaction. In: Annual book of ASTM standards. ASTM, West Conshohocken, Pennsylvania: 2005.

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