

Use of Fly Ash in Concrete

Reported by ACI Committee 232

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Fly ash is used in concrete primarily because of its pozzolanic and cementitious properties. These properties contribute to strength gain and may improve performance of fresh and hardened concrete. Use of fly ash often results in a reduction in the cost of concrete construction.

This report gives an overview of the origin and properties of fly ash, its effect on the properties of portland-cement concrete, and the proper selection and use of fly ash in the production of portland-cement concrete and concrete products. The report contains 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. 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 concretes, and recommended procedures for quality assurance. Referenced documents give more information on each topic.

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CHAPTER 1—GENERAL

1.1—Introduction

Fly ash, a by-product of coal combustion, is widely used as a cementitious and pozzolanic ingredient in portland cement concrete. It may be introduced either as a separately batched material or as a component of blended cement. The use of fly ash in concrete is increasing because it improves some properties of concrete, and often results in lower cost concrete. This report describes the technology of 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 the specification and

use of fly ash, along with information on quality control of fly ash and concrete made with fly ash.

According to ACI 116R, fly ash is “the finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases; known in UK as pulverized fuel ash (pfa).” ACI 116R defines “pozzolan” as “a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.” 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 contains pozzolanic materials, however some fly ashes possess varying degrees of cementitious value without the addition of calcium hydroxide or portland cement because they contain some lime.

Fly ash in concrete makes efficient use of the products of hydration of portland cement: (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) the heat generated by hydration of portland cement is an important factor in initiating the reaction of the fly ash. When concrete containing fly ash is properly cured, fly-ash reaction products fill in the spaces between hydrating cement particles, thus lowering the concrete permeability to water and aggressive chemicals (Manmohan and Mehta, 1981). The slower reaction rate of many fly ashes compared to portland cement limits the amount of early heat generation and the detrimental early temperature rise in massive structures. Properly proportioned fly ash mixtures impart properties to concrete that may not be achievable through the use of portland cement alone.

Fly ash from coal-burning electric power plants became available in quantity in the 1930s. In the United States, the study of fly ash for use in portland cement concrete began at about that time. In 1937, R. E. Davis and his associates at the University of California published results of research on concrete containing fly ash (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 portland cement, an expensive component of concrete. However, as the use of fly ash increased, researchers recognized the potential for improved properties of concrete containing fly ash. In subsequent research Davis and his colleagues studied the reactivity of fly ash with calcium and alkali hydroxides in portland-cement paste, and with the ability of fly ash to act as a preventive measure against deleterious alkali-aggregate reactions. Much research (Dunstan, 1976, 1980, and Tikalsky and Carrasquillo,

1992, 1993) has shown that fly ash often affects the resistance of concrete to deterioration when exposed to sulfates. The U.S. Army Corps of Engineers, the Bureau of Reclamation, major U.S. engineering firms, and others recognized the beneficial effect of fly ash on the workability of fresh concrete and the advantageous reduction of peak temperatures in mass concrete. The beneficial aspects of fly ash were especially notable in the construction of large concrete dams (Mielenz, 1983). Some major engineering projects in the United Kingdom, most notably the Thames Barrage, and the Upper Stillwater Dam in the United States, incorporated 30-75 percent mass replacement of portland cement by fly ash to achieve reduced heat generation and decreased permeability.

In the United States, 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 modern power plants, utilizing efficient coal mills and state-of-the-art pyroprocessing technology, produced finer fly ashes with a lower carbon content than those previously available. In addition, fly ash containing higher levels of calcium became available due to the use of new coal sources (usually subbituminous and lignitic). Concurrent with this increased availability of fly ash, extensive research in North America and elsewhere has led to better understanding of the chemical reactions involved when fly ash is used in concrete, and improved technology in the use of fly ash in the concrete industry. Fly ash is now used in concrete for many reasons, including reduced cost, 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 most areas of the United States and Canada, and in many other parts of the world. Fly ash is produced as a by-product of burning coals which have been crushed and ground to a fineness of 70 to 80 percent passing a 75 μm (No. 200) sieve. Approximately 45,000 Gg (50 million tons) of fly ash is produced annually in the United States (American Coal Ash Association, 1992). An estimated 10-12 percent of that total is utilized in the production of concrete and concrete products.

ASTM C 618 categorizes fly ashes by chemical composition, according to the sum of the iron, aluminum, and silica content (expressed in oxide form). Class F ashes are normally produced from coals with higher heat energy, such as bituminous and anthracite coals, although some subbituminous and lignite coals in the western United States also produce Class F fly ash. Bituminous and anthracite coal fly ashes rarely contain more than 15 percent calcium oxide. Subbituminous fly ashes typically contain more than 20 percent calcium oxide, and have both cementitious and pozzolanic properties. There are important differences in performance of fly ashes from different sources. As a group, Class F ashes and Class C ashes generally show different

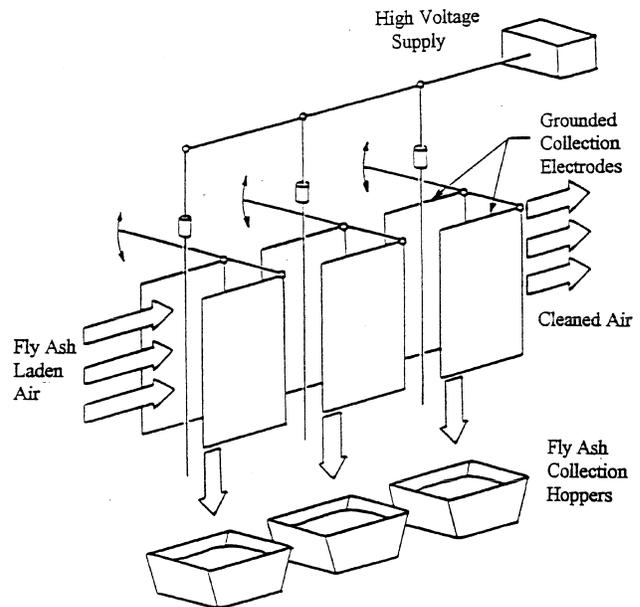


Fig. 1.1—Electrostatic precipitator

performance characteristics; however, the performance of a fly ash is not determined solely by its classification as either Class F or Class C. In general, the sulfate resistance and ability of a fly ash to mitigate the effects of alkali-silica reaction are a function of the coal sources. Strengthening characteristics of a fly ash vary widely depending on the physical and chemical properties of the ash.

