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ROAD MAP TRACK 1
Performance-Based Concrete Pavement Mix Design System

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Integrated Materials and Construction Practices for Concrete Pavements: State-of-the-Practice Manual
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Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. MAP Brief 1-3 provides information relevant to Track 1 of the CP Road Map, Performance-Based Concrete Pavement Mix Design System.

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MAP Brief 1-3 is available at: http://www.cproadmap.org/publications/ MAPbrief1-3.pdf

"Moving Advancements into Practice"

MAP Brief 1-3:

Describing promising technologies that can be used now to enhance concrete paving practices

Fly ash as a supplementary cementitious material in concrete mixtures

Introduction

Fly ash is the most widely used supplementary cementitious material (SCM) in concrete. It is used in about 50 percent of ready-mixed concrete (PCA 2000). When used in conjunction with portland cement, fly ash can enhance the properties of concrete through hydraulic or pozzolanic activity or both.

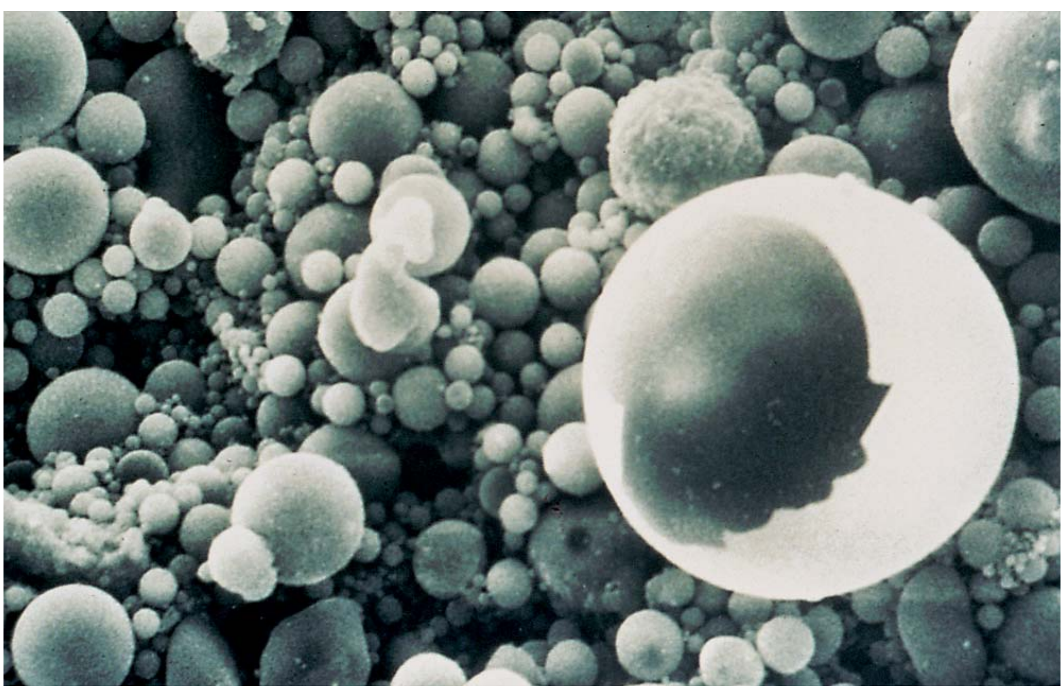
Hydraulic materials will set and harden when mixed with water. Pozzolanic materials require a source of calcium hydroxide (CH), usually supplied by hydrating portland cement. Class F fly ashes are typically pozzolanic while Class C fly ashes have both hydraulic and pozzolanic characteristics.

Use of fly ash in concrete mixtures has been growing in North America since the 1970s:

- The basic chemical components in fly ash are similar to those of portland cement.
- The judicious use of fly ash is desirable not only for the environment and energy conservation, but also for the technical benefits it provides to concrete.

Fly ash can be used to improve a particular concrete property, like resistance to alkali-aggregate reactivity. However, mixtures containing fly ash should be tested to determine whether (1) the fly ash is indeed improving the property, (2) the dosage is correct (an overdose or underdose can be harmful or may not achieve the desired effect), and (3) there are any unintended effects (for example, a significant delay in early strength gain).

It is also important to remember that different fly ashes may react differently with



Scanning electron micrograph of fly ash particles. Note the characteristic spherical shape that helps improve workability. Average particle size is approximately 10 µm. (PCA)

different cements, leading to changes in the performance of a given mixture. Fly ashes should not be switched out without laboratory evaluation to check setting times and strength development at a minimum.

