

# Use of Fly Ash in Concrete

## Reported by ACI Committee 232

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*Fly ash is used in concrete and other cement-based systems primarily because of its pozzolanic and cementitious properties. These properties contribute to strength gain and may improve the performance of fresh and hardened concrete, mortar, and grout. The use of fly ash may result in more economical concrete construction.*

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*This report gives an overview of the origin and properties of fly ash, its effect on the properties of hydraulic cement concrete, and the proper selection and use of fly ash in the production of hydraulic cement concrete and concrete products. Information and recommendations concerning the selection and use of Class C and Class F fly ashes generally conforming to the requirements of ASTM C 618 are provided. Topics covered include a detailed description of the composition of fly ash, the physical and chemical effects of fly ash on properties of concrete, guidance on the handling and use of fly ash in concrete construction, use of fly ash in the production of concrete products and specialty concrete, and recommended procedures for quality control. Relevant documents of standards-making bodies referred to in this document are cited and listed.*

**Keywords:** abrasion resistance; admixture; alkali-aggregate reaction; concrete pavement; controlled low-strength material; drying shrinkage; durability; efflorescence; fineness; fly ash; hydraulic cement; mass concrete; mixture proportion; pozzolan; precast concrete; quality control; reinforced concrete; roller-compacted concrete; soil cement; strength; sulfate resistance; workability.

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**CHAPTER 1—GENERAL****1.1—Introduction**

Fly ash, a by-product from the combustion of pulverized coal, is widely used as a cementitious and pozzolanic ingredient in hydraulic cement concrete. Because it improves many desirable properties of concrete, it is introduced either as a separately batched material (as in ASTM C 618, Class F or C) or as a component of blended cement (ASTM C 595 or C 1157).

This report describes the use of fly ash in concrete and lists references concerning the characterization of fly ash, its properties, and its effects on concrete. Guidance is provided concerning specifications, quality assurance and quality control of fly ash, and concrete produced using fly ash.

According to ACI 116R, fly ash is “the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system.” ACI 116R defines “pozzolan” as “a siliceous or siliceous and aluminous material that in itself possesses little or no cementitious value but that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties; there are both natural and artificial pozzolans.” Fly ash possesses pozzolanic properties similar to the naturally occurring pozzolans of volcanic or sedimentary origin found in many parts of the world. About 2000 years ago, the Romans mixed volcanic ash with lime, aggregate, and water to produce mortar and concrete (Vitruvius 1960). Similarly, fly ash is mixed with portland cement (which releases lime during hydration), aggregate, and water to produce mortar and concrete.

All fly ashes exhibit pozzolanic properties to some extent; however, some fly ashes display varying degrees of cementitious value without the addition of calcium hydroxide or hydraulic cement. The cementitious nature of these fly ashes is attributed to reactive constituents

that reside within the fly ash, such as crystalline, calcium aluminate phases, and a more highly substituted, and therefore, potentially reactive glass phase. Fly ash in concrete reacts with the hydrating hydraulic cement in the following ways:

1. Solutions of calcium and alkali hydroxide, which are released into the pore structure of the paste, combine with the pozzolanic particles of fly ash, forming a cementing medium; and

2. Heat generated by hydration of hydraulic cement helps initiate the pozzolanic reaction and contributes to the rate of the reaction.

When concrete containing fly ash is properly cured, fly-ash reaction products partially fill in the spaces originally occupied by mixing water that were not filled by the hydration products of the cement, thus lowering the concrete permeability to water and aggressive chemicals (Manmohan and Mehta 1981). The slower reaction rate of fly ash, when compared to hydraulic cement, limits the amount of early heat generation and the detrimental early temperature rise in massive structures. Concrete proportioned with fly ash can have properties that are not achievable through the use of hydraulic cement alone.

Fly ash from coal-burning electric power plants became readily available in the 1930s. In the U.S., the study of fly ash for use in hydraulic cement concrete began at about that time. In 1937, results of research on concrete containing fly ash were published (Davis et al. 1937). This work served as the foundation for early specifications, methods of testing, and use of fly ash.

Initially, fly ash was used as a partial mass or volume replacement of hydraulic cement, typically the most expensive manufactured component of concrete. As fly ash usage increased, researchers recognized that fly ash could impart beneficial properties to concrete. In subsequent research, Davis and colleagues studied the reactivity of fly ash with calcium and alkali hydroxides in portland-cement paste and the ability of fly ash to act as a preventive measure against deleterious alkali-aggregate reactions. Research (Dunstan 1976, 1980; Tikalsky, Carrasquillo, and Snow 1992; Tikalsky and Carrasquillo 1993) has shown that fly ash often improves the concrete's resistance to deterioration from sulfates. Fly ash also increases the workability of fresh concrete and reduces the peak temperature of hydration in mass concrete. The beneficial aspects of fly ash were especially notable in the construction of large concrete dams (Mielenz 1983). Some major projects, including the Thames Barrage in the UK and the Upper Stillwater Dam in the U.S., incorporated 30 to 75% mass replacement of hydraulic cement by fly ash to reduce heat generation and decrease permeability.

In the U.S., a new generation of coal-fired power plants was built during the late 1960s and 1970s, at least partially in response to dramatically increased oil prices. These power plants, using efficient coal mills and state-of-the-art pyroprocessing technology, produce finer fly ashes with a lower carbon content. In addition, fly ash containing high levels of calcium oxide became available due to the use of western U.S. coal sources (typically sub-bituminous and lignitic). Concurrent with this increased availability of fly ash,

extensive research has led to a better understanding of the chemical reactions involved when fly ash is used in concrete. Enhanced economics and improved technologies (material- and mechanical-based) have led to a greater use of fly ash, principally in the ready-mix concrete industry. Fly ash is now used in concrete for many reasons, including improvements in workability of fresh concrete, reduction in temperature rise during initial hydration, improved resistance to sulfates, reduced expansion due to alkali-silica reaction, and contributions to the durability and strength of hardened concrete.

## 1.2—Source of fly ash

Due to the increased use of pulverized coal as fuel for electric power generation, fly ash is now available in many areas of the world. Fly ash is a by-product of burning coals that have been crushed and ground to a fineness of 70 to 80% passing a 75  $\mu\text{m}$  (No. 200 [0.0030 in.]) sieve. Approximately 57,000 Gg (63 million tons) of fly ash is produced annually in the U.S. (American Coal Ash Association 2000). An estimated 18 to 20% of that total is used in the production of concrete and concrete products. ASTM C 618 categorizes fly ash by chemical composition, according to the sum of the iron, aluminum, and silicon content (expressed in oxide form). As a group, Class F and C ashes generally show different performance characteristics; however, the performance of a fly ash is not determined solely by its classification. Class F ashes are normally produced from coals with higher heat energy such as bituminous and anthracite, though some sub-bituminous and lignite coals in the western U.S. also produce Class F fly ash. Bituminous and anthracite coal fly ashes rarely contain more than 15% calcium oxide. Sub-bituminous fly ashes usually contain more than 20% calcium oxide and have both cementitious and pozzolanic properties. There are important performance differences between fly ashes from different sources. In general, sulfate-resistant characteristics and the ability of a fly ash to mitigate the effects of alkali-silica reaction in concrete are a function of the coal source. Strength enhancement characteristics of a fly ash vary widely, depending on the physical and chemical properties of the ash and the general characteristics of the cement in which it is used. Throughout this document, the terms Class F and Class C refer to fly ash characteristics defined in ASTM C 618.

**1.2.1 Production and processing**—The ash content of coals by mass may vary from 4 to 5% for sub-bituminous and anthracite coals, to as high as 35 to 40% for some lignites. The combustion process, which creates temperatures of approximately 1600 °C (2900 °F) liquefies the incombustible minerals. Rapid cooling of these liquefied minerals upon leaving the firebox causes them to form spherical particles with a predominantly glassy structure. Many variables can affect the characteristics of these particles. Among these are coal composition, grinding mill efficiency, the combustion environment (temperature and oxygen supply), boiler/burner configuration, and the rate of particle cooling.

Modern coal-fired power plants that burn coal from a uniform source generally produce very consistent fly ash. Fly ash particles, when from the same plant and coal source, will slightly vary in size, chemical composition, mineralogical

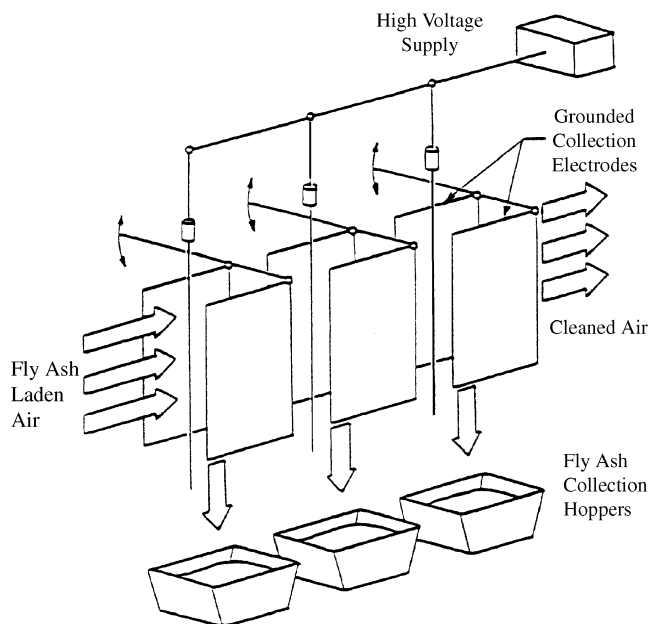


Fig. 1.1—Electrostatic precipitator.

composition, and density. Sizes may run from less than  $1\ \mu\text{m}$  ( $0.00004\ \text{in.}$ ) to more than  $200\ \mu\text{m}$  ( $0.008\ \text{in.}$ ), and density of individual particles from less than  $1\ \text{Mg/m}^3$  ( $62.4\ \text{lb/ft}^3$ ) hollow spheres to more than  $3\ \text{Mg/m}^3$  ( $187\ \text{lb/ft}^3$ ); although, the apparent true density of the bulk fly ash produced by a single coal-burning plant will typically not vary dramatically. Collection of these particles from the furnace exhaust gases is typically accomplished by electrostatic or mechanical precipitators or by bag houses. A typical gas flow pattern through an electrostatic precipitator is shown in Fig. 1.1.

As the fly ash particles are collected in a mechanical precipitator, they segregate in sequential precipitator hoppers according to their size and density; larger and heavier particles tend to accumulate closer to the fly-ash-laden air (gas inlet), while the smaller and lighter particles tend to collect farther from the inlet. In electrostatic precipitators, however, the particle size and density trends in sequential hoppers is disrupted due to the influence of the charged collection grids. The fineness, density, and carbon content of fly ash can vary significantly from hopper to hopper in both mechanical and electrostatic precipitators. The individual fly ash hoppers are usually emptied and conveyed to storage silos where fly ash is combined to produce a homogenous material.

**1.2.2 Impact of environmental regulations**—Nitrous oxide ( $\text{NO}_x$ ) emissions are considered to contribute to the production of acid rain in the U.S. The Clean Air Act required coal-fired boiler  $\text{NO}_x$  emissions to be cut by 2 million tons from 1980 levels by 2000.

The use of  $\text{NO}_x$  reduction technologies, such as low  $\text{NO}_x$  combustion system burners (LNB) or overfire air (OFA), on electric power plants has, in some cases, had a negative impact on the utilization of the coal ash because of increased levels of unburned carbon and other chemical residuals that are left in the ash.

The combustion modifications that reduce the creation of  $\text{NO}_x$  lower the peak flame temperature and reduce the excess

oxygen present. These changes impact fly ash characteristics. Usually, the unburned carbon (UBC) level in the ash increases. Lower flame temperatures also produce less ash melting. As a consequence, the ash particle-size distribution can be coarsened and individual particle morphology can be less spherical.

It has also been suggested that the lower combustion temperatures modify the glass content and composition of fly ash. Changes in fly ash glass content and mineralization, combined with changes in particle-size distribution and particle morphology, can have a significant effect on fly ash reactivity. The magnitude of this effect can vary from significant to inconsequential, depending on the specific fuel and combustion modification system employed.

Post-combustion system technologies for reducing  $\text{NO}_x$  emissions, such as selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR), also impact fly ash quality. Both of these systems involve introducing  $\text{NH}_3$  into the flue gas stream by injecting agents such as ammonia or urea. The  $\text{NH}_3$  is used to reduce  $\text{NO}_x$  to harmless elemental nitrogen ( $\text{N}_2$ ). Excess ammonia, however, may be available to deposit on the fly ash in the gas stream as ammonium salts such as ammonium bisulfate. These ammonium salts have been detected at concentrations ranging from barely measurable to levels in excess of several thousand  $\text{mg/kg}$  (Brendel, Rathbone, and Frey 2001). Low concentrations of ammonia have no impact on concrete properties (Koch and Dortmund 1989); however, a strong ammonia odor may be emitted. The ammonium salts will react to release ammonia gas if the ammoniated fly ash comes in contact with water under basic conditions such as exist in a concrete environment. The ammonia concentration, rate of evolution, and exposure level will depend on specific characteristics of the materials used and a large number of environmental factors. Some of the controlling factors are concentration of ammonia in the fly ash, concentration of fly ash in the concrete or controlled low-strength material (CLSM) mixture, mass of mixture, volume of space and degree of circulation enveloping a mixture, amount of mixing and transit time for a freshly mixed material, temperature, and wind speed (outdoor exposures).

Studies have reported on the release rate of ammonia gas from mortar systems during mixing (Rathbone, Tyra, and Harper 2002). A rapid method for determining the ammonia concentration of fly ash as a means for quality control of fly ash used for concrete was provided by Majors et al. (1999). When using fly ash containing ammonia, consideration should be given to material characteristics, applications, environment, and quality-control programs in place.

**1.2.3 Beneficiated fly ash**—Much fly ash produced from a power plant is suitable for use in concrete. If the quality of some or all of the fly ash produced is less than required by specification or market standards, however, methods may be used to beneficiate the fly ash. The properties that are commonly controlled by beneficiation are fineness and loss on ignition (LOI), an indicator of carbon content. The physical and chemical properties of fly ash can vary among individual precipitator or baghouse collection hoppers. This phenomenon

can be taken advantage of in some operations to produce a high-quality material. Where the control and piping systems in the power plant allow, fly ash can be selectively drawn from those hoppers that contain the higher-quality fly ash, while material of questionable quality is discarded.

Mechanical or air-classification equipment can be used to reduce the mean particle size of fly ash to meet specification or market requirements. Such classifiers effectively remove the denser particles and can be adjusted to vary the amount of coarser ash removed. Depending on the size, density, and distribution of particles containing carbon, the LOI can be increased, decreased, or unchanged by this technique. In general, the finer the fly ash, the lower the LOI and the greater the concrete's long-term compressive strength. Increased fineness also lowers the water demand and increases resistance to sulfate attack in concrete (EPRI ID-1006565). A typical centrifugal classifier installation involving one classifier, could beneficiate 54 to 91 Gg (60,000 to 100,000 tons) of classified material per year.

Numerous investigations have demonstrated that fly ash performance can be enhanced by significantly shifting the particle-size distribution to finer material (Butler 1981; Berry et al. 1989; Obla et al. 2001a). As compared to a normal fly ash with a mean particle diameter ranging from 15 to 35  $\mu\text{m}$  (0.0006 to 0.0014 in.), processed fly ash can be produced with a mean particle diameter of 2.5 to 4.0  $\mu\text{m}$  (0.0001 to 0.00016 in.). Particle-size reductions of this magnitude have been achieved by methods of specialized air classification systems (Cornelissan, Hellewaard, and Vissers 1995; Hassan and Cabrera 1998), and micronization (Paya et al. 1995; Bouzoubaâ et al. 1997). These processed, "ultra-fine fly ashes" can provide water reduction of 10 to 12% in mortar and reduce high-range water-reducer demand in concrete (Ferraris, Obla, and Hill 2001). Kruger, Sedat, and Dijkema (2001) and Obla et al. (2001a,b) have demonstrated that ultra-fine fly ashes contribute more toward concrete strength gain and permeability reduction than normal ASTM C 618 fly ash, and will, when properly proportioned, provide concrete characteristics comparable to highly reactive pozzolans such as silica fume. Concrete durability properties, such as resistance to alkali-silica reaction (Bérubé, Duchense, and Chouinard 1995), sulfate attack (Shashiprakash and Thomas 2001), and concrete permeability (Obla et al. 2000), are enhanced by ultra-fine fly ash. Technology is now available to reduce the carbon content of fly ashes. Triboelectric separation (Whitlock 1993) and carbon burnout techniques (Cochran and Boyd 1993) are commercially used to reduce the LOI of fly ash without deleterious effects to other properties. Triboelectric separation involves utilizing charge transfer between carbon and mineral particles occurring due to contact during conveying. The difference in charge separates the high carbon fraction from the carbon fraction of ash in a high-voltage electric field. Bittner and Gasiorowski (1999) reported on a commercial triboelectric process that uses a counter-current moving belt to facilitate the separation of carbon from fly ash in a high-voltage field. The report provides historical performance for a system that has been in operation since 1995. Triboelectric beneficiation systems have

generated 450,000 Mg (500,000 tons) of ash per year. Triboelectric operations based on alternate designs have also been demonstrated but not commercialized (Li et al. 1999; Soong et al. 1999). Carbon burnout is another means for reducing fly ash carbon content. This process burns the residual carbon in fly ash as a fuel source in an auxiliary fluidized bed combustor, producing a pozzolan meeting the required carbon content. In the process, heat is recovered and returned to the power plant that originally produced the high-carbon ash. One commercially operating facility has reported processing capabilities of 162,000 Mg (180,000 tons) per year (EPRI ID1006565; Frady, Keppeler, and Knowles 1999). In addition to burning the carbon, the temperature of the combustor can remove ammonia from the ash (Giampa 2001).

Froth flotation is a method derived from mineral processing that separates carbon from fly ash by introducing the fly ash into a slurry system. The slurry contains frothing chemicals that facilitate the flotation of less-dense carbon particles; whereas the inorganic fraction of fly ash is sluiced to a collection area. The processed fly ash is dried before use (Grosso 2001). Froth flotation can be useful for removing very fine carbon (EPRI ID-1006565).

The potential for a fly ash to impact the air-entrainment level in concrete is not always a simple function of residual carbon mass—as indexed by LOI values. Early work sponsored by Hurt et al. (1995) suggested that carbon in fly ash is heterogeneous—ranging from coke-like to lacy in morphology. More recent studies point to the fact that fly ash from different sources can exhibit varying impact on air entrainment even though LOI values are almost equivalent (Hill et al. 1997; Hill, Hower, and Rathbone, 1998; Hill, Rathbone, and Majors 1999). Hill and others (Freeman et al. 1997; Gao et al. 1997) have highlighted the important role that total carbon surface area, available surface area, and surface reactivity play in the interaction between fly ash carbon and chemical air-entraining admixtures. Studies have shown the potential to affect the adsorptive properties of fly ash carbon by modifying carbon surface properties without significantly reducing the carbon mass (Sabanegh et al. 1997; Hill and Majors 2001). Hurt has suggested ozonation as a means for chemically passivating carbon against chemical interaction with air-entraining admixtures as a means for fly ash beneficiation (Hurt et al. 2000).

## CHAPTER 2—FLY ASH COMPOSITION

### 2.1—General

Fly ash consists of heterogeneous combinations of amorphous (glassy) and crystalline phases. The largest fraction of fly ash consists of glassy spheres of two types: solid and hollow (cenospheres). These glassy spheres usually consist of 60 to 90% of the total mass of fly ash, with the remaining fraction of fly ash made up of a variety of crystalline phases. These two fractions are not completely independent of one another. Rather, the crystalline phases can be present within a glassy matrix or attached to the surface of the glassy spheres. This union of phases makes fly ash a complex material to classify and characterize in specific terms.