1.2.1 Production and processing—The ash contents of coals may vary from 4 to 5 percent for subbituminous and anthracite coals, to as high as 35 to 40 percent for some lignites. The combustion process, which creates temperatures of approximately 1600 C (2900 F) liquifies the unburned minerals. Rapid cooling of these by-products upon leaving the firebox causes them to form spherical particles, with a predominantly glassy structure. Many variables may 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 consistent source generally produce uniform fly ash. However, the fly ash particles vary in size, chemical composition, and density. Sizes may run from less than 1 μm (0.00004 in.) to more than 80 μm (0.00315 in.), and density of individual particles from less than 1 Mg/m^3 (62.4 lb/ft^3) hollow spheres to more than 3 Mg/m^3 (187 lb/ft^3). Collection of these particles from the furnace exhaust gases is accomplished by electrostatic or mechanical precipitators, or by baghouses. A typical gas flow pattern through an electrostatic precipitator is shown in Fig. 1.1.

As the fly ash particles are collected, they segregate in sequential precipitator hoppers according to their size and density; larger/heavier particles tend to accumulate closer to the gas inlet (typically called the “primary”) while the smaller/lighter particles tend to be collected farther from the inlet

(“backpasses”). The fineness, density, and carbon content of fly ash may vary significantly from hopper to hopper.

1.2.2 Beneficiated fly ash—Most fly ash produced from a power plant is of suitable quality for collection and use in concrete. However, if the quality of some or all of the fly ash produced is less than required by specification or market standards, methods may be used to beneficiate the fly ash. The properties which are commonly controlled by beneficiation are fineness and loss on ignition, LOI, (an indicator of carbon content). As noted in 1.2.1 above, segregation occurs in various precipitator or baghouse hoppers. If the control and piping systems in the power plant allow it, fly ash can be selectively drawn from those hoppers which contain the higher quality fly ash.

Mechanical or air-classification equipment may be employed to reduce the mean particle size of fly ash to meet specification or market requirements. Such classifiers effectively remove the denser particles, and may be adjusted to vary the amount of coarser ash removed. Depending on the size, density, and distribution of particles containing carbon, the LOI may be increased, decreased, or unchanged by this classification technique. A typical centrifugal classifier installation (one classifier) could beneficiate 54 to 91 Gg (60,000 to 100,000 tons) of classified material per year.

Technology is now being developed to reduce the carbon content of fly ashes. Electrostatic separation (Whitlock, 1993) and carbon burnout techniques (Cochran and Boyd, 1993) are considered effective in reducing the loss on ignition of fly ash without deleterious effects on its other properties.

CHAPTER 2—FLY ASH COMPOSITION

2.1—General

Fly ash is a complex material consisting 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 phases are typically 60 to 90 percent of the total mass of fly ash with the remaining fraction of fly ash made up of a variety of crystalline phases. These two phases are not completely separate and independent of one another. Rather, the crystalline phases may 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, Class C and Class F. The analytic bulk chemical composition analysis used to determine compliance with ASTM C 618 does not address the nature or reactivity of the particles. This type of analysis is used as a 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 typically 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.

Wide ranges exist in the amounts of the four principal constituents, SiO₂ (35 to 60 percent), Al₂O₃ (10 to 30 percent), Fe₂O₃ (4 to 20 percent), CaO (1 to 35 percent). The sum of the first three constituents (SiO₂, Al₂O₃, and Fe₂O₃) is required to be greater than 70 percent to be classified as an ASTM Class F fly ash, whereas their sum must only exceed 50 percent to be classified as an ASTM Class C fly ash. Class C fly ashes generally contain more than 20 percent of material reported as CaO; therefore the sum of the SiO₂, Al₂O₃, and Fe₂O₃ may be significantly less than the 70 percent Class F minimum limit.

The SiO₂ content of fly ash results mainly from the clay minerals and quartz in the coal. Anthracite and bituminous coals often contain a higher percentage of clay minerals in their incombustible fraction than do subbituminous and lignite coals; therefore the fly ash from the high-rank coals are richer in silica. The siliceous glass is the primary contributor from the fly ash to the pozzolanic reaction in concrete since it is the amorphous silica that combines with free lime and water to form calcium silicate hydrate (C-S-H), the binder in concrete.

The principal source of alumina (Al₂O₃) 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	Na(Al ₅ ,Mg)Si ₁₂ O ₃₀ (OH) ₆ · nH ₂ O
Illite	KAl ₅ Si ₇ O ₂₀ (OH) ₄
Kaolinite	Al ₄ Si ₄ O ₁₀ (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 Al₂O₃ 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 typically contain 40 percent less analytic Al₂O₃ than bituminous fly ashes.

The Fe₂O₃ 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 μm, with the lowest iron contents in particles less than 15 μm.

The source of the materials reported as 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 typically showing less than five percent CaO in the ash. Low-rank coals may produce fly ash with up to 35 percent CaO. The southern lignite coals found in Texas and Louisiana show the least CaO of the low-rank coals, about 10 percent.

The MgO in fly ash is derived from organic constituents, smectite, ferromagnesian minerals, and sometimes dolomite. These constituents are typically minimal in high-rank coals, but may result in MgO contents in excess of 7 percent in fly ashes from subbituminous and northern lignites (lignite coal sources in North Dakota, Saskatchewan, and surrounding ar-

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

	Bituminous	Subbituminous	Northern Lignite	Southern Lignite
SiO ₂ , percent	45.9	31.3	44.6	52.9
Al ₂ O ₃ , percent	24.2	22.5	15.5	17.9
Fe ₂ O ₃ , percent	4.7	5.0	7.7	9.0
CaO, percent	3.7	28.0	20.9	9.6
SO ₃ , percent	0.4	2.3	1.5	0.9
MgO, percent	0.0	4.3	6.1	1.7
Alkalies,* percent	0.2	1.6	0.9	0.6
LOI, percent	3	0.3	0.4	0.4
Air permeability fineness, m ² /kg	403	393	329	256
45 μm sieve retention, percent	18.2	17.0	21.6	23.8
Density, Mg/m ³	2.28	2.70	2.54	2.43

* Available alkalies expressed as Na₂O equivalent.

eas). Southern lignites (from Texas and Louisiana) have MgO contents of less than 2 percent.