Occasional reports are received of so-called incompatibility, in which unexpected reactions occur between components in the cement and fly ash, leading to rapid stiffening, delayed setting and/or slow strength development. These are most commonly observed in hot weather using fly ashes with high calcium content combined with the use of Type A water-reducing admixtures. Changing the mixture temperature, fly ash source or type of chemical admixture will often resolve the issue; otherwise, seek expert help.

SCMs should comply with the requirements of ASTM C 618 or AASHTO M 295. The table below provides typical chemical analyses and selected properties of typical fly ashes.

Fly ash generally affects concrete as follows:

- Less water is normally required to achieve workability.
- Setting time may be delayed.
- Early strengths may be depressed, but later strengths are increased, because fly ash reaction rates are initially slower but continue longer.
- Heat of hydration is reduced.
- Resistance to alkali-silica reaction and sulfate attack may be improved when the appropriate ash substitution rate is used.
- Permeability is reduced; consequently, resistance to chloride ion penetration is improved.

Class F fly ash is generally used at dosages of 15 to 25 percent by mass of cementitious material; Class C fly ash is generally used at dosages of 15 to 40 percent. Dosage should be based on the desired effects on the concrete (Helmuth 1987, ACI 232 2003).

Fly ash is a byproduct of burning finely ground coal in power plants. Fly ashes that are not used as an SCM in concrete or in other applications (ACAA 2011) must be placed in disposal facilities. During combustion of pulverized coal, residual minerals in the coal melt and fuse in suspension and then are carried through the combustion chamber by the exhaust gases. In the process, the fused material cools and solidifies into spherical glassy ash particles (see photo on page 1). The fly ash is then collected from the exhaust gases by electrostatic precipitators or fabric bag filters.

Fly ash is primarily silicate glass containing silica, alumina, calcium, and iron (the same primary components of cement). Minor constituents are sulfur, sodium, potassium, and carbon, all of which can affect concrete properties. Crystalline compounds should be present in small amounts only.

The relative density (specific gravity) of fly ash generally ranges between 1.9 and 2.8. The color is gray or tan. Particle sizes vary from less than 1 µm to more than 100 µm, with the typical particle size measuring under 35 µm. The surface area is typically 300 to 500 m^2/kg, similar to cement.

Chemical analyses and selected properties of Type I cement and several supplementary cementitious materials

	Type I cement	Class F fly ash	Class C fly ash	GGBF slag	Silica fume	Metakaolin
Silica (SiO_2), %	22.00	52.00	35.00	35.00	90.00	53.00
Alumina (Al_2O_3), %	5.00	23.00	18.00	12.00	0.40	43.00
Iron oxide (Fe_2O_3), %	3.50	11.00	6.00	1.00	0.40	0.50
Calcium oxide (CaO), %	65.00	5.00	21.00	40.00	1.60	0.10
Sulfate (SO_4), %	1.00	0.80	4.10	9.00	0.40	0.10
Sodium oxide (Na_2O), %	0.20	1.00	5.80	0.30	0.50	0.05
Potassium oxide (K_2O), %	1.00	2.00	0.70	0.40	2.20	0.40
Total eq. alkali (as Na_2O), %	0.77	2.20	6.30	0.60	1.90	0.30
Loss on ignition, %	0.20	2.80	0.50	1.00	3.00	0.70
Blaine fineness, m^2/kg	350.00	420.00	420.00	400.00	20,000.00	19,000.00
Relative density	3.15	2.38	2.65	2.94	2.40	2.50

Source: Kosmatka, Kerkhoff, and Panarese (2002)

Fly ash will lose mass when heated to 1,000°C (1,830°F), mainly due to organic volatiles and combustion of residual carbon. This mass loss is referred to as loss-on-ignition (LOI) and is limited in most specifications to less than 6 percent. Class F fly ashes typically contain less than 10 percent calcium (CaO), with 5 percent LOI. Class C materials often contain 18 to 30 percent calcium (CaO), with less than 2 percent LOI.

Effects of fly ash in concrete

SCMs in concrete affect a wide range of fresh and hardened concrete properties. Some of the effects may be considered desirable and are the reason why the materials are used. Other side effects may be less desirable and have to be accommodated. An understanding of all the potential effects is essential to prevent surprises.

The effects of SCMs on properties of fresh and hardened concrete are briefly discussed in the following sections. (For more information, see chapter 5 of the *Integrated Materials and Construction Practices: State-of-the-Practice Manual* [IMCP manual] for a complete discussion of concrete properties.)

In most cases, the extent of change in concrete behavior will depend on the particular material used, the amount used, and the properties of other ingredients in the concrete mixture.

Trial batching with unfamiliar material combinations is essential to provide assurance of critical concrete properties.