## 2.2—Chemical composition

The bulk chemical composition has been used by ASTM C 618 to classify fly ash into two types: Classes C and F. The chemical composition data used to determine compliance with ASTM C 618 do not address the nature or reactivity of the particles. This analysis is used as a quality-control or quality-assurance tool. Minor variations in the chemical composition of a particular fly ash do not relate directly to the long-term performance of concrete containing that fly ash. Although the constituents of fly ash are not normally present as oxides, the chemical composition of fly ash is so reported. The crystalline and glassy constituents that remain after the combustion of the pulverized coal are a result of materials with high melting points and incombustibility. The amounts of the four principal constituents— $\text{SiO}_2$  (35 to 60%),  $\text{Al}_2\text{O}_3$  (10 to 30%),  $\text{Fe}_2\text{O}_3$  (4 to 20%), and  $\text{CaO}$  (1 to 35%)—vary widely. The sum of the first three constituents ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ ) must exceed 70% to be classified as an ASTM C 618 Class F fly ash; whereas their sum must only exceed 50% to be classified as an ASTM C 618 Class C fly ash. Class C fly ashes generally contain more than 20% of material reported as  $\text{CaO}$ ; therefore, the sum of the  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  may be significantly less than the 70% Class F minimum limit.

The  $\text{SiO}_2$  content of fly ash results mainly from the clay minerals and quartz in the coal. Anthracite and bituminous (higher ranked) coals often contain a higher percentage of clay minerals in their incombustible fraction than do sub-bituminous and lignite coals; therefore, the fly ash from the high-rank coals is richer in silica. The siliceous glass from the fly ash is the primary contributor to the pozzolanic reaction in concrete because it is the amorphous silica that combines with lime and water to form calcium silicate hydrate (C-S-H), the binder in concrete.

The principal source of alumina ( $\text{Al}_2\text{O}_3$ ) in fly ash is the clay in the coal, with some alumina coming from the organic compounds in low-rank coal. The types of clays found in coal belong to three groups of clay minerals: smectite [ $\text{Na}(\text{Al}_5\text{Mg})\text{Si}_{12}\text{O}_{30}(\text{OH})_6 \cdot n\text{H}_2\text{O}$ ], illite [ $\text{KAl}_5\text{Si}_7\text{O}_{20}(\text{OH})_4$ ], and kaolinite [ $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$ ].

Northern lignites typically contain a sodium smectite; whereas bituminous coal typically contains only members of the illite group and kaolinite. This difference in types of clay explains the lower  $\text{Al}_2\text{O}_3$  in low-rank coal fly ash. From the alumina/silica ratios of smectite, 0.35; illite, 0.61; and kaolinite, 0.85, it is clear why lignite fly ashes usually contain 40% less analytic  $\text{Al}_2\text{O}_3$  than bituminous fly ashes.

The  $\text{Fe}_2\text{O}_3$  content of fly ash comes from the presence of iron-containing materials in the coal. The highest concentrations of iron-rich fly ash particles are between 30 and 60  $\mu\text{m}$  (0.0012 and 0.0024 in.), with the lowest iron contents in particles less than 15  $\mu\text{m}$  (0.0006 in.).

The source of the materials reported as  $\text{CaO}$  in fly ash is calcium, primarily from calcium carbonates and calcium sulfates in the coal. High-rank coals, such as anthracite and bituminous coal, contain smaller amounts of noncombustible materials, usually showing less than 5%  $\text{CaO}$  in the ash. Low-rank coals can produce fly ash with up to 35%  $\text{CaO}$ .

The southern lignite coals found in Texas and Louisiana show the least  $\text{CaO}$  of the low-rank coals, at about 10%.

Calcium oxide concentration has been suggested as another means of classifying coal fly ash. Thomas, Shehata, and Shashiprakash (1999) describe and discuss a recent revision of CSA A3000 to distinguish between fly ashes that have different effects on properties of fresh and hardened concrete, principally the total calcium content, expressed as percent by mass as  $\text{CaO}$ , as follows:

Type	$\text{CaO}$ , %	Loss on ignition, %
F	< 8	8 max.
CI	8 to 20	6 max.
CH	> 20	6 max.

They concluded that calcium oxide could be used as a reasonable measure of the general chemical composition of fly ash and its influence on concrete properties.

The  $\text{MgO}$  in fly ash is derived from organic constituents, smectite, ferromagnesian minerals, and sometimes dolomite. These constituents are usually minimal in high-rank coals, but can result in  $\text{MgO}$  contents exceeding 7% in fly ashes from sub-bituminous and northern lignites (lignite coal sources in North Dakota, Saskatchewan, and surrounding areas). Southern lignites (from Texas and Louisiana) have  $\text{MgO}$  contents of less than 2%.

The  $\text{SO}_3$  in fly ash is a result of pyrite ( $\text{FeS}_2$ ) and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) in the coal. The sulfur is released as sulfur dioxide gas and precipitated onto the fly ash or “scrubbed” from the flue gases, through a reaction with lime and alkali particles.

The alkalis in fly ash come from the clay minerals and other sodium and potassium-containing constituents in the coal. Alkali sulfates in northern lignite fly ash result from the combination of sodium and potassium with oxidized pyrite, organic sulfur, and gypsum in the coal. McCarthy et al. (1988) reported that  $\text{Na}_2\text{O}$  is found in greater amounts than  $\text{K}_2\text{O}$  in lignite and sub-bituminous fly ash, but the reverse is true of bituminous fly ash. Expressed as  $\text{Na}_2\text{O}$  equivalent (percent  $\text{Na}_2\text{O} + 0.658 \times \text{percent } \text{K}_2\text{O}$ ) alkali contents are typically less than 5%, but may be as high as 10% in some high-calcium fly ashes.

The carbon content in fly ash is a result of incomplete combustion of the coal and organic additives used in the collection process. Carbon content is not usually determined directly, but is often assumed to be approximately equal to the LOI; however, LOI will also include any combined water or  $\text{CO}_2$  lost by decomposition of hydrates or carbonates that are present in the ash. The analytical carbon concentration of most fly ashes will correlate well with LOI values, but the actual carbon content will usually range from 0.3 to 0.8% less than the LOI value. Class C fly ashes usually have LOI values less than 1%, but Class F fly ashes range from this low level to values as high as 20%. Fly ashes used in concrete typically have less than 6% LOI; however, ASTM C 618 provides for the use of Class F fly ash with up to 12.0% LOI if either acceptable performance records or laboratory test results are made available.

Minor elements that may be present in fly ash include varying amounts of titanium, phosphorus, lead, chromium,

and strontium. Some fly ashes also have trace amounts of organic compounds other than unburned coal. These additional compounds are usually from stack additives and are discussed in a subsequent section.

Table 2.1 gives typical values of North American fly ash bulk chemical composition for different sources. Other references that provide detailed chemical composition data are also available (Berry and Hemmings 1983; McCarthy et al. 1984; Tikalsky, Carrasquillo, and Snow 1992).

### 2.3—Crystalline constituents

From the bulk chemical composition of fly ash, a division can be made between the phases in which these chemical compounds exist in fly ash. Developments in the techniques of quantitative x-ray diffraction (XRD) analysis have made it possible to determine the approximate amounts of crystalline phases in fly ash (Mings et al. 1983; Pitt and Demirel 1983; McCarthy et al. 1988).

Low-calcium fly ashes contain only relatively chemically inactive crystalline phases: quartz, mullite, ferrite spinel, and hematite (Diamond and Lopez-Flores 1981). High-calcium fly ash can contain the previously mentioned phases, and may also contain additional crystalline phases such as: anhydrite, alkali sulfate, dicalcium silicate, tricalcium aluminate, lime, melilite, merwinite, periclase, and sodalite (McCarthy et al. 1984). The additional phases found in Class C fly ash are reactive, and this explains why Class C fly ash exhibits both cementitious and pozzolanic properties. A list of crystalline compounds found in fly ash is given in Table 2.2.

Alpha quartz is present in all fly ash. The quartz is a result of the impurities in the coal that failed to melt during combustion. Quartz is typically the most intense peak in the XRD pattern, but this peak is also subject to the most quantitative variability.

Mullite is found in substantial quantities only in low-calcium fly ashes. Mullite forms within the glass spheres as they solidify around it. It is the largest source of alumina in fly ash and is not normally chemically reactive in concrete.

In its purest form, magnetite ( $\text{Fe}_3\text{O}_4$ ) is the crystalline spinel structure closest to that found in fly ash. A slight decrease in the diffraction spacing of ferrite spinel is detected through XRD. Stevenson and Huber (1987) used a scanning electron microscope (SEM) electron probe on a magnetically separated portion of the fly ash to determine that the cause of this deviation is the Mg and Al substitution in the structure of this phase as an iron replacement. The ferrite spinel phase found in fly ash is not chemically active. Hematite ( $\text{Fe}_2\text{O}_3$ ), formed by the oxidation of magnetite, is also present in some fly ashes; it too is not chemically active.

Coal ashes containing high calcium contents often contain between 1 and 3% anhydrite ( $\text{CaSO}_4$ ). The calcium acts as a “scrubber” for  $\text{SO}_2$  in the combustion gases and forms anhydrite. Crystalline  $\text{CaO}$  (“free lime”) is present in most high-calcium fly ashes and may be a cause of autoclave expansion. Lime in the form of  $\text{Ca}(\text{OH})_2$  (“slaked lime”), however, does not contribute to autoclave expansion. Soft-burned  $\text{CaO}$  hydrates quickly and does not result in unsoundness in concrete; however, hard-burned  $\text{CaO}$  formed at higher

**Table 2.1—Example bulk composition of fly ash with coal sources**

	Bituminous	Sub-bituminous	Northern lignite	Southern lignite
$\text{SiO}_2$ , %	45.9	31.3	44.6	52.9
$\text{Al}_2\text{O}_3$ , %	24.2	22.5	15.5	17.9
$\text{Fe}_2\text{O}_3$ , %	4.7	5.0	7.7	9.0
$\text{CaO}$ , %	3.7	28.0	20.9	9.6
$\text{SO}_3$ , %	0.4	2.3	1.5	0.9
$\text{MgO}$ , %	0.0	4.3	6.1	1.7
Alkalies, %*	0.2	1.6	0.9	0.6
Loss on ignition, %	3	0.3	0.4	0.4
Air permeability fineness, $\text{m}^2/\text{kg}$	403	393	329	256
45 $\mu\text{m}$ sieve retention, %	18.2	17.0	21.6	23.8
Density, $\text{Mg}/\text{m}^3$	2.28	2.70	2.54	2.43

\* Available alkalies expressed as  $\text{Na}_2\text{O}$  equivalent.

**Table 2.2—Mineralogical phases in fly ash**

Mineral name	Chemical composition
Thenardite	$(\text{Na},\text{K})_2\text{SO}_4$
Anhydrite	$\text{CaSO}_4$
Tricalcium aluminate ( $\text{C}_3\text{A}$ )	$\text{Ca}_3\text{Al}_2\text{O}_6$
Dicalcium silicate ( $\text{C}_2\text{S}$ )	$\text{Ca}_2\text{SiO}_4$
Hematite	$\text{Fe}_2\text{O}_3$
Lime	$\text{CaO}$
Melilite	$\text{Ca}_2(\text{Mg},\text{Al})(\text{Al},\text{Si})_2\text{O}_7$
Merwinite	$\text{Ca}_3\text{Mg}(\text{SiO}_2)_2$
Mullite	$\text{Al}_6\text{Si}_2\text{O}_{13}$
Periclase	$\text{MgO}$
Quartz	$\text{SiO}_2$
Sodalite structures	$\text{Na}_8\text{Al}_6\text{Si}_6\text{O}_{24}\text{SO}_4$ $\text{Na}_6\text{Ca}_2\text{Al}_6\text{Si}_6\text{O}_{24}(\text{SO}_4)_2$ $\text{Ca}_8\text{Al}_{12}\text{O}_{24}(\text{SO}_4)_2$
Ferrite spinel	$\text{Fe}_3\text{O}_4$
Portlandite	$\text{Ca}(\text{OH})_2$

temperatures hydrates slowly after the concrete has hardened. Demirel et al. (1983) hypothesize that the carbon-dioxide-rich environment of the combustion gases causes a carbonate coating to form on poorly burned  $\text{CaO}$  particles, creating a high-diffusion energy barrier. This barrier retards the hydration of the particle and thereby increases the potential for unsoundness. If free lime is present as highly sintered, hard-burned material, there is a potential for long-term deleterious expansion from its hydration. Although there is no direct way to separate soft-burned lime from the sintered lime, McCarthy et al. (1984) note that when hard-burned lime is present, it is often found in the larger grains of fly ash. If there is sufficient hard-burned  $\text{CaO}$  to cause unsoundness, it can be detected as excessive autoclave expansion. Class F fly ash samples that were tested at the source by the Corps of Engineers at the Waterways Experiment Station and resampled by the North Pacific Division Laboratory at the site had extreme autoclave expansion. XRD showed  $\text{CaO}$  but not



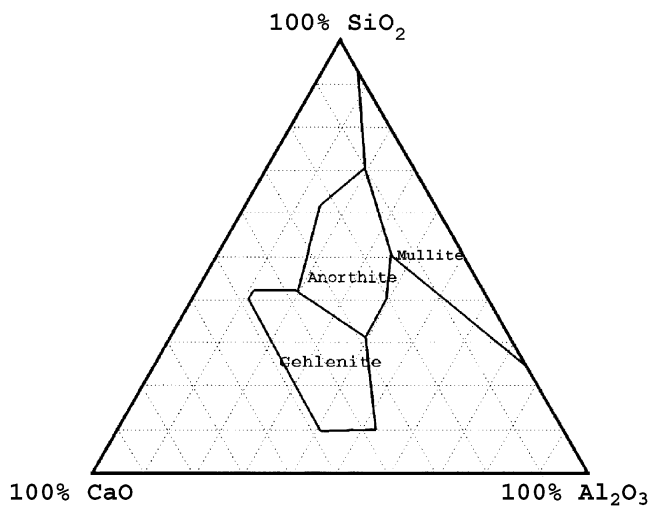


Fig. 2.1— $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$  ternary system diagram.

$\text{MgO}$ . After leaving the autoclave bars in moist curing another day and expecting that expansion would be reduced, it doubled. Examination revealed that  $\text{CaO}$  was in the largest particles, and several were apparently glass coated. Cores showed no abnormalities so the original acceptance was not invalidated.  $\text{Ca}(\text{OH})_2$  is also present in some high-calcium fly ash that have been exposed to moisture.

Crystalline  $\text{MgO}$  (periclase) is found in fly ashes with more than 2%  $\text{MgO}$ . Fly ash from low-rank coals can contain periclase contents as high as 80% of the  $\text{MgO}$  content. The periclase in fly ash is not “free”  $\text{MgO}$  like that found in some portland cements. Rather, the crystalline  $\text{MgO}$  in fly ash is similar to the phase of  $\text{MgO}$  found in granulated blast-furnace slags in that it is nonreactive in water or basic solutions at normal temperatures (Locher 1960).

Phases belonging to the melilite group include:

- Gehlenite ( $\text{Ca}_3\text{Al}_2\text{Si}_2\text{O}_{10}$ ); and
- Akermanite ( $\text{Ca}_4\text{Si}_3\text{O}_{10}$ ).

These phases have been detected in fly ash but are not chemically active in concrete. Each of these phases can have an Fe substituted for Mg or Al. Merwinite is a common phase in high-calcium fly ash, and the early stages of the devitrification of Mg-containing glasses. Northern lignites typically have higher  $\text{MgO}$  contents and lower  $\text{Al}_2\text{O}_3$  contents than subbituminous-coal fly ash, allowing the merwinite phase to dominate over the  $\text{C}_3\text{A}$  phase in the northern lignite fly ash. Merwinite is nonreactive at normal temperatures.

The presence of  $\text{C}_3\text{A}$  in high-calcium fly ash was confirmed by Diamond (1981) and others. The intense XRD peaks of this phase overlap those of the merwinite phase, making the quantitative interpretation difficult. McCarthy et al. (1988), however, reported that the  $\text{C}_3\text{A}$  phase is the dominant phase in fly ash with subbituminous-coal sources, and the merwinite phase is dominant in lignite fly ashes. Neither phase is present in low-calcium fly ash. The cementitious value of  $\text{C}_3\text{A}$  contributes to the self-cementing property of high-calcium fly ashes. The  $\text{C}_3\text{A}$  phase is extremely reactive in the presence of calcium and sulfate ions in solution.

Phases belonging to the sodalite group, formed from melts rich in alkalis, sulfate, and calcium, have a low silica

content. Nosean and hauyne phases have been identified in fly ash by McCarthy et al. (1988). Some researchers have found tetracalcium trialuminate sulfate ( $\text{C}_4\text{A}_3\bar{\text{S}}$ ) in Class C ash, the active constituent of Type K expansive cement.  $\text{C}_4\text{A}_3\bar{\text{S}}$  reacts readily with water, lime, and sulfate to form ettringite.

Among the other phases found in fly ash are alkali sulfate and dicalcium silicate. Dicalcium silicate ( $\text{C}_2\text{S}$ ) is a crystalline phase that is present in some high-calcium fly ashes. Northern lignite fly ash often contain crystalline alkali sulfates such as thenardite and apththilite.

Tishmack, Olek, and Diamond (1999) investigated high-calcium Class C fly ashes derived from Powder River Basin coal, which contains significant amounts of sulfur, calcium, and aluminum, and thus is a potential source of ettringite in concrete. Hydration products of fly-ash water pastes contain ettringite ( $\text{C}_6\text{A}\bar{\text{S}}_3\text{H}_{32}$ ), monosulfate ( $\text{C}_4\text{A}\bar{\text{S}}\text{H}_{12}$ ), and stratlingite ( $\text{C}_2\text{ASH}_8$ ). Portland cement/fly ash pastes were found to contain calcium hydroxide, ettringite, monosulfate, and smaller amounts of hemicarboaluminate and monocarboaluminate. The cement/fly ash pastes generally formed less ettringite than did the control cement pastes but formed more of the monosulfate phases.

## 2.4—Glassy constituents

Fly ash consists largely of small glassy spheres that form while the burned coal residue cools very rapidly. The composition of these glasses is dependent on the composition of the pulverized coal and the temperature at which it is burned. Fly ash glass content and glass composition strongly determines its reactivity. The major differences in fly ash glass composition lie in the amount of calcium present in the glass. Coal that has only small amounts of calcium—for example, anthracite and bituminous or some lignite coals—result in aluminosilicate glassy fly ash particles. Sub-bituminous and some lignite coals leave larger amounts of calcium in the fly ash and result in calcium aluminosilicate glassy phases (Roy, Luke, and Diamond 1984). This can be seen in the ternary system diagram shown in Fig. 2.1. The normalized average glass composition of high-calcium fly ash falls within the ranges where anorthite to gehlenite are the first phases to crystallize from a melt, whereas the low-calcium fly ashes fall within the regions of the diagram where mullite is the primary crystalline phase. The disordered structure of a glass resembles that of the primary crystallization phase that forms on cooling from the melt. In fly ash, the molten silica is accompanied by other molten oxides. As the melt is quenched, these additional oxides create added disorder in the silica glass network. The greater the disorder and depolymerization of the fly-ash glass structure, the less stable the network becomes.

In a simplified model, the mass of crystalline compounds is subtracted from the bulk mass, which yields the mass of the glassy portion of the fly ash. Extending this model to chemical compounds, the crystalline composition can be stoichiometrically subtracted from the bulk chemical composition to yield an average composition of the glass for any given fly ash. This is of importance when considering the level of reactivity of a fly ash.

The ternary diagram shown in Fig. 2.1 can also be used to illustrate the basic composition of the glassy portion of fly



ash. Fly ashes that have calcium-rich glassy phases are considerably more reactive than aluminosilicate glasses. Glasses in fly ash with a devitrified composition furthest from the mullite fields are most reactive within a hydraulic cement fly ash system because they have the most disordered network. This would indicate that fly ash containing high-calcium or high-alkali glasses possess a greater reactivity at early ages than low-calcium or low-alkali fly ashes, although this should be evaluated on a case-by-case basis. Additional discussions on the glass phases existing in fly ash can be found in Hemmings and Barry (1988) and Pietersen (1993).