The SO₃ in fly ash is a result of pyrite (FeS₂) and gypsum (CaSO₄·H₂O) 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 alkalies 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 Na₂O is found in greater amounts than K₂O in lignite and subbituminous fly ash, but the reverse is true of bituminous fly ash. Expressed as Na₂O equivalent (percent Na₂O + 0.658 x percent K₂O) alkali contents are typically less than 5 percent, but may be as high as 10 percent 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, ignition loss will also include any combined water or carbon dioxide, CO₂, lost by decomposition of hydrates or carbonates that may be present in the ash. Class C fly ashes usually have loss on ignition values less than 1 percent, but Class F fly ashes range from this low level to values as high as 20 percent. Fly ashes used in concrete typically have less than 6 percent LOI; however, ASTM C 618 provides for the use of Class F fly ash with up to 12.0 percent 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 and Carrasquillo, 1992).

2.3—Crystalline composition

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 material in fly ash (Mings et al., 1983; Pitt and Demirel, 1983; McCarthy et al., 1988).

Low-calcium fly ashes are characterized by having only relatively chemically inactive crystalline phases, namely, quartz, mullite, ferrite spinel, and hematite (Diamond, Lopez-Flores, 1981). High-calcium fly ash may contain these four phases plus anhydrite, alkali sulfate, dicalcium silicate, tricalcium aluminate, lime, melilite, merwinite, periclase, and sodalite (McCarthy et al., 1984). 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 X-ray diffraction (XRD) pattern, but this peak is also subject to the most quantitative variability.

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

In its purest form magnetite (Fe₃O₄) 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 into the structure of this phase as an iron replacement. The ferrite spinel phase found in fly ash is not chemically active. Hematite (Fe₂O₃), 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 percent anhydrite (CaSO₄). The calcium

Table 2.2—Mineralogical phases in fly ash

Mineral name	Chemical composition
Thenardite	(Na,K) ₂ SO ₄
Anhydrite	CaSO ₄
Tricalcium Aluminate (C3A)	Ca ₃ Al ₂ O ₆
Dicalcium silicate (C2S)	Ca ₂ SiO ₄
Hematite	Fe ₂ O ₃
Lime	CaO
Melilite	Ca ₂ (Mg,Al)(Al,Si) ₂ O ₇
Merwinite	Ca ₃ Mg(SiO ₂) ₂
Mullite	Al ₆ Si ₂ O ₃
Periclase	MgO
Quartz	SiO ₂
Sodalite structures	Na ₈ Al ₈ Si ₆ O ₂₄ SO ₄ Ca ₂ Na ₆ Al ₆ Si ₆ O ₂₄ (SO ₄) ₂ Ca ₈ Al ₁₂ O ₂₄ (SO ₄) ₂
Ferrite spinel	Fe ₃ O ₄
Portlandite	Ca(OH) ₂

acts as a “scrubber” for SO₂ in the combustion gases and forms anhydrite. Crystalline CaO, sometimes referred to as free lime, is present in most high-calcium fly ashes and may be a cause of autoclave expansion. However, lime in the form of Ca(OH)₂, “slaked lime,” does not contribute to autoclave expansion. Soft-burned CaO hydrates quickly and does not result in unsoundness in concrete. However, hard-burned CaO, formed at higher temperatures hydrates slowly after the concrete has hardened. Demirel et al., (1983) hypothesize that the carbon-dioxide rich environment of the combustion gases cause a carbonate coating to form on poorly burned 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 CaO to cause unsoundness it should be detected as excessive autoclave expansion. Ca(OH)₂ is also present in some high calcium fly ashes that have been exposed to moisture.

Crystalline MgO, periclase, is found in fly ashes with more than two percent MgO. Fly ash from low-rank coals may contain periclase contents as high as 80 percent of the MgO content. The periclase in fly ash is not “free” MgO such as that found in some portland cements. Rather, the crystalline MgO in fly ash is similar to the phase of 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	Ca ₂ Al ₂ SiO ₇
Akermanite	Ca ₂ MgSi ₂ O ₇
Sodium-Melilite	NaCaAlSi ₂ O ₇

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 ashes, and the early stages of the devitrification of Mg-containing glasses. Northern lignites typically have higher MgO contents and lower Al₂O₃ contents than subbituminous-coal fly ashes, allowing the merwinite phase to dominate over the C₃A phase in the northern lignite fly ash. Merwinite is non-reactive at normal temperatures.

The presence of C₃A in high-calcium fly ash was confirmed by Diamond (1982) and others. The intense X-ray diffraction peaks of this phase overlap those of the merwinite phase, making the quantitative interpretation difficult. However, McCarthy et al., (1988) reported that the C₃A phase is the dominant phase in fly ashes with subbituminous-coal sources, and the merwinite phase is dominant in lignite fly ashes. Neither phase is present in low-calcium fly ashes. The cementitious value of C₃A contributes to the self-cementing property of high-calcium fly ashes. The C₃A phase is extremely reactive in the presence of calcium and sulfate ions in solution.

Phases belonging to the sodalite group form from melts rich in alkalis, sulfate, and calcium and poor in silica. Nosean and hauyne compounds have been identified in fly ash by McCarthy et al., (1988). Mather (1980) and others have found tetracalcium trialuminate sulfate (C₄A₃S), the active constituent of Type K expansive cement. C₄A₃S 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 is a crystalline phase which is present in some high-calcium fly ashes and is thought to be reactive in the same manner as C₂S in portland cement. Northern lignite fly ashes often contain crystalline alkali sulfates such as thenardite and apththilite.