Fresh properties

In fresh concrete, fly ash can affect workability and setting times in the following ways:

- Fly ash will generally increase workability.
- The rate of slump loss (stiffening) may be increased if there are chemical incompatibilities.
- Setting times may be delayed and early strength gain slowed.

All of these factors can have a significant effect on the timing of finishing and saw cutting in pavements; thus, it is important that the performance of the cementitious system being selected for a project be tested in trial batches well before the project starts. Trial batches need to be tested at the temperatures expected when the paving operation will be conducted.

Durability/Permeability

Fly ashes generally improve potential concrete durability by reducing permeability. Almost all durability-related failure mechanisms involve the movement of fluids through the concrete. Tests show that the permeability of concrete decreases as the quantity of hydrated cementitious materials increases and the water-cementitious materials ratio decreases. With adequate curing, fly ash generally reduces the permeability and absorption of concrete.

Alkali-silica reactivity resistance

Alkali-silica reactivity (ASR) of most reactive aggregates can be controlled with the use of fly ash. Low-calcium Class F fly ashes have reduced reactivity expansion up to 70 percent or more in some cases. At optimum dosage, some Class C fly ashes can also reduce reactivity; however, at a low dosage (referred to as a pessimum limit), a high-calcium Class C fly ash, as well as a low-calcium Class F fly ash, can exacerbate ASR.

SCMs reduce ASR (Bhatty 1985) by:

(1) Providing additional calcium silicate hydrates (C-S-H) that chemically tie up the alkalies in the concrete.

(2) Diluting the alkali content of the system.

(3) Reducing permeability, thus slowing the ingress of water.

It is important to determine the optimum and pessimum dosages for a given set of materials to maximize the reduc-

Effect of pozzolans in cement paste

In very broad terms, the primary reaction in hydrating cement is the following:

water + cement = calcium silicate hydrate (C-S-H) + calcium hydroxide (CH)

Calcium silicate hydrate (C-S-H) is the primary compound that contributes to the strength and impermeability of hydrated cement paste. Calcium hydroxide (CH) is not as strong and is more soluble, so it is somewhat less desirable.

Adding a pozzolan like fly ash, in the presence of water, results in conversion of the calcium hydroxide (CH) to more calcium silicate hydrate (C-S-H):

calcium hydroxide (CH) + pozzolan + water = calcium silicate hydrate (C-S-H)

This conversion is a significant benefit of adding pozzolans like fly ash to the mixture. (See chapter 4 of the IMCP manual) for a detailed description of cement chemistry and hydration, including the effects of specific SCMs on the hydration process.)

tion in reactivity and to avoid dosages and materials that can aggravate reactivity. Dosage rates should be verified by tests, using the AASHTO protocol (AASHTO PP 65-10 Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction).

Sulfate resistance

With proper proportioning and materials selection, fly ash can improve the resistance of concrete to external sulfate attack. This is done primarily by reducing permeability and by reducing the amount of reactive elements (such as tricalcium aluminate, C_3A) that contribute to expansive sulfate reactions.

One study showed that for a particular Class F ash, an adequate amount was approximately 20 percent of the cementitious system (Stark 1989). It is effective to control permeability through mixtures with low water-cementitious materials ratios. Concretes with Class F ashes are generally more sulfate resistant than those with Class C ashes.

Resistance to freeze-thaw damage and deicer scaling

There is a perception that concrete containing fly ash is more prone to frost-related damage than plain concrete. This is partially due to the severity of the test methods used (ASTM C 666, ASTM C 672), but may also be related to the changing bleed rates and finishing requirements for concretes with fly ash (Taylor 2004).

With or without fly ash, concrete that is exposed to freezing cycles must have sound aggregates, adequate strength, a proper air-void system, and proper curing methods.

For concrete subject to deicers, the ACI 318 building code states that the maximum dosage of fly ash should be 25 percent by mass of cementitious materials. Total SCM content should not exceed 50 percent of the cementitious material. Concretes, including paving mixtures, with SCMs at dosages higher than these limits may still be durable, however.

Specifications for supplementary cementitious materials

Type of SCM	Specifications
Ground, granulated blast-furnace slag	ASTM C 989 / AASHTO M 302
Fly ash and natural pozzolans	ASTM C 618 / AASHTO M 295
Silica fume	ASTM C 1240
Highly reactive pozzolans	AASHTO M 321

Drying shrinkage

When used in low to moderate amounts, the effect of fly ash on the drying shrinkage of concrete of similar strength is generally small and of little practical significance.

For more information

For more information see chapters 3 and 5 of the IMCP manual, or contact Peter Taylor, ptaylor@iastate.edu, 515-294-9333.

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