## 2.5—Physical properties

The shape, size, particle-size distribution, and density of fly ash particles influence the properties of freshly mixed, unhardened concrete, and the strength development and other properties of hardened concrete. This is due in part to the influence of particle characteristics on the water demand of the concrete mixture. The properties of a fly ash produced at a particular power plant can vary from another fly ash originating from a different source. This is likely to be the case if the power plants are burning different coals or operate using different combustion systems. Plants operating under similar combustion regimes can produce fly ash with very similar chemical and physical characteristics. In addition, fly ashes produced at different power plants or at one plant with different coal sources may have different colors.

Fly ash color and the amount used can influence the color of the resulting hardened concrete in the same way as changes in cement or fine aggregate color. Fly ash color is generally not an engineering concern unless aesthetic considerations relating to the concrete require maintaining a uniform color in exposed concrete. A change in the color of an ash from a particular source can indicate changes in coal source, carbon content, iron content, or burning conditions and, therefore, changed properties.

**2.5.1 Particle shape**—Particle size and shape characteristics of fly ash are dependent on the source and uniformity of the coal, the degree of pulverization before burning, the combustion environment (temperature level and oxygen supply), uniformity of combustion, and the type of collection system used (mechanical separators, baghouse filters, or electrostatic precipitators). Lane and Best (1982) reported that the shape of fly ash particles is also a function of particle size. The majority of fly ash particles are glassy, solid, or hollow, and spherical in shape. Examples of fly ash particle shapes are shown in Fig. 2.2 and 2.3. Fly ash particles that are hollow are translucent to opaque, slightly to highly porous, and vary in shape from rounded to elongated. The intergrinding of fly ash with portland-cement clinker in the production of blended cement has improved its contribution to strength (EPRI SC-2616-SR). Grinding further reduces particle size, breaks up cenospheres, and separates particles that have surface attractions. As the mixture of fly ash and cement clinker is ground, an optimum fineness for water requirements can be established.

**2.5.2 Fineness**—Individual particles in fly ash range in size from less than 1  $\mu\text{m}$  (0.00004 in.) to greater than 1 mm

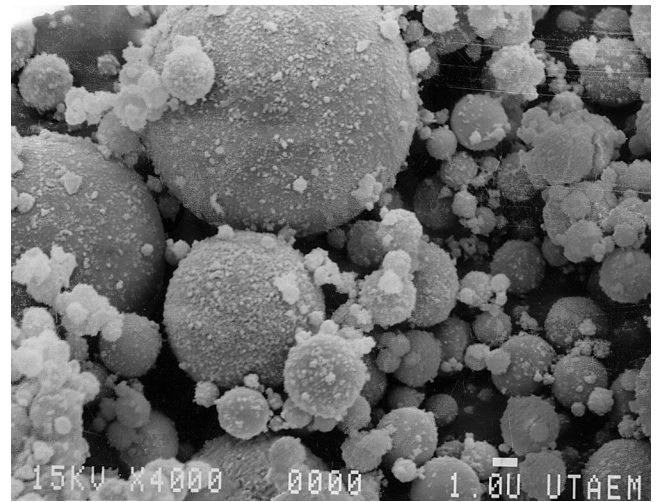


Fig 2.2—Fly ash at 4000 $\times$  magnification.

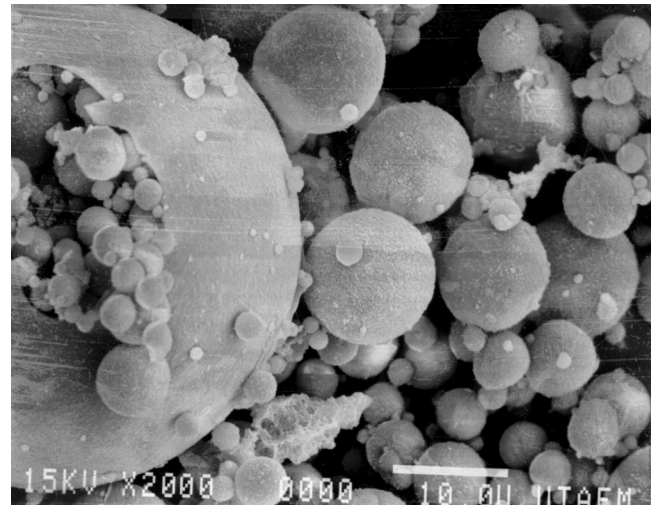


Fig 2.3—Fly ash showing plerospheres at 2000 $\times$  magnification.

(0.04 in.). A coarse fly ash often contains more porous particles with openings—plerospheres (Fig. 2.3). Fly ash of 5 to 30 micron particle size is highly reactive compared to coarser fly ash (Malhotra and Mehta 2002). In older plants where mechanical separators are used, the fly ash is coarser than in more modern plants that use electrostatic precipitators or bag filters. Fly ash that is suitable for use in concrete (ASTM C 618) shall have not more than 34% of the particles retained on the 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve. The 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve analysis of fly ash from a particular source will normally remain relatively constant, provided there are no major changes in the coal source, coal grinding, process operations, and plant load. Minor variations can be expected due to sampling techniques.

Fineness of a specific fly ash may have an influence on its performance in concrete. Lane and Best (1982) used ASTM C 430 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve fineness tests results as a means to correlate the fineness of Class F fly ash with certain concrete properties. For a particular source of fly ash, their data indicate that concrete strength, abrasion resistance, and resistance to freezing and thawing are direct

functions of the proportion of the fly ash finer than the 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve. They concluded that fineness within a particular source is a relatively consistent indicator of fly ash performance in concrete and that performance improves with increased fineness.

Fly ash fineness test methods (other than the ASTM C 430) are the air-permeability test (ASTM C 204), the turbidimeter method (ASTM C 115), and the hydrometer method. Fineness values obtained from these three tests can differ widely, depending on the procedure used. The test results are also strongly influenced by the density and porosity of the individual particles. The air-permeability test procedure provides a rapid method for detecting changes. Increased surface area, as determined by air-permeability tests, correlates with higher reactivity, especially when comparing ashes from a single source. Exceptions to this trend are found with some high-carbon fly ashes, which tend to have high fineness values that may be misleading. Useful information on size distribution of particles finer than 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve can be obtained by sonic sifting and by particle sizing equipment based on laser scattering (Popovics 1993). Data on the particle-size distribution of several Class C and F fly ashes indicate that a large percentage of particles smaller than 10  $\mu\text{m}$  (0.0004 in.) had a positive influence on strength (EPRI CS-3314).

**2.5.3 Density**—According to Luke (1961), the density of solid fly ash particles ranges from 1.97 to 3.02  $\text{Mg/m}^3$  (123 to 188  $\text{lb/ft}^3$ ), but is normally in the range of 2.2 to 2.8  $\text{Mg/m}^3$  (137 to 175  $\text{lb/ft}^3$ ). Some fly ash particles, such as cenospheres, are capable of floating on water. High density is often an indication of fine particles. Roy, Luke, and Diamond (1984) indicate that fly ashes high in iron tend to have higher densities, and those high in carbon have lower densities. ASTM Class C fly ashes tend to have finer particles and fewer cenospheres; thus, their densities tend to be higher, in the range of 2.4 to 2.8  $\text{Mg/m}^3$  (150 to 175  $\text{lb/ft}^3$ ).

**2.5.4 Trace metals in fly ash**—Coal fly ash particles, much like volcanic ash, are essentially insoluble aluminosilicate glasses. Ash consists of limestone, iron, aluminum, silica sand, and clay—essentially materials from the earth's crust oxidized by the heat of combustion.

In addition, coal ash contains trace quantities (in the parts-per-million range) of the oxidized forms of other naturally occurring elements. These same elements exist in soil, rock, and coal. Such trace elements typically include arsenic, boron, cadmium, chromium, copper, lead, selenium, and zinc, which can have adverse effects on human health if inhaled or ingested in sufficient quantity. Coal ash composition and mineralogy (including its trace element content and form) varies among power plants and is primarily related to that of the source coal and combustion conditions.

The U.S. Environmental Protection Agency (EPA) has reviewed extensive studies on coal ash for health and environmental risks and has examined coal ash samples collected from power plants around the country. In 1999, the agency determined that power-plant coal ash is nonhazardous and should be regulated accordingly. This determination culminated a 19-year review in accordance with the 1980 Resource Conservation and Recovery Act's Bevill Amendment,

which directed the EPA to review the issue and prepare a report to Congress.

## 2.6—Chemical activity of fly ash in hydraulic cement concrete

The principal products of the reactions of fly ash with calcium hydroxide and alkali in concrete is the same as that of the hydration of portland cement, calcium silicate hydrates (C-S-H), and calcium aluminate hydrates. The morphology of the Class F fly ash reaction product is suggested to be more gel-like and denser than that from portland cement (Idorn 1983). The reaction of fly ash depends largely on breakdown and dissolution of the glassy structure by the hydroxide ions and the heat generated during the early hydration of the hydraulic cement fraction. The reaction of the fly ash continues to consume  $\text{CaOH}_2$  to form additional C-S-H, as long as  $\text{CaOH}_2$  is present in the pore fluid of the cement paste and as long as there is remaining mixing water filling space that the C-S-H can occupy; at  $w/cm < 0.4$  by mass, there will be more space available before all cementitious material react (Philleo 1991). Regourd (1983) indicated that a very small, immediate chemical reaction also takes place when fly ash is mixed with water, preferentially releasing calcium and aluminum ions to solution. This reaction is limited, however, until additional alkali or calcium hydroxide or sulfates are available for reaction. The amount of heat evolved as a consequence of the reactions in concrete is usually reduced when fly ash is proportioned together with portland cement in the concrete. The rate of early heat evolution is reduced in these cases and the time of maximum rate of heat evolution is retarded (Mehta 1983; Wei, Grutzeck, and Roy 1984). When the quantity of portland cement per unit volume of concrete is kept constant, the heat evolved is increased by fly ash addition (Mehta 1983). Ma et al. (1994) ran an extensive calorimetric study of portland and blended cements systems containing a Class F fly ash to determine their activation energies. They reported that hydration is controlled by the same mechanism for all the blended cement systems tested.

Idorn (1984) has suggested that, in general, fly-ash reaction with portland cement in modern concrete is a two-stage reaction. Initially and during the early curing, the primary reaction is with alkali hydroxides and, subsequently, the main reaction is with  $\text{CaOH}_2$ . This distinction is not apparent when research is conducted at room temperature; at room temperature, the slower  $\text{CaOH}_2$  activation prevails and the early alkali activation is minimized. As was shown to be the case for portland cement by Verbeck (1960), the pozzolanic reaction of fly ashes with lime and water follows Arrhenius' law for the interdependence of temperatures and the rates of reaction. An increase in temperature causes a more-than-proportionate increase in the reaction rate.

Clarifying the basic principles of fly ash reaction makes it possible to identify the primary factors that, in practice, will influence the effectiveness of the use of fly ash in concrete. These factors include:

(a) The chemical and phase composition of the fly ash and of the hydraulic cement;

- (b) The alkali-hydroxide concentration of the reaction system;
- (c) The morphology of the fly ash particles;
- (d) The fineness of the fly ash and of the hydraulic cement;
- (e) The development of heat during the early phases of the hydration process; and
- (f) The reduction in mixing water requirements when using fly ash.

Variations in chemical composition and reactivity of fly ash affect early stage properties and the rheology of concrete (Roy, Skalny, and Diamond 1982).

It is difficult to predict concrete performance through characterization of fly ashes by themselves. Fly ash acceptability with regard to workability, strength characteristics, and durability should be investigated through trial mixtures of concrete containing the fly ash.

## 2.7—Future research needs

Future research needs in the area of fly ash composition include:

- (a) A better understanding of the effects of particle-size distribution;
- (b) Clarification of the influence of carbon particles as a function of their size and adsorption capability for chemical admixtures;
- (c) A better understanding of the nature of constituents in fly ash containing higher CaO concentration and how these fly ashes can affect the performance of concrete in the fresh and hardened states;
- (d) A better understanding of the effects that fly ash has on concrete microstructure and porosity over time and how these effects can be quantitatively related to concrete service life through the use of chloride diffusion data and service life models;
- (e) A better characterization of the glass phases in fly ash and their effect on pozzolanic properties; and
- (f) A better understanding of the effects that fly ash have on concrete performance after the concrete has been exposed to deicer salts.

## CHAPTER 3—EFFECTS OF FLY ASH ON CONCRETE

### 3.1—Effects on properties of fresh concrete

**3.1.1 Workability**—Fly ash typically has a lower specific gravity than cement. Therefore, when fly ash is used to replace a portion of cement in a unit volume of concrete, the amount of paste (assuming the  $w/cm$  is constant) will increase. In many cases, fly ash may be used as an addition or as a replacement and addition material (replacement ratio of greater than 1). This will result in a greater increase in paste volume for a given water content. Usually, this increase in paste volume produces a concrete with greater plasticity and better cohesiveness (Lane 1983). In addition, the increase in the volume of fines from fly ash can compensate for deficient aggregate fines. Fly ash changes the flow behavior of the cement paste (Rudzinski 1984). The generally spherical shape of fly ash particles normally permits the water in the concrete to be reduced for a given workability

(Brown 1980). Ravina (1984) reported on a Class F fly ash that reduced the rate of slump loss compared to non-fly ash concrete in hot weather conditions. Class C fly ashes generally have a high proportion of particles finer than 10  $\mu m$  (0.0004 in.) (EPRI CS-3314), which favorably influences concrete workability. Data on the rheology of fresh fly ash cement-water mixtures were reviewed in detail by Helmuth (1987).

**3.1.2 Bleeding**—Using fly ash in air-entrained and non-air-entrained concrete mixtures usually reduces bleeding by providing a greater surface area of solid particles and requiring a lower water content for a given workability (Idorn and Henriksen 1984).

**3.1.3 Pumpability**—Improved pumpability of concrete usually results when fly ash is used. For mixtures deficient in the smaller sizes of fine aggregate or of low cement content, the addition of fly ash will make concrete or mortar more cohesive and less prone to segregation and bleeding. Further, the spherical shape of the fly ash particles serves to increase workability and pumpability by decreasing friction between particles and between the concrete and the pump line (Best and Lane 1980).

**3.1.4 Time of setting**—The use of fly ash can extend the time of setting of concrete if the hydraulic cement content is reduced. Jawed and Skalny (1981) found that Class F fly ashes retarded early  $C_3S$  hydration. Grutzeck, Wei, and Roy (1984) and Eren, Brooks, and Celik (1995) also found retardation with Class C fly ash. The setting characteristics of concrete are influenced by ambient temperature and concrete temperature; cement type, source, content, and fineness; water content; water-soluble alkalies; use and dosages of several types of chemical admixtures; the amount of fly ash; and the fineness and chemical composition of the fly ash (Plowman and Cabrera 1984). When these factors are given proper consideration in the concrete mixture proportioning, an acceptable time of set can be obtained. The actual effect of a given fly ash on time of setting can be determined by testing when a precise determination is needed or by observation when a less precise determination is acceptable. Pressures on formwork can be increased when fly ash concrete is used if increased workability, slower slump loss, or extended-setting characteristics are encountered (Gardner 1984).

**3.1.5 Finishability**—Where Class F fly ash is used as an addition to cement content, time of setting is usually not impacted. Replacement of cement with Class F fly ash will often provide retardation in accordance with the amount of cement removed from the mixture. The cementitious properties of Class C fly ash can influence cement hydration to a greater extent than Class F, thus leading to more retardation in some cases and less in others. When fly ash concrete has a longer time of setting than concrete without fly ash, finishing should be delayed (just as with a slow-setting concrete without fly ash). Failure to finish slower-setting concrete at a later time could lead to premature finishing, which can seal the bleed water under the top surface, creating a plane of weakness. Set times can often be managed through the use of chemical admixtures and proportioning. Tests should be conducted to determine how a specific group of materials

interact. Longer set times for concrete with or without fly ash can increase the probability of plastic shrinkage cracking or surface crusting under conditions of high evaporation rates. Using very wet mixtures containing fly ashes with significant amounts of very light unburned coal particles or cenospheres can cause these particles to migrate upward and collect at the surface, which can lead to an unacceptable appearance. Sometimes the addition of fly ash results in stickiness and consequent difficulties in finishing. In such cases, the concrete may have too much fine material or too high of an air content.

**3.1.6 Air entrainment**—The use of fly ash in air-entrained concrete will generally require a change in the dosage of the air-entraining admixture. Some fly ashes, however, require little or no increase in the air-entraining admixture dosage. In fact, some Class C fly ashes can reduce the amount of air-entraining admixture required, particularly for those with significant water-soluble alkalis in the fly ash (Pistilli 1983). When using a fly ash with a high LOI, more frequent testing of air content at the point of placement is desirable to maintain control of air content in the concrete.

Meininger (1981) and Gebler and Klieger (1983) have shown that those fly ashes that require a higher admixture dosage (with similar  $w/cm$  to mixtures not containing fly ash) tend to exhibit more air loss in fresh concrete. When this problem is suspected, air tests should be made as the concrete is placed to measure the magnitude of the loss in air content and to provide information necessary to adjust the dosage level for adequate air content at the time of placement. Meininger (1981) showed that once the mixture is placed in the forms, no further appreciable loss of air content is encountered. Agitation of the concrete is a prerequisite for loss of air content to continue.

In one investigation dealing with air entrainment (Gebler and Klieger 1983), the retention of air content over a 90 min period in different fly ash concrete ranged from about 40 to 100%, as measured on the fresh concrete, expressed on the basis of the initial air content. Air contents were also measured in the hardened concrete. This particular study showed that for conditions where the air reduction occurred, the air content in the hardened concrete was not reduced below 3.5%. The spacing factor increased somewhat, but not above the accepted limit of 0.20 mm (0.008 in.).

The loss of air depends on a number of factors: properties and proportions of fly ash; cement; fine aggregate; length of mixing or agitating time; and type of air-entraining admixture used (Gaynor 1980; Meininger 1981).

The foam-index test (Section 5.8) is a rapid quality-control test that can be used to check successive shipments of fly ash to detect a change in the required dosage of air-entraining admixture in concrete. The test is used to predict needed adjustments in the admixture dosage. When the foam-index value increases by a large amount, the potential loss of air during delivery and placement should be checked. For quality-control purposes, a procedure can be adapted from Meininger (1981) or Gebler and Klieger (1983) that, when used in a consistent manner, can be useful at ready-mixed concrete plants.

### 3.2—Effects on properties of hardened concrete

#### 3.2.1 Compressive strength and rate of strength gain—

Both the strength at a given age and the rate of strength gain of fly ash concrete are affected by the characteristics of the particular fly ash, the cement with which it is used, and the proportions of each used in the concrete (EPRI CS-3314). Compared with concrete without fly ash proportioned for equivalent 28-day compressive strength, concrete containing a Class F fly ash can develop lower strength at 7 days or less when tested at room temperature (Abdun-Nur 1961). By using accelerators, activators, water reducers, or by changing the mixture proportions, equivalent 3- or 7-day strength may be achieved (Bhardwaj, Batra, and Sastry 1980; Swamy, Ali, and Theodorakopoulos 1983; Dhir, Zhu, and McCarthy 1998; Shi and Qian 2000). For example, test results indicate that silica fume can be used in concrete containing fly ash to increase the early strength. Simultaneous use of silica fume and fly ash resulted in a continuing increase in 56- and 91-day strengths, indicating the presence of sufficient calcium ions for both the silica fume reaction and the longer-term fly ash reaction to continue (Carette and Malhotra 1983). Also, Mukherjee, Loughborough, and Malhotra (1982) have shown that increased early strengths can be achieved in fly ash concrete by using high-range water-reducing admixtures and reducing the  $w/cm$  to at least as low as 0.28.