2.4—Glassy composition

Fly ash consists largely of small glassy spheres which 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. 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; e.g., anthracite and bituminous or some lignite coals, result in aluminosilicate glassy fly ash particles. Subbituminous and some lignite coals leave larger amounts of calcium in the fly ash and result in calcium aluminosilicate glassy phases (Roy et al., 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 plots 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. It is widely believed that 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

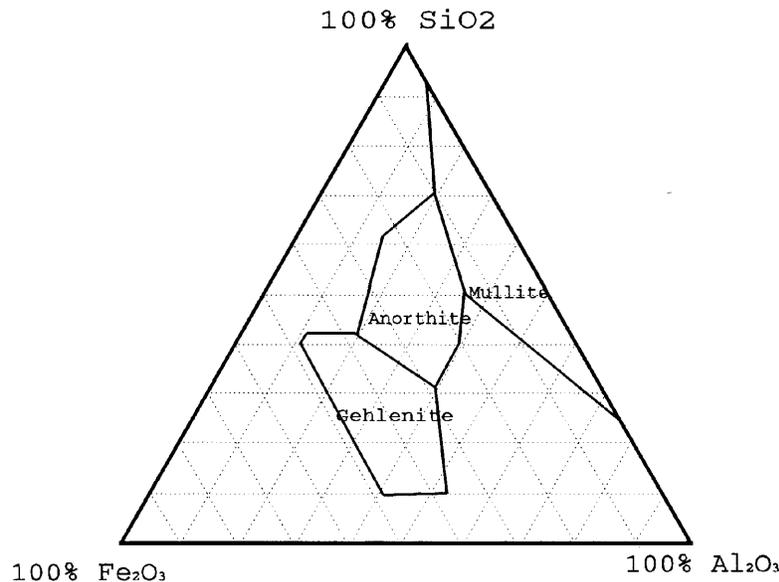


Fig. 2.1— $\text{CaO-SiO}_2 - \text{Al}_2\text{O}_3$ ternary system diagram

the fly-ash glass structure, the less stable the network becomes.

In a simplified model the mass of crystalline compounds can be subtracted from the bulk mass to yield 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 may also be used to illustrate the basic composition of the glassy portion of fly ash. Fly ashes which 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 portland 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 than low-calcium or low-alkali fly ashes.

2.5—Physical properties

The shape, fineness, particle-size distribution, and density of fly ash particles influence the properties of freshly mixed, unhardened concrete and the strength development of hardened concrete. This is primarily due to the particle influence on the water demand of the concrete mixture. 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 en-

gineering concern, unless aesthetic considerations relating to the concrete require maintaining a uniform color in exposed concrete. However, a change in the color of an ash from a particular source may be an indicator of changed properties due to changes in coal source, carbon content, iron content, or burning conditions.

2.5.1 Particle shape—Particle size and shape characteristics of fly ash are dependent upon the source and uniformity of the coal, the degree of pulverization prior to 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. It has been shown that the intergrinding of fly ash with cement 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 which have surface attractions. However, if the mixture of fly ash and cement clinker is ground too fine, water requirements can be increased.

2.5.2 Fineness—Individual particles in fly ash range in size from less than $1\ \mu\text{m}$ to greater than $1\ \text{mm}$. In older plants where mechanical separators are used, the fly ash is coarser than in more modern plants which use electrostatic precipitators or bag filters. In fly ash suitable for use in concrete, ASTM C 618 states that not more than 34 percent of the par-

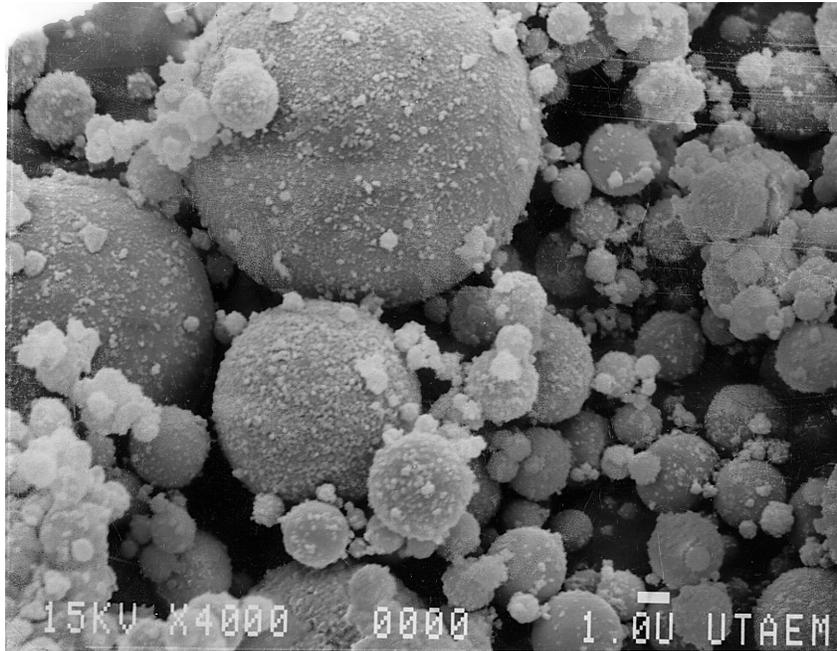


Fig. 2.2—Fly ash at 4000 magnification

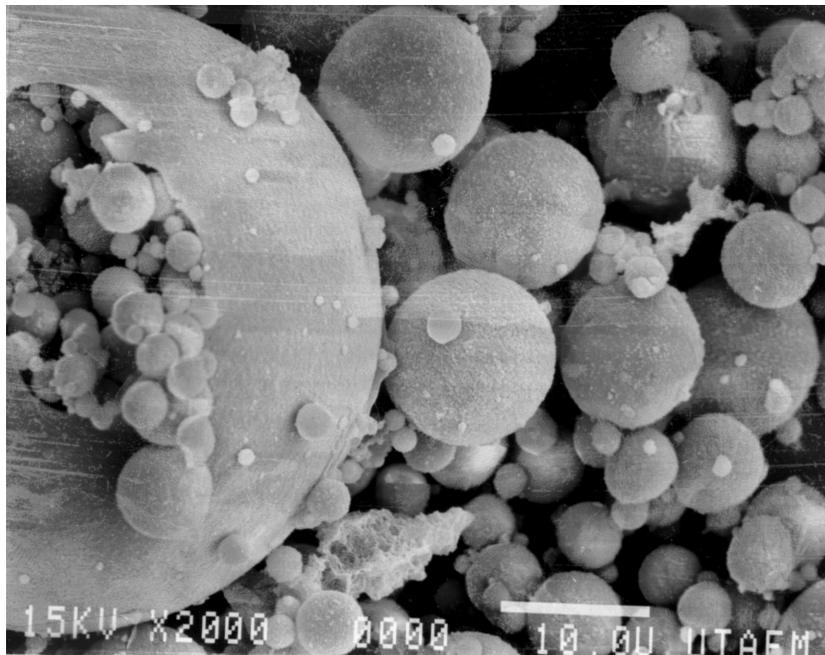


Fig. 2.3—Fly ash showing plerospheres at 2000 magnification

ticles should be retained on the 45- μm (No. 325) sieve. The 45- μm (No. 325) 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 may 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 results of tests by ASTM C 430, 45- μm (No. 325) sieve fineness, as a means to correlate the fineness of Class F fly ash with certain concrete properties.