After the rate of strength gain of hydraulic cement slows, the continued pozzolanic activity of fly ash provides strength gain at later ages if the concrete is kept moist; therefore, concrete containing fly ash with equivalent or lower strength at early ages may have equivalent or higher strength at later ages than concrete without fly ash. This strength gain will continue with time and result in higher later-age strengths than can be achieved by using additional cement (Berry and Malhotra 1980). Using 28-day strengths as references, Lane and Best (1982) reported strength increases of 50% at 1 year for concrete containing fly ash, as compared with 30% for concrete without fly ash. Other tests, comparing concrete with and without fly ash, showed significantly higher performance for the concrete containing fly ash at ages up to 10 years (Mather 1965). The ability of fly ash to aid in achieving high ultimate strengths has made it a very useful ingredient in the production of high-strength concrete (Blick, Peterson, and Winter 1974; Schmidt and Hoffman 1975; Joshi 1979).

Class C fly ashes often exhibit a higher rate of reaction at early ages than Class F fly ashes (Smith, Raba, and Mearing 1982). Even though Class C fly ash displays increased early-age activity, strength at later ages in high-strength concrete appears to be quite acceptable. Class C fly ashes typically give very good strength results at 28 days. Cook (1981) and Pitt and Demirel (1983) reported that some Class C fly ashes were as effective as hydraulic cement on an equivalent-mass basis. Certain Class C fly ashes, however, may not show the later-age strength gain typical of Class F fly ashes. The effect of an Australian Class F fly ash on strength development with different cements was demonstrated by Samarin, Munn, and Ashby (1983) and is shown in Fig. 3.1. Strength development for a Class C fly ash is shown in Fig. 3.2.

Elevated temperature curing has a much more beneficial effect on the early strength and strength gain of concrete containing fly ash than on concrete without fly ash. It can be explained by the apparent higher activation energy for pozzolanic reactions than that for hydration of cement. Large quantities of coarse fly ash may be used effectively in concrete under thermal curing conditions, with a significant improvement in its compressive strength, in contrast to the rather limited contribution under normal curing conditions at ages up to 28 days (Ravina 1981).

Cook (1982), with Class C fly ash, and Brink and Halstead (1956), with Class F fly ash, showed that, in most cases, the pozzolanic activity increased at all ages proportionally with the percent passing the 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve. Both Brink and Halstead (1956) and Mather (1958) showed that changes in the cement source can change the strengths of concrete with Class F fly ash as much as 20%. For example, cements with alkali contents of 0.60%  $\text{Na}_2\text{O}$  equivalent or more usually perform better with fly ash for strength measured beyond 28 days.

Popovics (1986), after analyzing Ghosh's (1976) test results and from his own experiments, noticed that the strength differences between plain portland-cement concrete and fly ash concrete decreased with the decrease of  $w/cm$ . He found that just like plain portland cement concrete, fly ash concrete follows Abram's (Abram 1919) rule not only qualitatively, but also quantitatively, that is, the strength  $F$  can be approximated as follows:

$$F = A/B^{[w/(c+p)]}$$

where  $w/(c+p)$  is the  $w/cm$ , and  $A$  and  $B$  are the appropriate parameters. Using Abram's rule, Popovics (1991) predicted strength contributions from the fly ash and cement phases in a fly ash concrete. His experiments indicated that even at 1 day, concrete containing 25% Class F fly ash had higher strengths than the predicted strength contribution from the cement phase alone. If the Class F fly ash did not react chemically with other components, where did the strength increase come from? Popovics suggested that this strength increase could be either attributed to the reduction in initial porosity of the paste by fine particles of fly ash and quartz powder or to the acceleration of hydration of the cement phase due to nucleation effects from fly ash particles for calcium silicate hydrate (C-S-H) gel.

**3.2.2 Modulus of elasticity**—Lane and Best (1982) report that the modulus of elasticity of Class F fly ash concrete and its compressive strength is somewhat lower at early ages and a little higher at later ages than similar concrete without fly ash. The effects of fly ash on modulus of elasticity are not as significant as the effects of fly ash on compressive strength. Figure 3.3 shows a comparative stress-strain relationship for fly ash and non-fly ash concrete with 19.0 mm (3/4 in.) nominal maximum-size aggregate. The increase in modulus of elasticity under these conditions with Class F fly ash is small. The study concludes that cement and aggregate characteristics will have a greater effect on modulus of elasticity than the use of fly ash (Cain 1979).

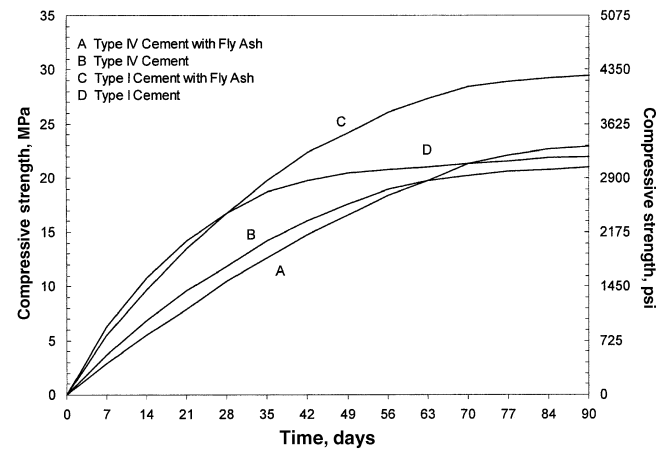


Fig. 3.1—Rate of strength gain for different cementitious materials: Class F fly ash (Samarin, Munn, and Ashby 1983).

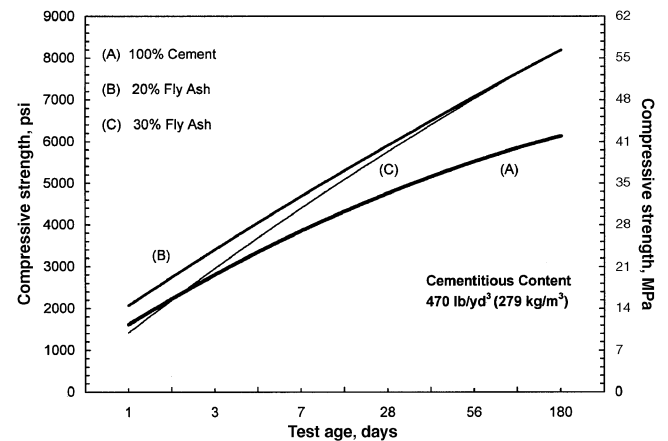


Fig. 3.2—Rates of strength gain of portland cement concrete and concrete in which part of the cement is replaced pound for pound with Class C fly ash (Cook 1983).

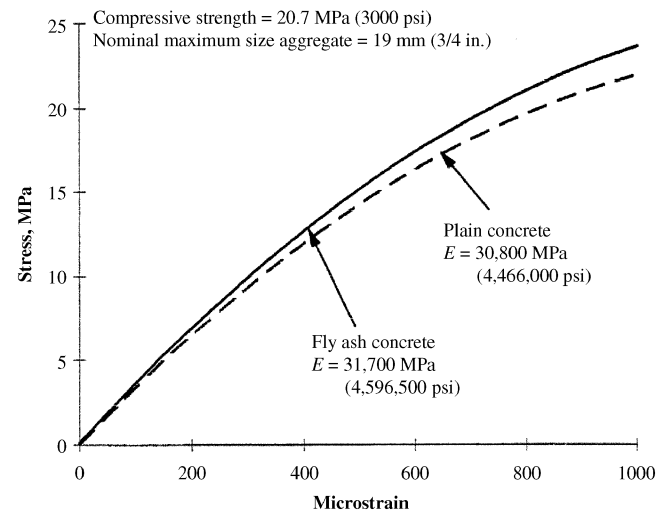


Fig. 3.3—Stress-strain relationship at 90 days (Tennessee Valley Authority 1981).

**3.2.3 Creep**—The rate and magnitude of creep strain in concrete depend on several factors, including ambient temperature and moisture conditions, strength of concrete, modulus of elasticity, aggregate content, the age of the concrete when load is applied, and the ratio of the sustained

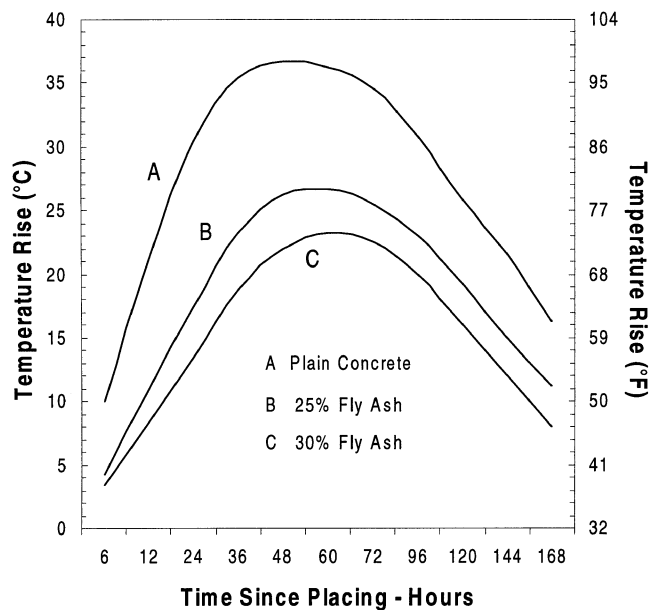


Fig. 3.4—Variation of temperature with time at the center of  $15 \text{ m}^3$  concrete blocks (Samarin, Munn, and Ashby 1983).

stress to the strength at the time of loading. The effects of fly ash on creep strain of concrete are limited primarily to the extent to which fly ash influences the ultimate strength and the rate of strength gain. When constant load is applied to concrete with a given volume of cement plus fly ash at ages of 28 days or less, a higher creep strain occurs when compared to concrete having an equal volume of cement only. This is due to the lower strength of fly ash concrete at the time of loading (Lane and Best 1982). Lane and Best (1982), however, showed that concrete with fly ash proportioned to have the same strength at the age of loading as concrete without fly ash produced less creep strain at all subsequent ages. When specimens with and without fly ash are sealed to prevent moisture losses, simulating conditions in mass concrete, creep strain values are essentially equal after loading at an age of 1 year (Ghosh and Timusk 1981). When unsealed specimens of equal strength were loaded at 1 year, creep strain values for concrete containing fly ash were half those measured for concrete without fly ash.

Most investigations have shown that when concrete with and without Class F fly ash having equivalent 28-day strengths are loaded equally at the same age, the fly ash concrete will exhibit lower long-term creep due to the greater late-age strength common to most fly ash concrete. Yuan and Cook (1983) investigated the creep of concrete with Class C fly ash. With 20% replacement, creep was about the same; at above 20%, creep increased with increasing fly ash content.

**3.2.4 Bond**—Concrete bond or adhesion to steel is dependent on a number of parameters, including the surface area of the steel in contact with the concrete, the location of reinforcement, and the density of the concrete. Fly ash usually increases paste volume and reduces bleeding. Thus, the contact at the lower interface where bleed water can collect may be increased, resulting in an increased surface contact area. The development length of reinforcement in concrete is

Table 3.1—Heat of hydration of portland cement/fly ash blends (Mather 1974)

Fly ash, % of cementitious material	Calories per gram		
	3 days	7 days	28 days
0	61	75	91
52	31	42	61
57	37	43	56
65	35	42	53
68	31	40	49
71	29	36	48

primarily a function of concrete strength. With proper consolidation and equivalent strength, the development length of reinforcement in concrete with fly ash should be at least equal to that in concrete without fly ash. These conclusions about concrete bond to steel are based on extrapolation of what is known about concrete without fly ash. The bonding of fresh concrete to existing concrete is minimally affected by the use of fly ash.

**3.2.5 Impact resistance**—The impact resistance of concrete is governed largely by the compressive strength of the mortar and the hardness of the coarse aggregate. The use of fly ash affects the impact resistance only to the extent that it affects the concrete's ultimate compressive strength.

**3.2.6 Abrasion resistance**—Compressive strength, curing, finishing, and aggregate properties are the major factors controlling the abrasion resistance of concrete (ACI 201.2R; ACI 210R). At equal compressive strengths, properly finished and cured concrete with and without fly ash will exhibit essentially equal resistance to abrasion.

**3.2.7 Temperature rise**—The chemical reaction of cement and water generates heat, which has an important bearing on the rate of strength gain and on early stress development due to differential volume change in concrete. Most of this heat is generated during the early stages of hydration of the alite (substituted  $\text{C}_3\text{S}$ ) and  $\text{C}_3\text{A}$  phases of the cement. The rate of hydration and heat generation depends on a number of parameters: quantity, fineness, and type of cement; mass of the structure; method of placement; temperature of the concrete at the time of placement; and curing temperature. The heat generated can be reduced by using fly ash as a portion of the cementitious material in concrete, as shown in Fig. 3.4 (Samarin, Munn, and Ashby 1983; Mehta 1983). As the amount of cement is reduced, the heat of hydration of the concrete is generally reduced (Mather 1974). Values for heat of hydration at three, seven, and 28 days for blends of Type II portland cement and a Class F fly ash when the fly ash made up more than 50% by mass of the cementitious material were reported (Mather 1974) and are given in Table 3.1. Some Class C fly ashes, however, do contribute to early temperature rise in concrete (Dunstan 1984). When heat of hydration is of critical concern, the proposed concrete mixture should be tested for temperature rise.

**3.2.8 Resistance to high temperatures**—With respect to the exposure of concrete to sustained high temperatures, Carrette, Painter, and Malhotra (1982) indicate that the use of fly ash in concrete does not change the mechanical properties of



concrete in relation to similar concrete containing only portland cement when exposed to sustained high-temperature conditions ranging from 75 to 600 °C (170 to 1110 °F).

**3.2.9 Resistance to freezing and thawing**—The resistance to damage from freezing and thawing of concrete made with or without fly ash depends on a number of parameters, including the adequacy of the air-void system, the soundness of the aggregates, age, maturity of the cement paste, and moisture condition of the concrete (Larson 1964). Care should be exercised in proportioning mixtures to ensure that the concrete has sufficient strength when first exposed to cycles of freezing and thawing while critically saturated. Concrete with or without fly ash should display a compressive strength of approximately 24 MPa (3500 psi) or more to ensure adequate protection. When compared on this basis in properly air-entrained concrete, investigators found no significant difference in the resistance to freezing and thawing of concrete with and without fly ash (Lane and Best (1982) for Class F fly ash and Majko and Pistilli (1984) for Class C fly ash). In addition, Halstead (1986) exposed fly ash concrete to freezing and thawing at very early ages and found no degradation of performance as compared with control concrete.

**3.2.10 Permeability and corrosion protection**—Concrete is permeable to water to the extent that it has permeable pore spaces through which water can move. Permeability of concrete is governed by many factors such as amount of cementitious material, water content, aggregate grading, consolidation, and curing efficiency. Powers, Copeland, and Mann (1959) showed that the degree of hydration required to eliminate capillary continuity from ordinary cement paste cured at standard laboratory conditions was a function of the water-cement ratio ( $w/c$ ) and time. Required time ranged from 3 days at a  $w/c$  of 0.40 to 1 year at a  $w/c$  of 0.70.

$\text{CaOH}_2$  liberated by hydrating cement is water soluble and may leach out of hardened concrete, leaving voids for the ingress of water. Through its pozzolanic properties, fly ash chemically combines with  $\text{CaOH}_2$  and water to produce C-S-H, thus reducing the risk of leaching  $\text{CaOH}_2$ . Additionally, the long-term reaction of fly ash refines the pore structure of concrete to reduce the ingress of water containing chloride ions. As a result of the refined pore structure, permeability is reduced (Manmohan and Mehta 1981; EPRI CS-3314).

Despite concern that the pozzolanic action of fly ash could reduce the pH of concrete, researchers found that an alkaline environment very similar to that in concrete without fly ash remains to preserve the passivity of steel reinforcement (Ho and Lewis 1983). Moreover, the reduced permeability of fly ash concrete can decrease the rate of ingress of water, corrosive chemicals, and oxygen.

The incorporation of fly ash in concrete results in very significant reductions in the chloride diffusion coefficient of cement paste, mortars, or concrete (Page, Short, and El-Tarras 1981; Li and Roy 1986; Thomas 1991; Dhir and Byars 1993; Kawamura and Torri 1989; Amoudi, Maslehudden, and Asi 1996). At early ages (such as 28 days), the difference in the diffusion coefficient of fly ash concrete and plain portland-cement concrete may be small, but the fly ash concrete undergoes very significant reductions in diffusion with age,

and at ages beyond 1 year, it may have a diffusion coefficient many times lower than concrete without fly ash (Thomas and Bamforth 1999). Laboratory measurements made on concrete cores extracted from a 30-year-old hydraulic dam indicated the diffusion coefficient of fly ash concrete to be approximately one order of magnitude lower than that of similar concrete without fly ash in the same structure (Thomas and Bamforth 1999).

Ternary cement blends containing silica fume and fly ash can produce concrete with exceptional resistance to chloride-ion penetration (Thomas et al. 1999) as the silica fume affects a reduction in the early-age diffusion whereas the fly ash contributes to the ongoing reduction in diffusion as the concrete matures. Significant reductions in chloride diffusion coefficients and chloride permeability have been measured at both early and later ages when small amounts (8 to 12%) of ultra-fine fly ash were used as a cement replacement (Obla et al. 2000).

**3.2.11 Reduction of expansion caused by alkali-silica reaction (ASR)**—The reaction between the siliceous glass in fly ash and the alkali hydroxides in the hydraulic cement paste consumes alkalies, which reduces their availability for expansive reactions with reactive aggregates. The use of adequate amounts of some fly ashes can reduce the amount of aggregate reaction and reduce or eliminate harmful expansion of the concrete (Farbiarz and Carrasquillo 1987; Snow 1991). Data for mixtures containing eight different fly ashes with a cement of 0.66%  $\text{Na}_2\text{O}$  equivalent and a highly reactive aggregate are shown in Fig. 3.5(a) and (b). Often, the amount of fly ash necessary to prevent damage due to ASR will be more than the optimum amount necessary for improvement in strength and workability properties of concrete. Figure 3.5(b) illustrates the phenomenon of a pessimum level, where particular replacement levels of some high-alkali fly ashes increase the problem of ASR and higher replacement levels of the same fly ash reduce the problem of ASR (Farbiarz and Carrasquillo 1987). The pessimum level of a particular fly ash is an important consideration when selecting mixture proportions using potentially reactive aggregates. The available methods for preventing harmful expansion due to ASR in concrete containing fly ash when reactive aggregates are used include use of a pozzolan meeting ASTM C 618 requirements in a sufficient amount to prevent excessive expansion or the use of blended cement demonstrated to control ASR expansion that meets ASTM C 595 or C 1157 requirements (Portland Cement Association 1998). Several case studies of ASR in concrete suggest that some aggregates that pass the current informal, nonmandatory ASTM limits may cause deleterious reactivity in the course of a number of years, even with low-alkali cement (Farbiarz and Carrasquillo 1987; Snow 1991). Therefore, Class F fly ash at 20 to 25% mass replacement can be used as a general preventive measure. Thomas, Hooton, and Rogers (1997) recommend minimum levels of replacement of portland cement by fly ash, namely, 20 to 30%, depending on the composition of the fly ash, to control alkali-silica reactivity. Bérubé, Duchense, and Chouinard (1995) provide data on effectiveness of a Class C and F fly ash



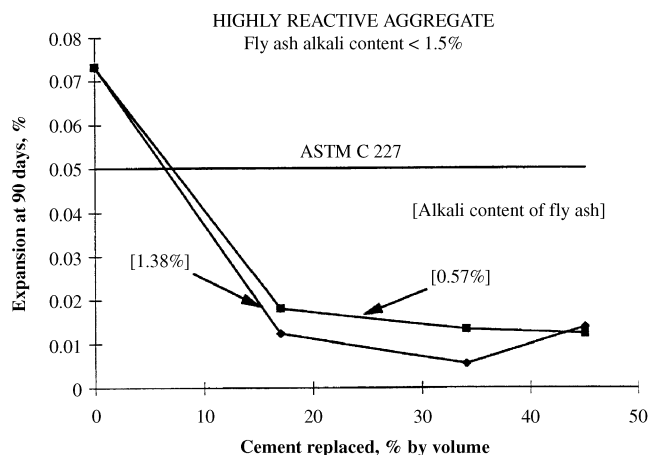


Fig. 3.5(a)—Mortar bar expansion versus percentage of cement replaced for all highly reactive aggregate mixtures containing fly ash with less than 1.5% alkali (Farbiarz and Carrasquillo 1987).

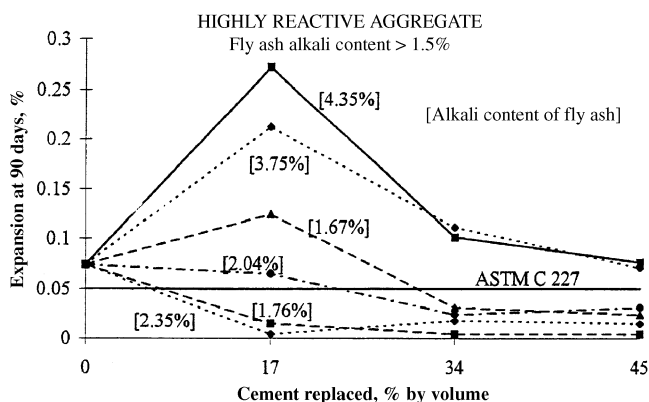


Fig. 3.5(b)—Mortar bar expansion versus percentage of cement replaced for all highly reactive aggregate mixtures containing fly ash with greater than 1.5% alkali (Farbiarz and Carrasquillo 1987).

in suppressing expansion due to alkali-silica reactivity using the accelerated mortar bar method, ASTM C 1260.

Lane and Ozyildirim (1999) reported on tests of four Class F fly ashes using mortars containing Pyrex glass as an aggregate and five portland cements having alkali contents ranging from 0.18 to 0.92%. Four of the fly ashes were tested at replacement levels ranging from 15 to 35% by mass of the total cementitious material. With cements of 0.40% alkali content and less, all replacement levels maintained expansion below 0.10%. With cements having alkali content above 0.60%, a replacement of 20 to 25% was necessary to control expansion, and this level of replacement appears to be effective with cements having alkali content up to 0.75 to 0.80%. One fly ash was used with one portland cement having alkali content of 0.64% to produce IP cements containing 18, 20, or 22% of fly ash. With these cements, expansion decreased as the proportion of fly ash increased. Expansion with the 18% blend exceeded 0.10%, whereas that of the 20 and 22% blends was maintained below 0.10%.

Lane (1999) provides results of tests of five fly ashes in mortar tests (ASTM C 441) with portland cements having alkali

contents of 0.60, 0.75, or 0.92%, respectively, with the fly ashes being used variously as cement replacements of 15, 20, 25, or 35% by mass. Also provided are data on tests of concrete (ASTM C 1293) consisting of one portland cement and one fly ash with or without silica fume and slag. The alkali content of the cement was gaged to 1.25% as  $\text{Na}_2\text{O}$  equivalent.

Replacement levels for fly ash, when used as the only mineral admixture, were 15, 25, and 35% by mass. The coarse and fine aggregates were known to be deleteriously alkali reactive from previous tests. The fly ash was effective in controlling the expansion of the concrete at the 15% replacement level.

Thomas and Innis (1999) used the accelerated mortar bar tests (CSA A23.2-25A and ASTM C 1260) to evaluate the effect of mineral admixtures on expansion due to ASR. The evaluation comprised use of 70 different material combinations, including two low-calcium fly ashes (< 8% CaO), three intermediate-calcium fly ashes (8 to 20% CaO), and nine high-calcium fly ashes (> 20% CaO). For aggregates that were shown to be deleteriously reactive by both test methods, there was generally good agreement between the test results when the failure criteria used were expansion of mortar bars at 14 days greater than 0.10% and expansion of concrete prisms at 2 years greater than 0.049%. It was concluded that combinations of fly ash and reactive aggregates that pass the accelerated mortar bar tests can be used in the field with a very low and acceptable risk of deleterious expansion due to ASR. Using a highly reactive siliceous limestone as aggregate, the safe replacement level for the tested fly ashes ranged from 15 to 51% in the concrete prism test at 2 years and from 13 to 56% in the mortar test at 14 days.

Barringer (1999) describes use of combinations of fly ash as a mineral admixture and use of lithium salts to control the deleterious effects of ASR in concrete. The investigation included four Class F and one Class C fly ashes, five aggregate sources, and one Type 1-11 cement having an alkali content of approximately 0.55% as equivalent  $\text{Na}_2\text{O}$ . Lithium nitrate was used to provide water-soluble lithium when used as a supplementary admixture. AASHTO Test Method T303 was employed, comprising 121 sets of four mortar bars.

A Class F fly ash producing the greatest reduction of expansion was chosen for use with the lithium nitrate. The Class C fly ash and the blend of Class C and F fly ash did not perform well and were not included in tests involving the lithium salt. The combinations of lithium nitrate and Class F fly ash are more effective in the reduction of expansion than in lesser proportions that would be required with either material used singly.

If an aggregate produced expansion in this test of approximately 0.80% at 14 days, it is recommended that the initial trial batch include a 25% by mass Class F fly ash replacement of the total cementitious material or a combination of 15% of Class F fly ash and lithium nitrate at 100% of the manufacturer's recommendation.

**3.2.12 Sulfate resistance**—As a general rule, Class F fly ash can improve the sulfate resistance of concrete mixtures. The increase in sulfate resistance is believed to be due in part

to the continued reaction of fly ash with calcium hydroxides in concrete to continue to form additional C-S-H, which fills in capillary pores in the cement paste, reducing permeability and the ingress of sulfate solutions. The situation with Class C fly ash is somewhat less clear. Evidence suggests that some Class C fly ashes may reduce sulfate resistance when used in normal proportions. Mather (1982) found that several Class C fly ashes used at 30% replacement of several high  $C_3A$  cements made the system less sulfate resistant. Tikalsky, Carrasquillo, and Snow (1992); Tikalsky and Carrasquillo (1993); and Dunstan (1976) showed that concrete containing some high-calcium fly ashes are susceptible to sulfate attack, and generally, higher volumes of high-calcium fly ash mixtures have a greater susceptibility to sulfate deterioration.

Deterioration due to sulfate attack depends on chemical reactions that yield products of greater volume than those of the original reactants, resulting in expansion. A reaction occurs between the sulfates (usually of external origin, such as sulfate-bearing soils or sulfate-rich groundwater) and reactive phases, producing calcium sulfoaluminates. Damage due to this reaction can be reduced by minimizing the amount of  $C_3A$  in the concrete. Dikeou (1975) and Pierce (1982) established that certain fly ashes used in concrete under wetting-and-drying conditions greatly improve the sulfate resistance of concrete made with all types of cement. The cement and cement-fly ash combinations studied indicated a descending order of resistance to sulfate attack:

- (a) Type V plus fly ash—most resistant to sulfate;
- (b) Type II plus fly ash;
- (c) Type V;
- (d) Type II;
- (e) Type I plus fly ash; and
- (f) Type I—least resistant.

All fly ashes used in this study were Class F, and the ratios of the fly ash to total cementitious material by mass varied from 15 to 25%.

The sulfate resistance of fly ash concrete is influenced by the same factors that affect concrete without fly ash: curing conditions, exposure, and  $w/cm$ . The effect of fly ash on sulfate resistance will be dependent on the class, amounts, and the individual chemical and physical characteristics of the fly ash and cement used.

An indicator of the relative sulfate resistance of a fly ash is the  $R$  value developed by Dunstan (1980) and discussed by Pierce (1982). The  $R$  value is the ratio of the percentage of calcium oxide minus 5% ( $CaO\% - 5\%$ ) to the percentage iron oxide ( $Fe_2O_3$ ) in a fly ash, based on the bulk chemical analysis. More recent research (Mehta 1986; Tikalsky, Carrasquillo, and Snow 1992) has shown that the  $R$  value is not a definitive method for predicting sulfate resistance. They found that sulfate resistance depended on the amount of reactive alumina and the presence of expansive phases in the fly ash and was not as strongly influenced by  $Fe_2O_3$  as indicated by the  $R$  factor. Generally, ASTM C 618 fly ashes with less than 15%  $CaO$  content will improve the sulfate resistance of concrete. Fly ashes with more  $CaO$  should be tested for sulfate expansion using ASTM C 1012 or USBR Test 4908.

The maximum sulfate resistance will be achieved in a given exposure and situation by employing a low  $w/cm$ , sulfate-resisting portland cement, and fly ash that exhibits good sulfate-resistance qualities. In attempting to select the fly ash that will give the maximum sulfate resistance to a concrete mixture, one should test blends of cements and fly ashes using ASTM C 1012. ASTM C 1157, the performance-based specification for hydraulic cements (which included blended cements), sets a limit on expansion at 6 months (tested in accordance with ASTM C 1012) of 0.10% for moderate sulfate resistance and 0.05% for high sulfate resistance. Fly ashes with large amounts of chemically active alumina can adversely affect sulfate resistance.

**3.2.13 Drying shrinkage**—Parameters influencing the drying shrinkage of concrete include fractional volume of paste, water content, cement content and type, and type of aggregate. Where the addition of fly ash increases the paste volume, drying shrinkage may be increased slightly if the water content remains constant. If there is a water-content reduction, shrinkage should be about the same as concrete without fly ash. Davis et al. (1937) studied different fly ash cement mixtures and found no apparent differences in drying shrinkage between concrete with up to 20% fly ash content and non-fly ash concrete. Dunstan (1984) and Symons and Fleming (1980) found that increased fly ash content resulted in slightly less drying shrinkage.

**3.2.14 Efflorescence**—Efflorescence is caused by leaching of water-soluble  $CaOH_2$  and other salts to external concrete surfaces. The leached  $CaOH_2$  reacts with  $CO_2$  in air to form  $CaCO_3$ , the source of the white discoloration on concrete. The use of fly ash in concrete can be effective in reducing efflorescence by reducing permeability. Reduced permeability helps maintain the high-alkaline environment in hardened concrete. Certain Class C fly ashes of high alkali and sulfate contents, however, can increase efflorescence.

**3.2.15 Deicing scaling**—Scaling of concrete exposed to deicing chemicals occurs when immature or non-air-entrained concrete pavements are exposed to large quantities of deicing chemicals in a freezing-and-thawing environment. Concrete pavements and other flatwork containing fly ash that are exposed to deicing chemicals should be air entrained and allowed to reach a specified strength or maturity. Deicing chemicals are not recommended for use on any concrete during its first year of maturation. There is some laboratory research that indicates concrete containing 40% fly ash, as a percentage of the total mass of cementitious material, may be more susceptible to scaling (Gebler and Klieger 1986; Ernzen and Carrasquillo 1992; Johnston 1994).

**3.2.16 Expansion produced by free magnesia**—Liu, Tang, and Cui (1998) reported that the addition of fly ash or slag reduces the expansion of cements containing free magnesia (crystalline  $MgO$ ), the effect increasing with an increase in the proportion of the fly ash. Fly ash was found to be more effective than slag in this regard.

Schlorholtz (1998) has summarized soundness characteristics of more than 5000 fly ash samples, primarily based on the autoclave soundness test (ASTM C 311). Expansive constituents in fly ash are free lime ( $CaO$ ), free crystalline

magnesia (MgO), and  $C_3A$ . The autoclave test is especially sensitive to presence of free lime.

## CHAPTER 4—CONCRETE MIXTURE PROPORTIONING

### 4.1—General

The most effective method to evaluate the performance of a given fly ash in concrete and establish proper mixture proportions for a specific application is a trial batch and testing program (ACI 211.1). Because different fly ashes have different properties and concrete requirements differ, fly ash and cement proportions cannot be prescribed for all materials combinations and requirements. Therefore, a series of mixtures should be prepared and tested to determine the required total amount of cementitious materials to obtain a specified strength with various percentages of fly ash (Ghosh 1976; Cook 1983). Fly ash is normally used at the rate of 15 to 35% by mass of total cementitious material. Larger proportions of fly ash can be used for mass concrete to reduce the likelihood of cracking upon cooling, improve sulfate resistance, reduce expansion caused by alkali-aggregate reaction or in other special applications (Malhotra 1984; Haque, Langan, and Ward 1984).

### 4.2—Considerations in mixture proportioning

Fly ash may be used in concrete either as a constituent of an ASTM C 1157 blended cement or as specified in ASTM C 595 for portland-pozzolan cement, Type IP (pozzolan-modified portland cement), Type I (PM), or it may be introduced separately at the concrete mixer. When used as part of blended cement, the proportions of portland cement to fly ash are fixed by the cement manufacturer. In the case of ASTM C 595, the proportions are given in the specification, while in ASTM C 1157 there are no composition limits in the specification. In mixture proportioning using Type IP cement or fly ash blended cement, the total amount of the blended cement to achieve the desired concrete properties needs to be determined. Fly ash blended cement is specified under ASTM C 1157 for general use, moderate heat and sulfate resistance, high early strength, low heat of hydration, high sulfate resistance, or low reactivity with alkali-reactive aggregate. When fly ash is batched separately, the individual proportions of cement and fly ash are selected, and their relative ratios should be adjusted as appropriate for each job situation.

Rahhal and Batic (1994) provide data on heat of hydration, flexural strength, and compressive strength produced by replacement of portland cement by 10, 20, 30, 50, 70, and 90% of fly ash at ages up to 180 days. The strength tests were performed on mortar specimens.

It is usually possible to proportion concrete mixtures for a particular strength level with a blend of cement and fly ash in which the volume of portland cement is less than it would be in similar strength mixtures not containing fly ash. If water-reducing admixtures are also used, the cement content is usually further reduced, as it is with non-fly ash concrete. Lovewell and Washa (1958), Cannon (1968), Shashiprakash et al. (1994), and others have suggested methods of proportioning concrete containing fly ash with and without chemical

admixtures. When fly ash is used in the absence of a water-reducing admixture, indications are that the total volume of cementitious material used (cement plus fly ash) should exceed the volume of cement used in portland-cement concrete mixtures to produce equal early strength and equal slump. The total mass of the cementitious material and the optimum proportion of fly ash selected depend on the class and quality of fly ash; the type, quality, and alkali content of the portland cement; the presence of chemical admixtures; placement conditions; and parameters such as strength requirements, curing conditions, and weather conditions at the time of placement (Prusinski, Fouad, and Donovan 1993; Majko and Pistilli 1984).

The optimum use of fly ash and chemical admixtures may require adjustments to the ratio of cement to fly ash be made between winter and summer conditions. For example, in cold weather, a reduction in the fly ash percentage of the cementitious material may be prudent, or a change in the type of chemical admixture or dosage rate may be indicated to permit earlier finishing or form removal. Conversely, hot weather concreting provides greater opportunities for using high proportions of fly ash because higher curing temperatures tend to increase the relative strength of fly ash concrete compared with non-fly ash concrete at all ages, especially if long-term curing is provided.

Because the use of fly ash normally contributes additional volume to the concrete, adjustments are made to proportions. Following ACI 211.1, the volume of fine aggregates should be adjusted to compensate for this increase and for any change in volume of mixing water and air content. Ordinarily, a reduction in the mixing water demand can be expected when fly ash is used.

In ACI,  $w/cm$  is used to indicate water-cementitious material ratio, as opposed to  $w/c$  for water-cement ratio. This is a consistent approach because the fly ash in a blended cement meeting ASTM C 595 or C 1157 will be counted as part of the cement. In those cases where a maximum  $w/cm$  or a minimum cement content is specified or recommended, it is generally accepted practice to count the mass of the fly ash as part of the amount of cementitious material required when separately batched fly ash is used.

Where there is uncertainty concerning the proper  $w/cm$  to use in air-entrained concrete to attain frost resistance of concrete, it may be advantageous to specify a  $w/cm$  of 0.45 or lower as stipulated in ACI 211.1 for concrete exposed to cycles of freezing-and-thawing while saturated with water. A minimum strength level is needed to achieve a reasonably low porosity of concrete and thus minimize capillary continuity in the paste (Powers, Copeland, and Mann 1959; Buck and Thornton 1967). This is the same approach used in ACI 318 for concrete with low-density (lightweight) aggregate because it is difficult to calculate accurately the  $w/cm$  in such mixtures.

Similar to non-fly ash concrete, the water requirements of concrete containing fly ash can be reduced an additional 5 to 10% by using conventional water-reducing admixtures. Data reported by Vollick (1959) indicate that the amount of water reduction obtained in concrete incorporating fly ash can vary depending on the specific fly ash used and its proportion in

the concrete. The use of high-range water-reducing admixtures in concrete containing fly ash can lead to water reductions of 15 to 40%. The results appear to be largely dependent on type and dosage of admixture, chemical composition of the cement, and the cementitious material content of the concrete; generally, however, the admixture is more effective in concrete containing fly ash (Popovics 1993). Cementitious material contents in excess of  $385 \text{ kg/m}^3$  ( $650 \text{ lb/yd}^3$ ) usually are required for 20% or greater water reduction. Ryan and Munn (1978) have reported that when a rapid rate of slump loss of concrete incorporating high-range water-reducing admixtures is experienced, it is not appreciably affected by the amount of fly ash used.

## CHAPTER 5—FLY ASH SPECIFICATIONS, TEST METHODS, AND QUALITY ASSURANCE/CONTROL

### 5.1—Introduction

The ASTM specification for fly ash is ASTM C 618, and the relevant sampling and test methods are outlined in ASTM C 311. These standards are under the jurisdiction of ASTM Committee C09. ASTM C 618 was originally published in 1968 to combine and replace ASTM C 350 on fly ash and ASTM C 402 on other pozzolans for use as mineral admixtures. Standard ASTM C 311 for sampling and testing was originally published in 1953. Specifiers of fly ash should use the latest edition of ASTM C 618. The Canadian Standards Association has a published standard for fly ash—CSA A3000. This standard is very similar to ASTM C 618, with exceptions that will be noted in the following discussions.

The following discussion is based on the requirements of ASTM C 618 and C 311, which were in effect at the time this report was written. It is not intended to be a detailed review of all requirements. ASTM C 618 states that Class F fly ash is “normally produced from burning anthracite or bituminous coal;” and Class C fly ash is “normally produced from lignite or sub-bituminous coal.” Many power plants blend various types of coals for power generation. Some fly ashes produced from sub-bituminous coals and lignite meet all the physical and chemical requirements of Class F and are thus marketed as Class F.

ASTM C 618 classifies fly ashes as Class F, which should have at least 70% sum of the oxides ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ), or Class C, which should have at least 50% of these oxides on chemical analysis. Class C fly ash generally contains more CaO than Class F and has cementitious and pozzolanic properties. The CaO content of Class C fly ash by chemical analysis is generally greater than 10% and may exceed 35%. The CaO is mainly combined in siliceous and aluminous glass.

### 5.2—Chemical requirements

As pointed out by Halstead (1981), early studies sought to relate fly ash performance to individual chemical oxide analysis results for silica, alumina, or iron oxide with little success. Today many, but not all, specifications have a minimum requirement for the sum of the oxides (Manz 1983). The intent is to ensure that sufficient reactive glassy constituents are present. A lower requirement is necessary for Class C because the CaO content may be substantial, thus making it

impossible in some cases for the sum of the oxides to be 70% or more.

There has been a criticism of this sum of the oxides approach to fly ash classification, and it has been suggested that fly ash should be classified by its CaO content (Roy, Luke, and Diamond 1984). The problem is illustrated in the paper by Majko and Pistilli (1984), where properties of five ashes are reported. They referred to these ashes as Class C because of the good strength development obtained in concrete and CaO contents in the 9 to 25% range; however, four of the five fly ashes contained more than 70% ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ), which means they were chemically classified as Class F.

Virtually all specifications have a limit on the amount of what is reported as sulfur trioxide ( $\text{SO}_3$ ) in fly ash. ASTM C 618 has a limit of 5.0% for both classes; other specification limits range from 2.5 to 12.0% (Manz 1983). The sulfate in fly ash and cement can affect the optimum amount of fly ash needed for maximum strength development and acceptable time of setting for the portland cement mixture in which it is used. An upper limit is considered necessary to avoid an excess of sulfate remaining in the hardened concrete that could contribute to detrimental sulfate attack.