Their data indicate that for a particular source of fly ash, concrete strength, abrasion resistance, and resistance to freezing and thawing are direct functions of the proportion of the fly ash finer than the 45 μm (No. 325) 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 45- μm (No. 325) sieve procedure 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, and 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 in many cases 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 which may be misleading. Useful information on size distribution of particles finer than 45- μm (No. 325) sieve can be obtained by sonic sifting and by particle sizing equipment based on laser scattering. Data on the particle size distribution of several Class C and Class F fly ashes indicate that a large percentage of particles smaller than 10 μm 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 Mg/m^3 (123 to 188 lb/ft^3), but is normally in the range of 2.2 to 2.8 Mg/m^3 (137 to 175 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 that 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 Mg/m^3 (150 to 175 lb/ft^3).

2.6—Chemical activity of fly ash in portland cement concrete

The principal product 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 hydrate (C-S-H). 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 upon breakdown and dissolution of the glassy structure by the hydroxide ions and the heat generated during the early hydration of the portland cement fraction. The reaction of the fly ash continues to consume calcium hydroxide to form additional C-S-H as long as calcium hydroxide is present in the pore fluid of the cement paste.

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 used 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, et al., 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).

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 calcium hydroxide. This phase distinction is not apparent when research is conducted at room temperature; at room temperature the slower calcium-hydroxide 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 which, 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 portland 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 portland 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 must 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) better understanding of the effects of particle-size distribution
- b) determining the acceptable levels of variation within the chemical and phase composition
- c) clarifying the role of carbon particles as a function of their size and adsorption capability for chemical admixtures
- d) identifying the chemically active aluminate present in some fly ashes that causes such ashes to increase rather than to reduce the severity of sulfate attack on concrete.
- e) determining the minimum effective C ratio of C-S-H as this allows more pozzolanic silica to be converted to C-S-H by combination with a given amount of calcium ion that is released to the pore fluid by the hydration of portland cement. If one uses 60 percent fly ash with 40 percent portland cement will there be enough calcium ion to make useful C-S-H out of all the silica in the cement and in the fly ash?
- f) characterizing of glass phases of fly ash and their effect on pozzolanic properties

CHAPTER 3—EFFECTS OF FLY ASH ON CONCRETE

3.1—Effects on properties of fresh concrete

3.1.1 Workability—The absolute volume of cement plus fly ash normally exceeds that of cement in similar concrete

mixtures not containing fly ash. This is because the fly ash normally is of lower density and the mass of fly ash used is usually equal to or greater than the reduced mass of cement. While it depends on the proportions used, this increase in paste volume produces a concrete with improved 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 which 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- μ m (EPRI CS-3314), which favorably influences concrete workability. Data on the rheology of fresh fly ash-cement-water mixtures was 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 greater surface area of solid particles and 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 may extend the time of setting of concrete if the portland cement content is reduced. Jawed and Skalny (1981) found that Class F fly ashes retarded early C_3S hydration. Grutzeck, Wei, and Roy (1984) also found retardation with Class C fly ash. The setting characteristics of concrete are influenced by ambient and concrete temperature; cement type, source, content, and fineness; water content of the paste; water soluble alkalis; use and dosages of other 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 setting can usually be obtained. The actual effect of a given fly ash on time of setting may be determined by testing when a precise determination is needed or by observation when a less precise determination is acceptable. Pressures on form work may 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—When fly ash concrete has a longer time of setting than concrete without fly ash, such mixtures should be finished at a later time than mixtures without fly ash. Failure to do so could lead to premature finishing, which can seal the bleed water under the top surface creating a

plane of weakness. Longer times of setting may 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 may lead to an unacceptable appearance. Some situations are encountered when 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 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 rate of the air-entraining admixture. Some fly ashes with LOI values less than 3 percent require no appreciable increase in air-entraining admixture dosage. Some Class C fly ashes may reduce the amount of air-entraining admixture required, particularly for those with significant water-soluble alkalis in the fly ash (Pistilli, 1983). To maintain constant air content, admixture dosages must usually be increased, depending on the carbon content as indicated by LOI, fineness, and amount of organic material in the fly ash. When using a fly ash with a high LOI, more frequent testing of air content at the point of placement is desirable to maintain proper control of air content in the concrete.

Required air-entraining admixture dosages may increase with an increase in the coarse fractions of a fly ash. In one laboratory study, separate size fractions of a fly ash were used in a series of mortar mixtures with only one size fraction per mixture. The finer fractions required less air-entraining admixture than the total ash sample (Lane, 1983). The coarse fraction usually contains a higher proportion of carbon than the fine fraction. The form of the carbon particles in fly ash may be very similar to porous activated carbon, which is a product manufactured from coal and used in filtration and adsorption processes. In concrete, these porous particles can adsorb air-entraining admixtures, thus reducing their effectiveness (Burns, Guarnashelli, and McAskill, 1982). Adjustments must be made as necessary in the admixture dosage to provide concrete with the desired air content at the point of placement.

Meininger (1981) and Gebler and Klieger (1983) have shown that there appears to be a relationship between the required dosage of air-entraining admixture to obtain the specified air content and the loss of air in fly ash concrete with prolonged mixing or agitation prior to placement. Those fly ashes that require a higher admixture dosage tend to suffer 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 and to provide information necessary to adjust properly 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 is encountered. Agitation of the concrete is a prerequisite for loss of air to continue.