Limits on moisture content of fly ash are necessary to ensure proper handling characteristics. Many ashes with a high CaO content will begin to hydrate in the presence of moisture. ASTM C 618 limits moisture to 3.0%; other specification limits are as low as 1.0%.

The maximum allowable LOI in ASTM C 618 is 6.0% for both Class C and F fly ashes. CSA A3000 allows 12% for Class F and 6% for Class C. Some specifiers modify this limit to a value lower than 6%, particularly where air-entrained concrete is involved. Many of fly ashes from base-load power plants are well below 6% LOI, mainly due to the efficiency of operation required to make economical use of coal as an energy source. In some special circumstances, a user may elect to use a fly ash with a higher LOI when acceptable laboratory or performance data are available.

### 5.3—Physical requirements

Fly ash fineness is specified in most cases by limiting the amount retained on the  $45 \mu\text{m}$  (No. 325 [0.0018 in.]) sieve by wet sieving. Reactivity of fly ash has been found to be related directly to the quantity passing this sieve because the coarser particles generally do not react as rapidly in concrete. ASTM C 618 limits the amount retained to 34% for both Class F and C fly ashes. Some specifications classify fly ash by fineness grades based on different percentages retained on the  $45 \mu\text{m}$  (No. 325 [0.0018 in.]) sieve. Control of fineness has occasionally been specified by surface area (air permeability). Surface area is normally reported by mass for portland cement and by volume for fly ash; the test results are not directly comparable. The relationship between fineness based on various densities is shown in Table 5.1.

The strength activity index with portland cement is considered only as an indication of reactivity and does not predict the compressive strength of concrete containing fly ash. It does

**Table 5.1—Relationship between particle size and surface area**

Mean particle diameter, $\mu\text{m}$	Surface area, $\text{m}^2/\text{m}^3$	Equivalent surface area, $\text{m}^2/\text{kg}$ at various densities			
		2.0 $\text{Mg}/\text{m}^3$	2.5 $\text{Mg}/\text{m}^3$	3.0 $\text{Mg}/\text{m}^3$	3.15 $\text{Mg}/\text{m}^3$
2	3000	1500	1200	1000	950
3	2000	1000	800	670	630
4	1500	750	600	500	480
5	1200	600	480	400	380
6	1000	500	400	330	320
7	860	430	340	290	270
8	750	380	300	250	240
9	670	330	270	220	210

not necessarily bear any relation to the optimum proportion of fly ash for use in concrete.

In the past, the strength activity test with lime filled a need for more rapid results on strength performance (7 days rather than 28 days). More recent revisions of ASTM C 618 have included a 7-day strength activity test with portland cement. The 7-day C 618 test uses standard 23 °C (73 °F) laboratory curing temperatures, whereas CSA 3000 specifies curing at 65 °C (149 °F) for 7 days.

The water requirement of the mortar is used in the strength activity test to ensure that fly ash does not cause a large increase in mixing water demand. The ASTM standards limit the water demand of mortar mixtures when performing the strength activity test as described in ASTM C 311. The water requirement of mortar is measured as a percent of the water used in the reference portland-cement mortar. The allowable water content is limited to a maximum of 105% by ASTM C 618. Other ASTM specifications have lower limits with some as low as 95% maximum. Helmuth (1996) has proposed a new procedure to replace the present strength activity index test for fly ash in ASTM C 311.

Soundness is measured by autoclave expansion or contraction. Where the fly ash constitutes more than 20% of the cementitious material in the proposed concrete, the paste used for autoclave testing shall contain the anticipated percentage of fly ash. The test measures the delayed expansion that can occur if sufficient amounts of MgO are present in the concrete as periclase, or CaO as hard-burned crystalline lime (Halstead 1981; Pitt and Demirel 1983). Bobrowski and Pistilli (1979) found no correlation among autoclave expansion,  $\text{SO}_3$  content, and concrete strength in their laboratory study. A length change of 0.8% is the maximum allowed by ASTM C 618.

The uniformity requirements given in ASTM C 618 limit the variation of density and fineness of the fly ash for shipments over a period of time. For fly ash used in air-entrained concrete, there is an optional limit on the variation of demand for air-entraining admixture caused by variability of the fly ash source. This requirement captures the quantity of air-entraining admixture required to produce an air content of 18.0% volume of mortar.

The optional multiple factor, applicable only to Class F, is calculated as the product of LOI (percent) and amount retained on the 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve (percent).

The maximum value of 255 restricts sieve residue (less than 34%) only when the LOI exceeds 6%.

The limit on the increase in drying shrinkage of mortar bars at 28 days should be applied only at the request of the purchaser to show whether the fly ash will cause a substantial increase in shrinkage in mortar bars as compared to bars with portland cement only.

Fly ash is considered to be effective in controlling ASR when its use leads to ASR resistance that is equal to or better than the use of a low-alkali control cement. Optional mortar-bar expansion tests should be requested if a fly ash is to be used with an aggregate regarded as deleteriously reactive with alkalis. ASTM C 618 limits the actual expansion of potentially reactive aggregate/paste combinations, whereas CSA A3000 determines the effect of fly ash in reducing expansion as compared to portland-cement-only samples.

Fournier and Malhotra (1999) provide a detailed review of laboratory test methods for evaluation of ASR of cement-aggregate mixtures, including recommendations regarding the use of fly ash as a supplementary material. For testing of laboratory specimens of concrete, ASTM C 1293 and CSA A23.2-14A are recommended. For testing of mortar specimens, ASTM C 1260 and CSA A23.2-25A are recommended.

#### 5.4—General specification provisions

ASTM C 618 requires that the purchaser or an authorized representative have access to stored fly ash for the purpose of inspection and sampling. The fly ash may be rejected if it fails to meet any of the specified requirements.

#### 5.5—Methods of sampling and testing

ASTM C 311 outlines the sampling and testing procedures of fly ash. For a number of test procedures, reference is made to other cement, mortar, or concrete tests. In some procedures, ASTM C 311 modifies proportions, preparation procedures, or test parameters needed to accommodate fly ash testing.

Either individual grab samples or composite samples are used, depending on the circumstances. The method provides detailed procedures for sampling from conveyor delivering to bulk storage, bulk storage at points of discharge, bulk storage by means of sampling tubes, and railroad cars or trucks.

The chemical analysis first requires the determination of moisture content by drying to constant mass and then determining the LOI from the resulting sample. The latter requires igniting the dried sample to constant mass in a muffle furnace at  $750 \pm 50$  °C ( $1382 \pm 122$  °F) in an uncovered porcelain crucible (unlike the platinum crucible used for cement). Many of the required chemical determinations are then made using procedures that are the same as, or very similar to, those used in testing portland cement.

Physical tests on fly ash, including density and amount retained on the 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve, are determined using test methods developed for portland cement. Soundness and strength activity testing procedures are specifically outlined in ASTM C 311, with reference to cement testing procedures where appropriate.

Of all the tests conducted, the two that are most difficult to obtain credible and repeatable results are fineness and

strength activity. The primary reason for variation in results reported for fineness is because test sieves are not precisely manufactured to exactly 45  $\mu\text{m}$  (No. 325 [0.0018 in.]). The standard procedure calls for calibrating sieves using a portland cement reference sample and computing a correction factor for the sieve. Because the fly ash particles retained on the test sieve tend to be much larger than 45  $\mu\text{m}$  (No. 325 [0.0018 in.]), sieves' large correction factors give inaccurate results. Sieves with small correction factors give more accurate results. In the strength activity index test with portland cement, results are highly dependent on the cement used by the laboratory. Because the performance of the cement is not controlled by the test method standards, tests conducted by different laboratories on the same fly ash sample may yield significantly different results. For many of the chemical and physical tests on fly ash contained in ASTM C 311, the precision and bias estimates have not been established.

### 5.6—Source quality control

Fly ash intended to be marketed as in conformance with ASTM C 618 should be produced under a quality-control program that is technically and statistically sound. The first recommended step in starting a fly ash quality-control program is to establish its quality history. The purpose of the quality history is to demonstrate that the fly ash consistently conforms to specification and uniformity requirements. For a new source of fly ash, at least 6 months of testing is recommended. This quality history should include monthly ASTM C 618 material certification and at least 40 individual test results for moisture, LOI, fineness, specific gravity, and  $\text{SO}_3$ . An analysis of these data by statistical techniques helps determine whether the proposed source of fly ash is suitable for the intended use (Dhir, Apte, and Munday 1988). After the quality history is established, the source should be tested at the frequency described in ASTM C 311, Table 1, to ensure continued conformance.

A quality-control program should be established for each individual source. Such programs can vary with coal type, collection systems, and other factors. The important characteristics of a particular fly ash source should be taken into account when developing a quality-control program. The quality-control program should consider both the fly ash characteristics and the specific requirements for its use in concrete. Testing for critical requirements may be needed more frequently than prescribed in ASTM C 311. All fly ashes do not have the same critical characteristics. These characteristics may not need to be included in every quality-control program. Periodic samples may also be detained and stored in the event that future testing and evaluation is desirable.

A quality-control program should maintain test reports on the fly ash to demonstrate product compliance to the physical, chemical, and variability requirements of ASTM or other project requirements, as well as monitor variability of critical characteristics. Statistical evaluations of the test data provide information on long-term variations.

ASTM C 311 provides for tests to be conducted on fly ash samples from established sources at a frequency not more than one test every 360 Mg (400 tons) for certain tests and

not more than one test every 2900 Mg (3200 tons) for the remainder (testing frequency is higher for new sources). Some of the tests require at least 28 days to be completed. Consequently, it is often desirable to establish a quality-control program employing rapid-testing techniques as indicators of certain critical fly ash characteristics, in addition to ASTM compliance testing. Sampling and testing on a time schedule basis, in addition to the shipping basis prescribed by ASTM C 311, may be a useful part of the program.

Fly ash testing using rapid techniques is a basis for making continual judgments as to the selection of fly ash from a source and its suitability for a desired end use or directing it to alternative uses. (See [Section 5.8](#) and the [Appendix](#) for descriptions of rapid tests.) In conjunction with the quality-control program, the fly ash supplier should be knowledgeable about power-plant operation and take action to exclude questionable fly ash when variations in the power-plant operation can influence fly ash quality. The chemical composition and fineness of fly ash are not likely to vary significantly at a power plant where the coal source is consistent, maintenance of the coal pulverizers and fly ash collectors is satisfactory, and the load on the power plant is fairly constant.

The performance of fly ash in concrete is related to the variation of properties with continuing shipments from the source of supply. Variations in other ingredients in the concrete will also affect the performance of the mixture. For Class F fly ash from a single coal source, the properties that are most likely to affect its performance in concrete are fineness, LOI, and autoclave expansion (Minnick, Webster, and Purdy 1971). Significant properties of Class C fly ash that affect performance in concrete include fineness, LOI autoclave expansion, and the amounts of  $\text{SO}_3$ , CaO, and alkalis present. Variability of fly ash color should also be monitored because changes in color can be important in architectural concrete applications. Fly ash color can also indicate changes in carbon content or power-plant burning conditions, which could alter the performances of the fly ash, especially in air-entrained concrete.

Schlorholtz and Dubberke (1995) report on use of x-ray fluorescence to determine the amount of fly ash in portland-cement fly ash mixtures, both in dry mixtures before batching and in hardened concrete and mortars.

Hooton and Rogers (1995) describe procedures using optical microscopy to estimate the fly ash content in hardened concrete.

McKerall, Ledbetter, and Teague (1981) have developed regression equations for fineness and specific gravity of fly ashes produced in Texas from sub-bituminous coal and lignite. These regression equations can be used to find close approximations of fineness, CaO content, and specific gravity given the results of the tests on the 75  $\mu\text{m}$  (No. 200 [0.0030 in.]) sieve test and a CaO heat evolution test described in the [Appendix](#).

### 5.7—Startup, oil, and stack additives

The fly ash distributor and user should be aware of changes in the ash properties that result from changes in power-plant operation, such as use of stack additives, flue-



gas conditioners, and changes in other aspects of production such as boiler startup (Ravina 1981). Changes in burning conditions and fly ash collection procedures at the power station can affect fly ash quality. The use of oil (to supplement burning) or stack additives, some of which may produce strong ammonia odors, needs to be detected rapidly. The addition of sodium sulfate to reduce blinding of precipitators can affect the time of setting of concrete, especially when certain admixtures are used. Liaison between the fly ash supplier and the power-station shift engineers, combined with frequent, rapid tests, should be used to detect problems early and divert questionable-quality fly ash to alternative destinations. When a coal-boiler unit is first fired, oil is often used to help initiate combustion, and the ash can contain hydrocarbon residues from the oil. In power plants where this is done during startup or under some other transient, short-term condition, the fly ash collected during these brief oil-burning periods should not be used in concrete. There are also some operations—in the UK, for example—where oil is burned with coal on a continuous basis. Fly ash from these operations may be suitable for concrete under certain circumstances, particularly in non-air-entrained concrete where control of admixture dosage is not a factor.

Materials are sometimes used by electric utilities during coal burning and fly ash collection to improve the efficiency of these operations. Materials termed “fireside additives” (EPRI CS-1318) are sometimes used in the burner to reduce  $\text{SO}_3$  emissions, reduce corrosion and fouling, and improve the collection efficiency of the electrostatic precipitators. Fireside additives are used more in oil-fired boilers than in coal-fired plants.

Materials injected into the flue gas to enable the electrostatic precipitators to collect a greater proportion of the fly ash are termed “flue gas conditioners.” Flue gas conditioners are often used in coal-burning power plants. When these types of materials are used, however, the fly ash may contain a small amount of substances such as magnesia, ammonium compounds, alkalis, or  $\text{SO}_3$ . Before using fly ash containing an additive, the variability of the amount of additive used in the power plant or present in the fly ash, and its effect in concrete, should be carefully evaluated.

### 5.8—Rapid quality-control tests

Fly ash collection at a base-load power plant usually continues around the clock, and because of limitations in storage capacity, decisions are made fairly rapidly concerning the probable quality of the fly ash so that material that does not meet requirements can be designated for other uses or directed to waste disposal. Some of the properties specified in ASTM C 618 and other characteristics are used in making these rapid fly-ash quality judgments. Several test methods have been devised to make daily, and in some cases hourly, quality estimates.

One or more of the rapid tests listed in the [Appendix](#) can be used as indicators of quality. The principal objective is to determine by rapid tests if the fly ash meets pre-established parameters for quality. These results should be supported by periodic comparison with results of standard tests of the fly

ash and could be used in developing correlations between fly ash characteristics and concrete performance. The testing may be used by the fly ash distributor at the power plant or by the user to check shipments of fly ash for changes in properties or to predict air-entraining admixture dosage or strength performance in concrete. The rapid testing procedures discussed in the [Appendix](#) are:

1. Loss on ignition (LOI);
2. Carbon analysis;
3. Material retained on 45  $\mu\text{m}$  (No. 325 [0.0018 in.]) sieve;
4. Air-jet sieving;
5. Air-permeability fineness;
6. Color;
7. Density (specific gravity);
8. Foam-index test;
9. Organic material;
10. CaO content;
11. Presence of hydrocarbons (startup oil); and
12. Presence of ammonia (precipitator additive).

## CHAPTER 6—FLY ASH IN CONCRETE CONSTRUCTION

### 6.1—Ready-mixed concrete

A survey of the ready-mixed concrete industry in the U.S. in 1998 indicated that, of the companies who responded to the questionnaire, 94% use at least some fly ash, compared with 31% in 1983 (Portland Cement Association 2000). Approximately 55% of the concrete produced contained fly ash, compared with 46% in 1983. Some reasons for this substantial increase are:

- (a) Technical benefits;
- (b) Increased cost of energy to produce cement encouraged cost savings in concrete through the use of cement-fly ash combinations;
- (c) The increased use of high-strength concrete of 52 MPa (7500 psi) or greater, which commonly requires the use of fly ash (Cook 1981; Albinger 1984);
- (d) Increasing availability of fly ashes meeting applicable standards in the U.S. and Canada; and
- (e) Governmental policies encouraging the use of fly ash to the maximum extent practicable.

Many concrete producers use fly ash to overcome deficiencies in aggregate grading or have developed mixtures specifically for pumping because concrete containing fly ash can pump higher and further at faster rates and with less segregation (Malhotra and Ramezaniapour 1994). Both lightweight and normalweight ready-mixed concrete containing 30% Class C fly ash were successfully pumped 305 m (1000 ft) vertically on a 75-story office tower in Houston, Tex. (Cook 1982).

Concrete with strengths up to 100 MPa (14,000 psi) in the field and higher in the laboratory, has been made with certain Class C fly ashes. The 72-story Interfirst Plaza in Dallas, Tex. contains approximately 60,000  $\text{m}^3$  (85,000  $\text{yd}^3$ ) of cast-in-place concrete using 30% Class C fly ash. Of this total, 15,700  $\text{m}^3$  (20,560  $\text{yd}^3$ ) was 70 MPa (10,000 psi) concrete with a reported average strength in excess of 83 MPa (12,000 psi) at an age of 56 test days (Cook 1989). Class F fly ashes are also used in high-strength concrete because of



the contribution to workability and long-term strength gain. Class F fly ash can contribute significantly to strength at 56 days.

Class F fly ashes are used to reduce the deleterious expansion associated with ASR. Aggregates that are otherwise unsuitable for use due to reactivity can be used when a fly ash known to adequately reduce alkali-silica expansion is used at the proper proportion in the concrete mixture.

Albinger (1984) stated that the decision to use or not use fly ash should be based on four factors:

1. Fly ash properties;
2. Effectiveness of the quality-control program of the supplier;
3. Ability to adjust to concrete changes, such as delayed finishability and increased air-entraining admixture demand; and
4. Cost effectiveness.

The cost of additional equipment to store and batch fly ash may be offset by the savings in material cost.

### 6.2—Concrete pavement

A 1992 EPRI study of 32 states found that all 32 states permitted the use of fly ash in pavement concrete and permitted the use of blended cements containing fly ash (EPRI 1992). Halstead (1981) summarized quality assurance and logistic problems relating to the use of concrete containing fly ash. Problems with the control of air entrainment and costs of transporting fly ash long distances were identified as the principal deterrents to more extensive use. Franklin (1981) reported on studies in the UK that considered the incorporation of fly ash in pavement concrete. In the U.S., the use of increased amounts of fly ash in highway construction is encouraged because of the availability of quality fly ash in most areas and governmental policies on funding as it relates to the use of fly ash to the maximum extent practical (Cain 1983). Hester (1967) reported on the use of fly ash in concrete pavement and structures in Alabama. This study found that for mixtures containing fly ash with reduced cement contents, higher flexural strengths were obtained. In Kansas, after 10 years of exposure and service, fly ash reduced, but did not eliminate, map-cracking and abnormal expansion in a 1949 test road (Scholer 1963; Stingley et al. 1960; Mather and Mielenz 1960). During the 1950s, Illinois, Nebraska, Wisconsin, Michigan, and Kentucky constructed experimental pavements with fly ash concrete to evaluate strength, crack resistance, placing and finishing qualities, and long-term wear resistance. All of these roads are reported to have performed well. Naik, Ramme, and Tews (1994) report that Class C and Class F fly ashes can replace portland cement in amounts as high as 50 or 40% by mass, respectively, to produce high-quality pavements.

### 6.3—Mass concrete

Mass concrete was one of the first applications in which fly ash was used in the U.S. Hungry Horse Dam in Montana, completed in 1953, contains over 2.3 million m<sup>3</sup> (3 million yd<sup>3</sup>) of concrete and a total of 110,000 Mg (120,000 tons) of fly ash. From that time until 1970, at least 100 major locks and dams using fly ash were constructed under the direction of

either the Corps of Engineers, the U.S. Bureau of Reclamation, the Tennessee Valley Authority, or private engineering firms. There are few mass concrete dams built in any part of the world that do not contain fly ash or natural pozzolan in the concrete (Hyland 1970). Large volumes of fly ash have also been used in roller-compacted concrete dams (Schrader 1982).