In one investigation dealing with air entrainment (Gebler and Klieger, 1983), the retention of air over a 90-min period in different fly ash concretes ranged from about 40 to 100

percent, 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 percent. The spacing factor increased somewhat, but not above the accepted limit of 0.20 mm (0.008 in.).

The loss of air depends upon 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). Neutralized Vinsol resin air-entraining admixtures did not perform well with fly ashes having high LOI values. For a given fly ash, the most stable air content was achieved with the cement-fine aggregate combinations that had the highest air-entraining admixture requirement. On the other hand, a change in fly ash that requires a higher admixture dosage to obtain the specified air content is more likely to cause loss of air if the mixture is agitated or manipulated for a period of time. High loss on ignition of fly ash is often, but not always, an indicator of the likelihood of air-loss problems; so far, the problem seems to be confined to the lower CaO, Class F fly ashes.

The foam-index test (see Appendix) is a rapid 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 useful to predict needed changes in the amount of admixture, and if the foam-index value increases by a large amount, it is an indicator that loss of air during delivery and placement should be checked. For quality-control purposes a procedure can be adapted from the references (Meininger, 1981; Gebler and Klieger, 1983) which, 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—Strength at any given age and rate of strength gain of 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). The relationship of tensile strength to compressive strength for concrete with fly ash is not different from that of concrete without fly ash. Compared with concrete without fly ash proportioned for equivalent 28-day compressive strength, concrete containing a typical Class F fly ash may develop lower strength at 7 days of age or before when tested at room temperature (Abdun-Nur, 1961). If equivalent 3-day or 7-day strength is desired, it may be possible to provide the desired strength by using accelerators or water-reducers, or by changing the mixture proportions (Bhardwaj, Batra, and Sastry, 1980; Swamy, Ali, and Theodor-Akopoulos, 1983). Test results indicate that silica fume can be used, for example, in fly ash concrete to increase the early-age 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 ion 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 to reduce the water to cementitious material ratio to at least as low as 0.28.

After the rate of strength contribution of portland cement slows, the continued pozzolanic activity of fly ash contributes to increased 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 higher rate of 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 a reference, Lane and Best (1982) reported strength increases of 50 percent at one year for concrete containing fly ash, as compared with 30 percent 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. 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- μm (No. 325) sieve. 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 portland cement on an equivalent-mass basis. However, certain Class C fly ashes may not show the later-age strength gain typical of Class F fly ashes. The effect of 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 Class C fly ash is shown in Fig. 3.2.

Both Brink and Halstead (1956) and Mather (1958) showed that changes in cement source may change concrete strengths with Class F fly ash as much as 20 percent. For example, cements with alkali contents of 0.60 percent Na_2O equivalent or more typically perform better with fly ash for strength measured beyond 28 days. However, when potentially alkali-reactive aggregates are used in concrete, low-alkali cement should be used, even if fly ash is also used.

3.2.2 Modulus of elasticity—Lane and Best (1982) report that the modulus of elasticity of Class F fly ash concrete, as well as its compressive strength, is somewhat lower at early ages and a little higher at later ages than similar concretes without fly ash. The effects of fly ash on modulus of elasticity are not as significant as the effects of fly ash on strength. Fig. 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 elas-

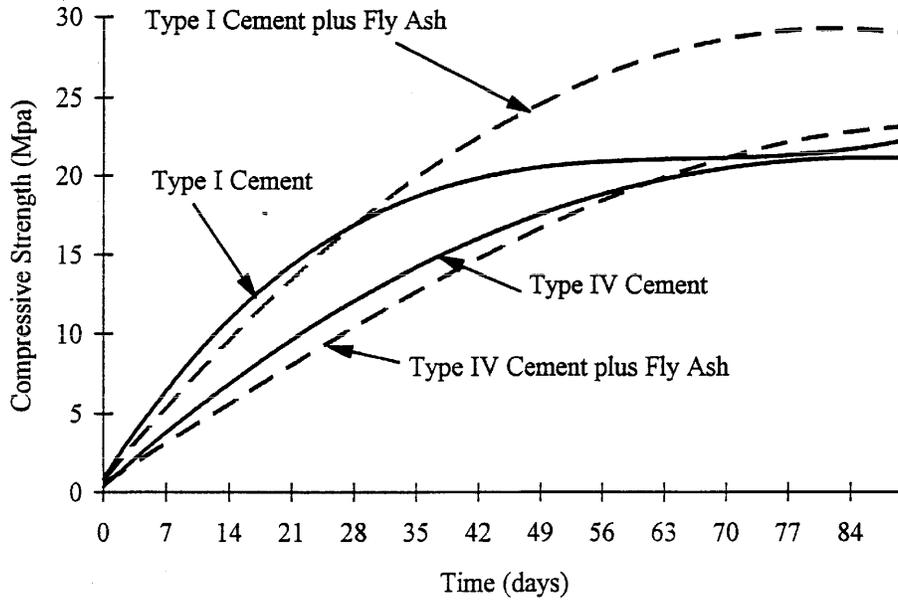


Fig. 3.1—Rate of strength gain for different cementitious materials: Class F fly ash (Samarin, Munn, and Ashby 1983)

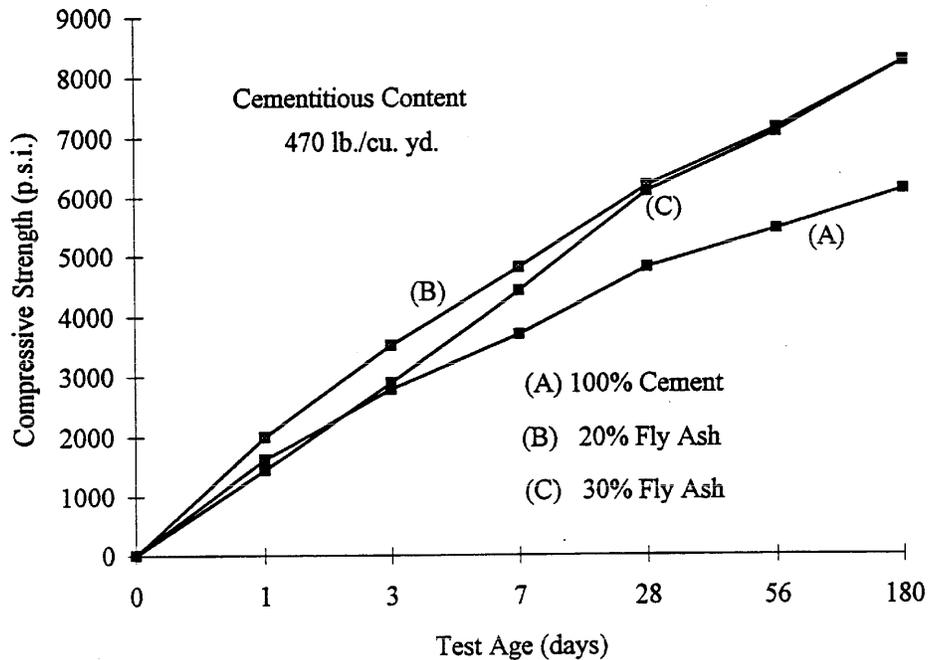


Fig. 3.2—rates of strength gain of portland cement concrete and concrete in which part of the cement is replaced pound-for-pound with a Class C fly ash (Cook 1983)

ticity 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).

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 loaded, and the ratio of the sustained 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. Concrete with a given volume of cement plus fly ash loaded at ages of 28 days or less to a constant stress will normally exhibit higher creep strain than concrete having an equal volume of cement only, due to the lower strength of fly ash concrete at the time of loading (Lane and Best, 1982). However, both Lane and Best (1982) showed that concrete with fly ash proportioned to have the same strength at the age of loading as concrete without fly ash pro-

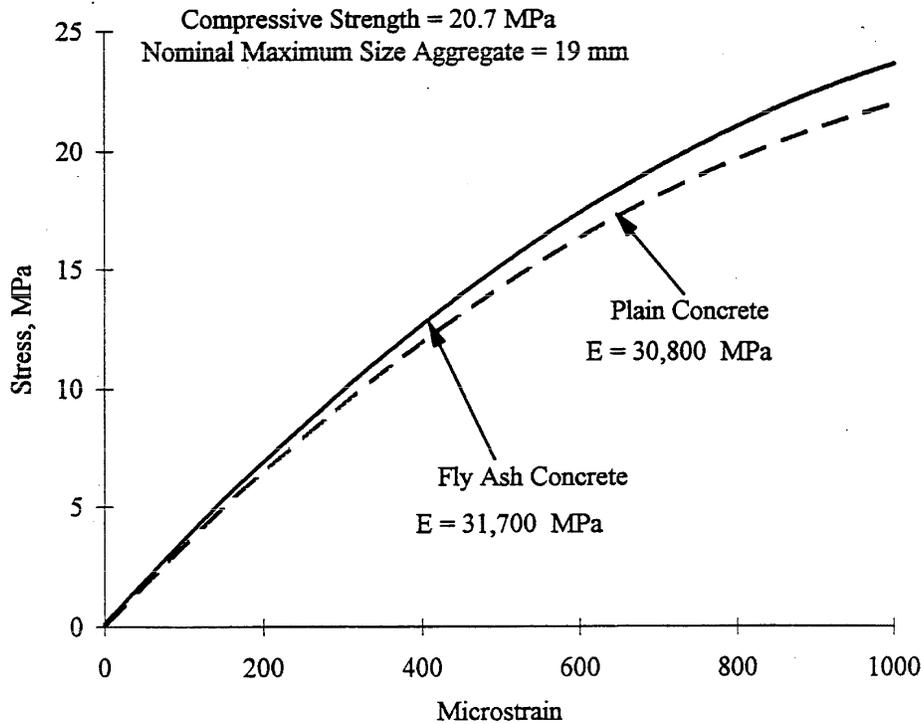


Fig. 3.3—Stress-strain relationship at 90 days (TVA Technical Report CR-81-1)

duced 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 also loaded at 1 year, creep strain values for concrete containing fly ash were only half those measured for concrete without fly ash.

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

3.2.4 Bond of concrete—The bond or adhesion of concrete to steel is dependent on the surface area of the steel in contact with the concrete, the location of reinforcement, and the density of the concrete. Fly ash usually will increase paste volume and may reduce bleeding. Thus, the contact at the lower interface where bleed water typically collects may be increased, resulting in improved bond. Development length of reinforcement in concrete is 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 bond of concrete to steel are based on extrapolation of what is known about concrete without fly ash. The bonding of new concrete to old is little 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. Use of fly ash affects the impact resistance only to the extent that it improves ultimate compressive strengths.

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, 210R). At equal compressive strengths, properly finished and cured concretes with and without fly ash will exhibit essentially equal resistance to abrasion.

3.2.7 Temperature rise—The chemical reaction of cement with water generates heat, which has an important bearing on the rate of strength development 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 C_3S) and C_3A phases of the cement. The rate of hydration and heat generation depends on the quantity, fineness, and type of the cement, the mass of the structure, the method of placement, the temperature of the concrete at the time of placement, and the curing temperature. The temperature rise 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 3, 7, 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 percent by mass of the cementitious material were reported (Mather, 1974) and are given in Table 3.1. However, some Class C fly ashes do contribute to early temperature rise in concrete (Dunstan, 1984). When heat of hy-

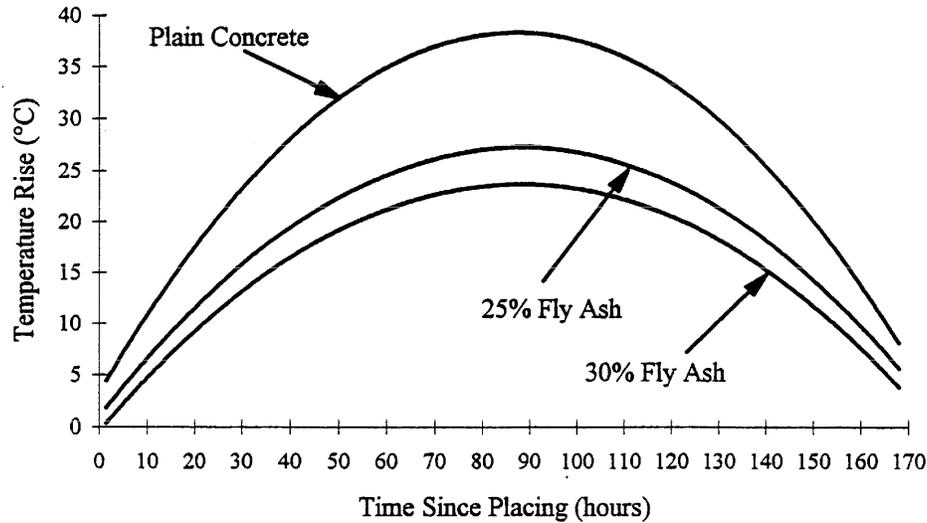


Fig. 3.4—Variation of temperature with time at the center of 15 cubic meter concrete blocks (Samarin, Munn, and Ashby, 1983)