The use of fly ash can reduce thermal stresses by reducing the heat of hydration in mass concrete structures (Nasser and Marzouk 1979; Blanks, Meissner, and Rawhauser 1938; Carlson, Houghton, and Polivka 1979). By using fly ash concrete in massive structures, it is possible to achieve a reduction in temperature rise and reduce the risk of thermal cracking without incurring the undesirable effects associated with very lean mixtures, that is, harshness, bleeding, tendency to segregate, and tendency for increased permeability (Price 1982; Montgomery, Hughes, and Williams 1981). Improved sulfate resistance and reduction of expansion due to alkali-aggregate reaction provided by proper use of fly ash in the concrete mixture are other important considerations in the construction of mass concrete.

### 6.4—Roller-compacted concrete

Roller-compacted concrete (RCC) is used principally in mass concrete and pavements. ACI Committee 207 developed ACI 207.5R, which discusses its use in the construction and repair of dams. This form of concrete is transported and placed by dump truck or belt at the construction site, spread by conventional earth-fill placement methods, and then consolidated by rollers. Final consolidation is normally done by vibrating rollers. Construction time is very fast, the mixture is economical, and it achieves the strength of richer conventional mixtures.

ACI Committee 325 maintains report 325.10R on RCC pavements. RCC for pavement is a low-slump concrete with a 19 mm (3/4 in.) nominal maximum-size aggregate, low water content, and not less than 11% by mass of cementitious materials, of which 70% may be fly ash. The materials are mixed to a low slump consistency and laid down in lifts, usually by a lay-down machine. Rubber and steel-wheel vibrating rollers are used to consolidate the lifts. The pavement then receives a water cure or curing compound. Control joints are not normally provided. Uses include military vehicle, car, truck, aircraft parking areas, log sorting and storage yards, forestry and mine haul roads, and railroad unloading yards.

### 6.5—Self-consolidating concrete

Self-consolidating concrete (SCC) is a highly flowable yet stable concrete that can spread readily into place and fill formwork without consolidation and without undergoing significant separation of the material constituents. The use of SCC can provide a reduction in the labor demand needed for vibration and surface finishing, accelerate the placement rate, and secure superior surface quality. SCC can provide a homogeneous mixture of highly flowable concrete with good bonding properties, adequate structural performance, and proper durability (Khayat 1999). The proportioning of

SCC may vary based on specifics of a particular application and performance requirements such as flowability, resistance to dynamic and static segregation, and bleed characteristics. SCC is characterized by mixtures that provide good flowing characteristics while maintaining sufficient viscosity and cohesion to avoid material separation and segregation. These requirements can be achieved by proportioning the concrete with reduced amounts of coarse aggregate and higher amounts of fine material than usual. Another proportioning technique for SCC is to keep the usual concrete mixture proportions or use higher coarse-aggregate contents and use a viscosity-modifying admixture to provide stability and less segregation. Using either proportioning technique, higher proportions of fine materials such as cement and fly ash can be used to obtain the stability necessary to produce SCC.

Bouzoubaâ and Lachemi (2001) reported on SCC made with fly ash representing over 50% of the cementitious materials used in this product.

### 6.6—High-volume fly ash concrete

Haque, Langan, and Ward (1984) reported that high-volume fly ash (HVFA) concrete had emerged as a construction material in its own right and normally contains more than 40% fly ash by weight of total cementitious materials. Their report dealt with concrete suitable for concrete paving applications.

HVFA concrete may be defined as having a fly ash content of 50% or greater by mass of cementitious materials. Ramme and Tharaniyil (2000) described concrete with 37% fly ash as being HVFA. HVFA concrete can be considered to represent concrete containing higher percentages of fly ash than normal for the intended application of the concrete.

Dunstan (1981a,b) and Schrader (1982) reported on RCC mixtures using high volumes of fly ash for the construction of pavements and dams. This material maintains a low *w/cm* content and is batched to a dry consistency. Several researchers have reported on development of HVFA concrete of moderate to high slumps using high-range water-reducers and possessing suitable properties for commercial construction.

Mehta (1999) discussed CO<sub>2</sub> and the role it plays in global warming and illustrates the need to increase consumption of mineral admixtures to help offset the production of CO<sub>2</sub>. Mehta and Burrows (2001) further discuss the role HVFA concrete can play in concrete to gain durability.

Attention to HVFA concrete has recently come from the U.S. Green Building Council through their program called LEED (U.S. Green Building Council 2001). The LEED program is intended to define green building criteria by providing a rational standard for measurement. The LEED program has developed a point system for project certification, which recognizes sustainable use of materials, land utilization, and design considerations. Points earned under various criteria lead to certification for 26 points or the enhanced levels of silver, gold, and platinum for point levels of 33, 39, and 52, respectively.

Fly ash is included in the LEED system in that it is defined as an environmentally free post-industrial recycled material.

As such, its value in concrete is determined and combined with all other recycled materials in a structure. Higher-than-normal fly ash contents relative to portland cement enhance recycled material contents and gain certification points. The desire to increase recycled content value to achieve maximum recycled material content has led specifiers to require HVFA concrete mixtures in structural applications.

Manmohan and Mehta (2001) reported on HVFA concrete used for the seismic rehabilitation of Barker Hall at the Berkeley Campus of the University of California. Concrete for the structural wall contained 50% Class F fly ash of a total cementitious material content of 390 kg/m<sup>3</sup> (658 lb/yd<sup>3</sup>). Concrete for the foundation contained 55% Class F fly ash of a total cementitious material content of 356 kg/m<sup>3</sup> (600 lb/yd<sup>3</sup>). The mixtures contained moderate dosages of midrange water-reducing admixtures and exhibited better workability than conventional concrete at equivalent slumps. Formed surface finish was judged to be as good as or better than that achieved with conventional concrete. Compressive strength and set times were satisfactory for use in the project. Drying shrinkage was reported to be low, and satisfactory heat control was achieved as no thermal cracking has been exhibited.

Bilodeau, Malhotra, and Seabrook (2001) reported on the use of HVFA concrete in the Liu Centre in Vancouver, British Columbia, Canada. While concrete containing high-range water-reducer was previously considered mandatory, it was found that the use of high volume fly ash achieved adequate water contents 130 kg/m<sup>3</sup> (219 lb/yd<sup>3</sup>) with normal dosages of conventional water-reducing admixtures. Strength adequate for form stripping was achieved at one day and met the structural requirements at 28 days of age. HVFA concrete was placed in the foundation and structural elements using conventional concreting practices.

Brooks and Fox (2003) reported on the GAP Embarcadero project in San Francisco, which consumed over 3820 m<sup>3</sup> (5000 yd<sup>3</sup>) of concrete containing 50% class F fly ash and over 3440 m<sup>3</sup> (4500 yd<sup>3</sup>) of concrete containing 33% Class F fly ash. The concrete mixtures were found to have satisfactory set time and strength gain for use in modern high-rise construction.

### 6.7—High-performance concrete

Fly ash is often an essential component in the production of high-performance concrete (HPC). HPC is defined by ACI 116 as “concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.”

HPC was employed for a major project in Salt Lake City, Utah, for which the concrete not only had to achieve a minimum specified compressive strength of 55 MPa (8000 psi) but more critically had to also achieve a modulus of elasticity of 48,280 MPa (7,000,000 psi). This HPC was used as a hollow core-stiffening component of the world's largest King Truss 562 Mg (620 tons). To achieve this performance, the concrete incorporated a very dense, stiff aggregate imported to Salt Lake City from Iron Mountain, Mo., and also used a substantial volume of Class F fly ash in addition to silica fume

and a high-range water reducer. This HPC mixture had to be capable of being pumped into the hollow portions of the truss. Success was achieved on all accounts (Snow 2001).

### 6.8—Bulk handling and storage

Because fly ash is normally of lower density than portland cement, its bulk density should be considered when ordering or taking inventory. Fly ash storage usually requires approximately 30 to 40% more volume per unit mass than does portland cement; a 100 Mg (110.2 ton) portland-cement bin will hold about 70 to 75 Mg (77.2 to 82.7 tons) of fly ash. Packaging in paper bags, “big bags,” or other bulk containers may also reflect these differences in bulk density. The bulk density of fly ash in bins or silos is generally between 880 and 1280 kg/m<sup>3</sup> (55 and 80 lb/ft<sup>3</sup>), whereas cement in bins and silos is generally between 960 and 1500 kg/m<sup>3</sup> (60 and 94 lb/ft<sup>3</sup>). Both fly ash and cement may have lowered bulk density immediately after conveying (Strehlow 1973). Rail cars cannot carry as much mass of fly ash as of cement. Bulk pneumatic tank trucks that typically carry cement or fly ash are usually large enough in volume to receive a full legal load for over-highway delivery.

The spherical particle shape of fly ash and significant quantities of very fine grains mean that fly ash will require handling and storage facilities slightly different than those used for portland cement. When aerated, fly ash tends to exhibit very fluid handling characteristics, with an aerated angle of repose of 10 to 15 degrees. As a result, bins for storage of fly ash and transport systems (pneumatic or mechanical) should be well sealed to prevent leakage.

Bins and silos intended for cement can be used to store fly ash. Bins or silos should be large enough to receive at least two deliveries. The fluid nature of aerated fly ash can require slightly different unloading techniques than those used for portland cement. Due to the similar appearance of fly ash and cement, it is prudent to color-code and label the fill pipes or to take other precautions to minimize the possibility of cross contamination. Care should also be taken to clearly identify which storage compartments contain fly ash and establish proper materials-management procedures (Gaynor 1994). Bins should be completely cleaned when they are being converted to handle a different material. As with cement from different mills, fly ash from different sources should not be mixed in the same bin.

Because it is virtually impossible to detect fly ash contamination of a cement storage compartment by visually examining the cement as batched or the concrete as mixed, care in avoiding the intermingling of cement and fly ash is of great importance. A separate silo for fly ash is preferred. Segmented storage bins containing fly ash and portland cement (in adjacent bins) should be separated by a double bin wall with an air space between to prevent fly ash and cement from flowing together through a breach in a common wall. Otherwise, fly ash may move from one bin to the other through faulty welded connections or through holes caused by wear. If cement and fly ash are stored in different compartments of the same bin or silo and are separated by a



Fig. 6.1—Cement and fly ash silo with separate dust collection systems.

common dividing partition, frequent inspections of the partition should be made.

Each storage bin and silo should be equipped with a positive shutoff to control the flow of the fly ash to the weigh-batcher. Rotary valves, rotary-valve feeders, and butterfly valves are generally suitable for this purpose. A conventional scissor gate can be used if it is well maintained. Independent dust collectors on cement and fly ash bins, as shown in Fig. 6.1, are recommended to prevent cross contamination.

### 6.9—Batching

When batching fly ash and cement at a concrete plant, it is usually not necessary to install separate batchers. Fly ash and cement may have their masses determined cumulatively in the same batcher. Due to the lower density of fly ash, batchers should be sized adequately to handle larger volumes of cementitious material. Cement should be batched first so that accidental overbatching of fly ash will not cause underbatching of cement (Gaynor 1994). Care should be taken to accurately batch the correct amounts of both cement and fly ash because overbatching or underbatching can result in unacceptable variations in the properties of the fresh and hardened concrete. ASTM C 94 provides guidance for acceptable batching tolerances.

To transport fly ash from bin to batcher, methods such as gravity flow, pneumatic or screw conveyors, or air slides are most often used. The method depends on the location of the fly ash bin relative to the batcher. Fly ash from overhead storage is normally conveyed by gravity flow or an air slide. If the fly ash storage is at nearly the same level as the batcher, an air slide or a screw conveyor can be used (Fig. 6.2(a) and (b)). Because fly ash flows very easily, a positive shut-off valve should be installed to ensure that overbatching does not result from fly ash flowing through the air slide or screw when the device is stopped. Fly ash can be conveyed from lower level storage by pneumatic conveyor. During storage and batching, fly ash should be protected from moisture (in the air, from condensation, or from inclement weather) to avoid problems in handling and changes in the fly ash characteristics.

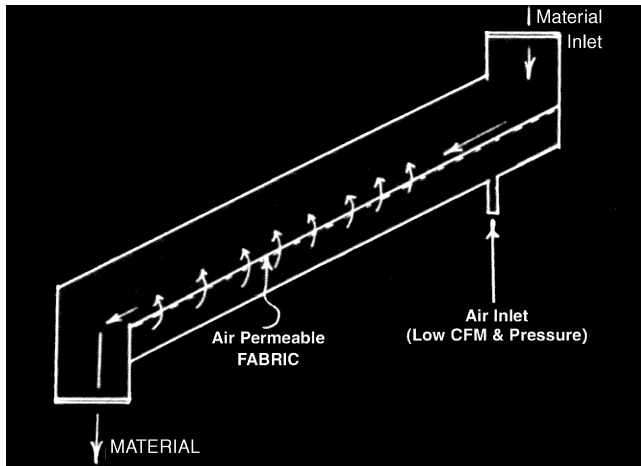


Fig. 6.2(a)—Schematic of an air slide.



Fig. 6.2(b)—A screw conveyor for transporting fly ash.

## CHAPTER 7—FLY ASH IN CONCRETE PRODUCTS

### 7.1—Concrete masonry units

The manufacture of concrete masonry units usually involves a dry, harsh concrete mixture consolidated in molds with mechanical force. When demolded, these units maintain their shape during handling and transportation into a curing environment. Fly ash has found widespread use in the manufacture of these products as a cementitious material and filler.

Curing methods for masonry units include autoclave and atmospheric-pressure steam. Manufacturers using either curing system can incorporate fly ash in their concrete mixtures and obtain the required strength. In addition, they obtain better mold life, and products with improved finish and texture and sharper corners. Fly ash gives added plasticity to the relatively harsh mixtures used in concrete masonry units (Belot 1967). Autoclave curing is still used to manufacture high-quality masonry units. Concrete masonry units cured in autoclaves show an early strength equivalent to that of 28-day moist-cured strength and reduction in volume change in drying (Hope 1981). The process uses temperatures of 135 to 190 °C (275 to 375 °F) and pressure of 0.52 to 1.17 MPa (75 to 170 psi). These conditions allow for the use of fly ash in amounts up to 35% for Class C fly ashes and 30% of the

cementitious material for Class F fly ashes. Percentages greater than these can result in efflorescence and reduced strength with Class C fly ash, and color variation and reduced strength with Class F fly ash. Particular care should be taken to ensure that the fly ash meets the soundness requirement of ASTM C 618, especially when the fly ash will constitute more than 20% of the total cementitious material in the product. While these values are usual, individual mixtures should be evaluated to determine the optimum level of fly ash that can be used.

Atmospheric-pressure steam curing is usually carried out in insulated kilns. The exact curing temperature is a function of the materials and the amount of fly ash used. Up to 35% for Class C and 25% for Class F fly ashes by mass of total cementitious material have been used satisfactorily with a curing temperature above 71 °C (160 °F). Drying shrinkage of atmospheric-pressure steam-cured concrete units can be reduced by the addition of fly ash. Optimum curing temperature is 82 to 93 °C (180 to 200 °F).

Accelerated curing techniques require a period of preset before the concrete products are subjected to elevated temperatures. When fly ash is used in conjunction with cement, it may be necessary to extend the preset period to avoid damage to the end products.

Proportioning of mixtures for the manufacture of concrete masonry units is not an exact science. Conditions can vary widely from plant to plant. When proportioning mixtures, concrete product producers should check the grading and types of aggregates, cements, equipment, and kiln temperatures, and then adjust trial batches with various amounts of fly ash to achieve specific technical or economic objectives (Valore 1970).

### 7.2—Concrete pipe

The manufacture of concrete pipe is accomplished by two different processes: one that uses extremely dry concrete mixtures and the other that uses more fluid concrete mixtures. Dry-cast concrete pipe uses mechanical compaction, vibration, or both, to consolidate the dry concrete mixture into a form that is removed as soon as the casting is finished. With removal of the form, the green pipe is carefully transported to its place of curing. Accelerated, atmospheric curing is normally used to obtain early-age performance.

Wet-cast concrete uses more fluid concrete placed and compacted in a form that remains around the pipe until certain levels of performance are achieved. Wet-cast pipe may be manufactured by the spinning process to remove excess water and air to produce high strength, high density, and low permeability.

Fly ash has found widespread use in the manufacture of concrete pipe as a cementitious material and as a filler to enhance quality and economy. Because properly proportioned mixtures containing fly ash make the concrete less permeable, concrete containing fly ash may be more resistant to weak acids and sulfates (Davis 1954; Mather 1982). Factors pertaining to the life of concrete pipe exposed to sulfate attack include the type of cement, class of fly ash, quality of concrete, bedding and backfill used, and sulfate concentration.

Dry-cast concrete pipe mixtures without fly ash typically use greater cement contents than necessary for strength to obtain the required workability. In a packerhead pipe casting operation, concrete with a very dry consistency and low water content is consolidated in a vertical pipe form using a revolving consolidation tool. Vibratory pipe processes use mechanical vibration to consolidate dry concrete into a form. The cement content can be reduced by replacing some of the cement with fly ash. Fly ash is used as a cementitious material and as a filler to provide added workability and plasticity. Equipment used in pipe production may last longer due to the lubricating effect of the fly ash. The use of fly ash can increase the cohesiveness of the no-slump, freshly placed concrete facilitating early form stripping and movement of the product to curing.

Other benefits attributed to the use of fly ash include a reduction in the heat of hydration of concrete mixtures containing fly ash, which can reduce the amount of hairline cracks on the inside surface of stored pipe sections (Cain 1979). Concrete mixtures containing fly ash also tend to bleed less, which is beneficial in wet-cast pipe.

Current ASTM specifications for the production of concrete pipe require the use of fly ash meeting the provisions of ASTM C 618, Class F or C. These specifications allow for the use of portland-pozzolan cement meeting ASTM C 595 requirements, containing a maximum of 25% fly ash by mass. Where fly ash is used separately, it is limited between 5 and 25% of total cementitious material. The cementitious material content for concrete for pipe production should not be less than  $280 \text{ kg/m}^3$  ( $470 \text{ lb/yd}^3$ ). The concrete mixture shall also have a maximum  $w/cm$  of 0.53.

### 7.3—Precast/prestressed concrete products

Precast concrete products can be produced with or without reinforcement. Reinforcement includes fibers, conventional reinforcing steel, and prestressing steel tendons, either pretensioned or post-tensioned, or combinations thereof. By definition, precast concrete products are cast and cured in other than their final position (ACI 116R). This facilitates the use of reusable forms that, for economy, are cycled as rapidly as possible. These concrete products generally achieve their competitive positions in the marketplace by using a limited number of forms with a rather short production cycle. Normal production schedules use one set of forms per day; however, 10 to 12 h schedules are common. Accelerated curing is used to enhance early-age concrete performance for handling, shipping, and product use.

Concrete mixtures for these products are proportioned for high levels of performance at early ages. Compressive strengths of 24 to 34 MPa (3500 to 5000 psi) are usually required at the time of form removal or stripping. These early concrete strengths are generally achieved with cement contents of  $355$  to  $445 \text{ kg/m}^3$  ( $600$  to  $750 \text{ lb/yd}^3$ ). Conventional and high-range water-reducing admixtures are often used for workability at very low water content. Non-chloride accelerating admixtures are also sometimes used for decreased times of setting. Under these conditions, fly ash generally has not been considered as an appropriate ingredient

for concrete mixtures; however, conditions appear to be changing toward the use of fly ash in these applications.

Responding to a questionnaire distributed in August 1986, 77 members of the Prestressed Concrete Institute (PCI) responded to questions about their use of fly ash in prestressed concrete products (Shaikh and Feely 1986). Of the total, 32% indicated that they were currently using fly ash in their products, 9% had used fly ash but had stopped, and 58% had never used fly ash. Of those responding that they were using fly ash, the average fly-ash content as a percentage of total cementitious material was 19%, with the lowest being 12% and the highest 30%. Of the respondents who have discontinued the use of fly ash, 86% stated that low initial strength gain as a problem. Other problems experienced in using fly ash were lack of consistency of fly ash, slump loss, and difficulty in obtaining uniform mixing. It was felt that additional studies should be carried out to define the effect of fly ash on some of the critical parameters such as early strength gain, creep, shrinkage, permeability, and elastic modulus.

Favorable results were obtained by Dhir, Zhu, and McCarthy (1998) in investigations on concrete containing fly ash at ages from 18 h to 1 year measuring strength development (compressive and tensile) and deformation behavior (elastic, creep, and shrinkage) using Class F fly ash. The amount of fly ash used as a percentage of total cementitious material ranged from 22 to 45%, and the ratio (by mass) of Class F fly ash added versus cement replaced ranged from 1.23:1 to 1.59:1. Concrete containing fly ash should perform as well as, or better than, concrete containing only rapid-hardening cement. Another investigation was conducted with Class C fly ash and a Type I cement to determine the extent of strength gain obtainable (Naik and Ramme 1990). Cement replacements of 10 to 30% were investigated with fly ash replacing cement at a ratio of 1.25:1 using an established nominal 34.5 MPa (5000 psi) concrete mixture without fly ash. This study concluded that high-early strength concrete can be produced with high replacement of cement by fly ash for precast/prestressed concrete operations. This work was done with the cooperation of two different prestressed concrete operators. One of the operations uses fly ash as 20% of the cementitious material in daily work year around.

In cases where fly ash can not be economically justified as a cementitious material, it may be used to enhance other product features. Fly ash used in precast concrete products improves workability, resulting in products with sharp, distinctive corners and edges; fly ash may also improve flowability, resulting in products with better surface appearance. Better flowability and workability properties achieved by using fly ash are particularly desirable for products with intricate shapes and surface patterns and for those that are heavily reinforced. Additionally, an appropriate fly ash may be used in areas with potentially reactive aggregates or unknown sulfate conditions to provide protection against these types of long-term durability problems.

The most common reasons for using fly ash are the savings in cost of materials and labor that can generally be achieved and improved quality of concrete. Fly ash may make sense

for the reasons noted in the previous programs. In any case, proportions and curing procedures should produce adequate early strength or the turnaround time on forms or molds will be increased (Ravina 1981). In general, fly ash becomes more desirable for applications where early strength is not a critical parameter. This usually occurs only when the specifications prohibit form removal before specified ages.

#### 7.4—No-slump extruded hollow-core slabs

Pretensioned hollow-core structural slabs are produced using no-slump concrete. It is consolidated and shaped as it passes through an extrusion machine. The particle shape of the coarse aggregate and the amount of fine aggregate are very important to workability. Fly ash is usually added to increase the workability of these dry, harsh mixtures.

### CHAPTER 8—OTHER USES OF FLY ASH

#### 8.1—Grouts and mortar

According to ACI 116R, grout is “a mixture of cementitious material and water, with or without aggregate, proportioned to produce a pourable consistency without segregation of the constituents; also a mixture of other composition but of similar consistency.” Its primary purpose is to permanently fill spaces or voids. Mortar contains the same basic ingredients, but with less water so that a less-fluid consistency is achieved. Mortar is used primarily in masonry construction. The benefits derived from using fly ash in grouts and mortars are much the same as those obtained when fly ash is used in concrete (Bradbury 1979). These include economy, improved workability, lower heat of hydration, reduced expansion due to ASR, reduced permeability, and improved sulfate resistance. The flowability of grout is generally improved, particularly under pressure, due primarily to the favorable particle shape and lower specific gravity of the fly ash particles, which tend to stay in suspension longer and reduce segregation (Hempling and Pizzella 1976).

Common uses of grout include:

- (a) Preplaced aggregate concrete where grout is injected into the void of previously placed coarse aggregate to produce concrete (ACI 304R);
- (b) Contact grouting either under machinery to fill the space between a base plate and substrate concrete or between the top surface of concrete placed or pumped under existing concrete or rock, as in tunnel linings;
- (c) Providing support for deep mine applications;
- (d) Curtain grouting where very fluid mixtures (often without aggregate) are used to fill voids in rock foundations;
- (e) Soil stabilization to fill voids in soil or between soil particles to densify and generally improve its load-carrying capacity;
- (f) Slab jacking to raise and realign concrete slabs or structures that have settled; and
- (g) Underwater placing and slope protection where grout is generally injected into preplaced inflatable cloth blankets that are flexible enough to conform to the surrounding contour to completely fill the void and provide complete contact.

#### 8.2—Controlled low-strength material

Controlled low-strength material (CLSM) is discussed in ACI 229R and is often known by other names such as flowable fill, lean-mix backfill, controlled-density fills, flowable mortar, K-krete™, fly ash slurry, and flowable fly ash. CLSM normally consists of fly ash, cement, water, and fine aggregate. It may include coarse aggregate, lightweight aggregate, and admixtures such as air-entraining admixtures, water-reducers, and high-range water-reducers. The U.S. Department of Transportation Federal Highway Administration (FHWA) has issued a Technical Report, “Fly Ash Facts for Highway Engineers,” FHWA-SA-94-081, which includes flowable fill applications, mixture proportions, and specification requirements.

#### 8.3—Soil cement

ACI 230.1R explains soil cement in detail. Soil cement is used as a base for road, street, and airport paving. It provides uniform, strong, solid support for paving. It is used for slope protection for dams and embankments and liners for reservoirs, lagoons, and other channels. It has been used as a mass placement for dikes, foundations, and coal-containment berms in power plants. It has also been used in rammed-earth wall systems and as regular backfill material. Fly ash can be used in soil cement as a cementitious material. Usually, the cementitious material content is 4 to 16% of the dry weight of soil, of which any portion of the cementitious material can be fly ash. The use of self-cementing coal fly ash as the sole stabilizing agent is addressed in *1999 Coal Combustion Byproduct—Production and Use* (American Coal Ash Association 2000).

#### 8.4—Sulfur concrete

Sulfur concrete is reported in ACI 548.2R. Sulfur concrete construction materials are now used in many specialized applications throughout industry and transportation. They are used primarily in areas where conventional materials like portland-cement concrete fail, such as acidic and saline chemical environments. These new construction materials are thermoplastic and achieve compressive strength in excess of 62 MPa (9000 psi) within 1 day of casting. The materials are impervious to moisture permeation and extremely resistant to attack by mineral acids and salts. ACI 548.2R includes historical background information and a guide to sulfur concrete construction and reports the use of fly ash as a fine mineral filler.

#### 8.5—Plastering

ACI 524R covers the use of current materials and methods for plastering. Recommendations for producing good portland-cement-based plaster are given. Various mixtures characteristics, procedures, and alternates with advantages and disadvantages are discussed. Fly ash and other minerals can be added to a plaster mixture to improve sulfate resistance.

#### 8.6—Cellular concrete

ACI 523.3R presents information on materials, fabrication, properties, design, and handling of cellular concrete with oven-dry densities greater than 800 kg/m<sup>3</sup> (50 lb/ft<sup>3</sup>) and aggregate concrete with oven-dry densities greater than 800 kg/m<sup>3</sup> (50 lb/ft<sup>3</sup>) but whose compressive strengths are less than



17.24 MPa (2500 psi). The density range of such concrete is generally used for thermal and sound insulation fills for roofs, walls, and floors. At the higher densities, cellular concrete is used in cast-in-place walls, floors, and roofs, and also for precast elements such as wall and floor panels. Pozzolans are used in normally cured, low-pressure steam-cured, and high-pressure steam-cured (autoclaved) lightweight aggregate and cellular concrete. Fly ash and natural pozzolans used should conform to ASTM C 618. A thorough description of the use of pozzolans in autoclaved lightweight products can be found in ACI 516R.

### 8.7—Shotcrete

ACI 506R provides information on material and properties of both dry-mix and wet-mix shotcrete. Most facets of the shotcrete process are covered, including application procedures, equipment requirements, and responsibilities of the shotcrete crew. Preconstruction, prequalifying, and acceptance testing of workers, material, and shotcrete are also considered. ACI 506R recommends that cement conform to ASTM C 150 or ASTM C 595. In ASTM C 595, the blending or intergrinding of a pozzolan in which the pozzolan constituent is between 15 and 40% mass of the portland-pozzolan cement is allowed.

### 8.8—Waste management

“Wastecrete” is the term given to the solidification and stabilization of hazardous waste with fly ash or with various combinations of cementitious materials. Hazardous wastes include manufacturing wastes streams, incinerator ash, landfill waste, mine tailings, radioactive wastes, and superfund wastes. Properties associated with this use of fly ashes are:

1. Reduction in permeability;
2. pH adjustment;
3. Pozzolanic activity;
4. Economy;
5. Free water; and
6. Ease of application.

Fly ash immobilizes many toxic heavy metals as relatively insoluble hydroxides or carbonates. This immobilization is accomplished by maintaining a pH in the range between 8 and 12. Other additives are sometimes used to treat the wastes and decrease leachability of various organic compounds. When solidifying hazardous wastes with fly ash, treatability studies should be conducted on the combined wastes and solidifying agents so that appropriate results are obtained (Roy, Eaton, and Cartledge 1991; Roy and Eaton 1992).

“Oilcrete” is a term given to the solidification and stabilization of various oil wastes with fly ash and other solidifying agents. The oil wastes include oil-based drilling fluids, water-based drilling fluids, and listed or unlisted refinery sludges. Fly ash has been used for many years to stabilize oil wastes in Louisiana and Texas; recently, these techniques were modified for use in the Western and Plain states.

In-place treatment of oil-reserve pits is a relatively simple procedure accomplished by mixing fly ash by pneumatic injection or mechanical methods. The oil waste and fly ash mixture hardens to form a low-permeability, solid mass.

Generally, 0.14 MPa (20 psi) will support 10 m (30 ft) of overburden, but some agencies require 1.4 MPa (200 psi), which will necessitate the use of additional fly ash. After stabilization, oilcrete is covered and the natural grade restored.

### 8.9—Cements and lime

The use of pozzolans such as fly ash Class F, Class C, uncalcined natural pozzolan, and calcined natural pozzolans are allowed in the production of cement, the blending of cement, and use with lime. Information in detail can be found in ASTM C 595, ASTM C 1157, and ASTM C 593.

### 8.10—Fillers

There are a number of publications regarding using fly ash/pozzolans as filler in non-concrete applications: asphalt roofing products, cast aluminum, plastics, ceramics, paints, and stone matrix asphalt.

1. *Use of Fly Ash in Asphalt Roofing Products* discusses mineral stabilizer, or filler, as a major raw material requirement in the manufacture of the majority of prepared asphalt roofing products such as shingles (Pike and Shaw 1995);

2. “Microstructure and Properties of Cast Aluminum-Fly Ash Particle Composites” presents the microstructure and selected properties of cast aluminum-silicon alloy matrix-fly ash particle composite (Rohati et al. 1993);

3. “Fly Ashes as Modifiers for Low Cost Polymeric Materials” discusses polymeric materials used in electro-technical field due to their insulation, lightness, and chemical inertia features (Quattroni, Levita, and Marchetti 1993);

4. “Fly Ash a 21st Century Ceramic Filler” discusses how fly ash generated in coal-fired power plants is an abundant mineral resource that has been successfully used in protective coatings as a very hard and inert filler pigment (Mainieri and Growall 1996); and

5. *Guidelines for Materials, Production, and Placement of Stone Matrix Asphalt (SMA)* tells how SMA is a relative new paving mixture in the U.S., which shows promise as a tough, stable, rut-resistant surface mixture in certain applications (IS 118 1994).

### 8.11—Oil-well cementing

The Halliburton Company introduced the use of fly ash in the cementing of wells to the oil industry in 1949. The advantages of using fly ash portland-cement mixtures in wells are fundamentally the same as for concrete, except the conditions of placement and curing are variable and the nomenclature of properties are expressed somewhat differently. In some instances, deep wells have been cemented by mixtures of fly ash and hydrated lime together with an activator that is used as a catalyst for setting (Smith 1956). The fly ash used in oil-well cementing shall conform to ASTM C 618 according to the oil-well cementing industry and American Petroleum Institute (API) “Specification for Material and Testing for Well Cement” (American Petroleum Institute 1990).

## CHAPTER 9—REFERENCES

### 9.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because



these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

*American Association of State Highway and Transportation Officials (AASHTO)*

- T303 Accelerated Detection of Potential Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction

*American Concrete Institute*

- 116R Cement and Concrete Terminology  
 201.2R Guide to Durable Concrete  
 207.5R Roller-Compacted Mass Concrete  
 210R Erosion of Concrete in Hydraulic Structures  
 211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete  
 229R Controlled Low-Strength Materials  
 230.1R State-of-the-Art Report on Soil Cement  
 304R Guide for Measuring, Mixing, Transporting and Placing Concrete  
 318 Building Code Requirements for Structural Concrete  
 325.10R Report on Roller-Compacted Concrete Pavements  
 506R Guide to Shotcrete  
 516R High-Pressure Steam Curing: Modern Practice, and Properties of Autoclaved Products  
 523.3R Guide for Cellular Concrete Above 50 pcf and for Aggregate Concretes Above 50 pcf with Compressive Strengths Less than 2500 psi  
 524R Guide to Portland Cement Plastering  
 548.2R Guide for Mixing and Placing Sulfur Concrete in Construction

*ASTM International*

- C 94 Standard Specification for Ready-Mixed Concrete  
 C 115 Test Method for Fineness of Portland Cement by the Turbidimeter  
 C 150 Standard Specification for Portland Cement  
 C 204 Test Method for Fineness of Portland Cement by Air Permeability Apparatus  
 C 311 Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete  
 C 430 Test Method for Fineness of Hydraulic Cement by the 45- $\mu$ m (No. 325 – 0.0018 inches) Sieve  
 C 441 Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete due to the Alkali-Silica Reaction  
 C 593 Standard Specification for Fly Ash and Other Pozzolans for Use With Lime  
 C 595 Specification for Blended Hydraulic Cements  
 C 618 Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete  
 C 1012 Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

- C 1157 Standard Performance Specification for Hydraulic Cement  
 C 1260 Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)  
 C 1293 Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction

*Electric Power Research Institute*

- SC-2616-SR Workshop Proceedings: Research and Development Needs for Use of Fly Ash in Concrete  
 CS-1318 Electric Utility Use of Fireside Additives  
 CS-3314 Testing and Correlation of Fly Ash Properties with Respect to Pozzolanic Behavior  
 ID-1006565 Coal Ash Carbon Removal Technologies  
 TR-101686 Institutional Constraints to Coal Ash use in Construction

*U.S. Bureau of Reclamation*

- USBR 4908 Length Change of Hardened Concrete Exposed to Alkali Sulfates

*Canadian Standards Association*

- CSA A3000 Cementitious Materials Compendium  
 CSA A23.2-14A Potential Expansivity of Aggregates (Procedure for length change due to alkali-aggregate reaction in concrete prisms)  
 CSA A23.2-25A Test Method for Detection of Alkali-Silica Reactive Aggregates by Accelerated Expansion of Mortar Bars

These publications may be obtained from the following organizations:

American Concrete Institute  
 P.O. Box 9094  
 Farmington Hills, MI 48333-9094

ASTM International  
 100 Barr Harbor Drive  
 West Conshohocken, PA 19428-2959

Electric Power Research Institute  
 Box 50490  
 Palo Alto, CA 94303

U. S. Bureau of Reclamation  
 P.O. Box 25007  
 Denver, CO 80225

Canadian Standards Association  
 5060 Spectrum Way  
 Mississauga, Ontario  
 Canada L4W 5N6

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## **APPENDIX—RAPID QUALITY-CONTROL TESTS**

### **A.1—Loss of ignition**

The test, in accordance with ASTM C 311, involves drying to constant mass for moisture content. If the moisture content is known to be low, however, a quick LOI can be run in less than an hour using a preheated muffle furnace, a crucible providing greater surface area, and a cooling unit that increases heat loss from the sample. In this case, any moisture would be included in the ignition loss value.

### **A.2—Carbon analysis**

Carbon content of fly ash is related to LOI, but it is not a totally comparable measurement. A rapid Leco furnace method is available to make a total carbon determination. Gebler and Klieger (1983) tested a number of Class F and Class C fly ashes using this procedure. In all cases, the carbon determination was somewhat less than the ASTM C 311 LOI, but the correlation between the two test values was very good.

### **A.3—Material retained on 45 $\mu$ m (No. 325 [0.0018 in.]) sieve**

The ASTM C 311 procedure generally involves at least 2 h of drying of the residue on the sieve after the wet-sieving operation. A hot plate or higher oven temperature, however, can be employed to obtain more rapid results; this method is preferred for Class C fly ash to minimize weight gain during drying due to hydration.

Wet sieving of fly ash may produce errors if the fly ash contains significant water-soluble materials or materials that react rapidly with water.

### **A.4—Air-jet sieving**

Alpine air-jet sieve equipment is available that may not provide accurate information because the sieving operation is conducted using air instead of water, and the material retained on the sieve can be weighed directly. Other rapid particle size distribution instruments (such as ATM sonic sieve equipment) are also available that can be employed to indicate changes in the particle size distribution of fly ash.

### **A.5—Air-permeability fineness**

The ASTM C 204 method can be used to measure the specific surface of fly ash within 10 min. Specific surface is not currently specified in ASTM C 618; however, it has been cited in previous versions of the specification. It is a fast procedure that may be used to detect changes in fly ash fineness from given source, particularly changes at the lower end of the size distribution.

### **A.6—Color**

Color changes can be checked by comparing the color of the fly ash with that of a reference fly ash. Spread the two fly ashes side by side on a white surface and compare the color under daylight or a controlled light source. If necessary, a piece of clear glass can be an indicator of change in fly ash properties, and it may cause changes in concrete color—important in architectural uses. A concrete producer can save a jar sample from each fly ash delivery for a period of several

months. A comparison of color of a new delivery with previous deliveries from the same source can provide an immediate indication of changed conditions.

### **A.7—Density (specific gravity)**

Changes in density or the amount of cenospheres that float on water in another fairly rapid procedure that may be used in identifying changes. The density procedure for fly ash referenced in ASTM C 311 is C 188. The measurement can be made in an hour or two; however, excellent temperature control is required for good accuracy.

### **A.8—Foam-index test**

Foam-index values are based on the amount of air-entraining admixture needed in a slurry of 50 mL of water, 4 g of fly ash, and 16 g of cement to produce a layer of foam just covering the surface of liquid in a 473 mL (16 oz) wide-mouthed jar after vigorous shaking (Meininger 1981; Gebler and Klieger 1983). There is a good relationship between the minimum amount of admixture in this test necessary to cause foam to cover the surface, without discontinuities, and the admixture dosage needed in concrete containing the same sources of fly ash and cement.

### **A.9—Organic material**

Analysis of fly ash by the Wakeley-Black soil testing method is one approach that has been used to estimate the easily oxidizable organic matter or carbon in fly ash using sodium dichromate and sulfuric acid (Meininger 1981; Gebler and Klieger 1983). Those fly ashes with greater oxidizable material measured in this manner tended to require higher admixtures demand and caused more loss of air in concrete.

The University of Maryland method used in these fly ash studies provides a value that is increased by a factor to give an estimate of total oxidizable matter. The factor used for soils may not apply to fly ash so the direct amount of oxidized material should be used. Previous work on the effect of organic material in cement also showed that it can have an effect on air entrainment (Greening 1967).

### **A.10—CaO content**

Measurement of heat evolution when fly ash is reacted with an appropriate chemical solution is described by McKerral, Ledbetter, and Teague (1981). In addition to the cited reference, some trials using automated equipment have been used. Future development of this type of equipment may provide indicators of CaO content, which can be obtained in less than 15 min.

### **A.11—Presence of hydrocarbons (startup oil)**

Mix the fly ash with tap water and note the presence of a black film on the surface of the water.

### **A.12—Presence of ammonia (precipitator additive)**

Add 20 to 50 g fly ash to tap water that includes cement or other alkaline material. Cover the bottle and mix. Open the bottle to detect ammonia odor (Ravina 1981).