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

Fly ash, percent 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

dration 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, Carette, 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 upon 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). Because of the often slower strength gain of concretes with Class F fly ash, more cementitious material (cement plus fly ash) may be used in mixtures to achieve comparable strength at 28 days.

Care should be exercised in proportioning mixtures to insure that the concrete has adequate strength when first exposed to cyclic freezing and thawing, that is, about 24 MPa (3500 psi) or more. When compared on this basis in properly air-entrained concrete, investigators found no significant difference in the resistance to freezing and thawing of concretes

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 interconnecting void 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 et al., (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 to cementitious materials ratio and time. Required time ranged from 3 days at a water to cement ratio of 0.40 to 1 year at a water to cement ratio of 0.70.

Calcium hydroxide 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 calcium hydroxide and water to produce C-S-H, thus reducing the risk of leaching calcium hydroxide. Additionally, the long-term reaction of fly ash refines the pore structure of concrete to reduce the ingress of chloride ions. As a result of the refined pore structure, permeability is reduced (Manmohan and Mehta, 1981; and EPRI CS-3314).

Despite concern that the pozzolanic action of fly ash could reduce the pH of concrete, researchers have 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.

3.2.11 Reduction of expansion caused by alkali-silica reaction (ASR)—The reaction between the siliceous glass in

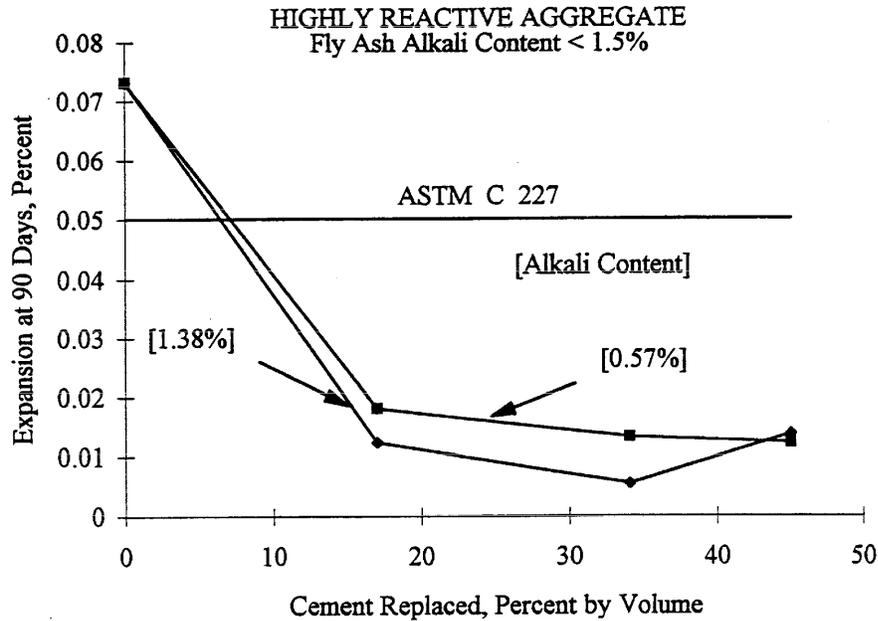


Fig. 3.5a—Mortar bar expansion versus percentage of cement replaced for all highly reactive aggregate mixtures containing fly ash with less than 1.5 percent alkalis

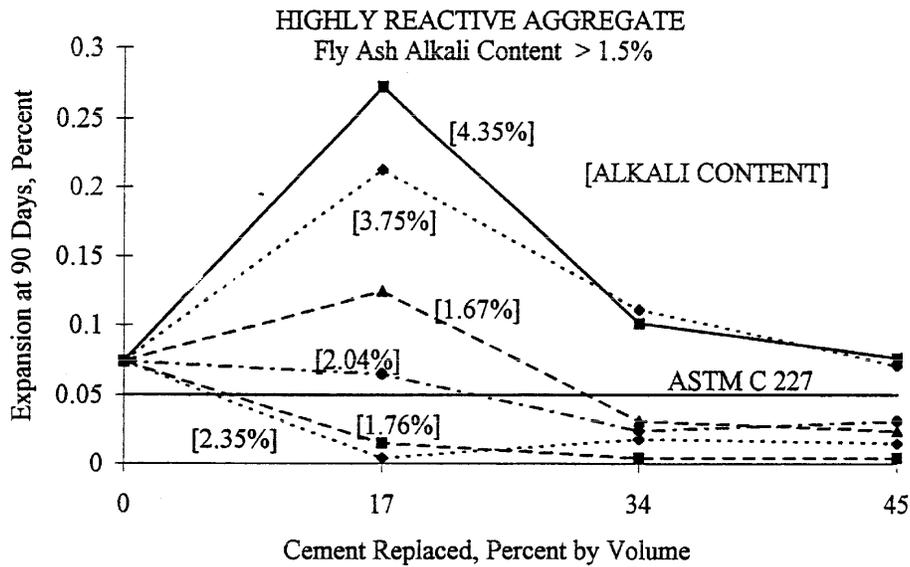


Fig. 3.5b—Mortar bar expansion versus percentage of cement replaced for all highly reactive aggregate mixtures containing fly ash with more than 1.5 percent alkalis

fly ash and the alkali hydroxides in the portland-cement paste consumes alkalis, 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). Data for mixtures containing eight different fly ashes with a cement of 0.66 percent Na₂O equivalent and a highly reactive aggregate are shown in Fig. 3.5a and 3.5b. Often the amount of fly ash necessary to prevent damage due to alkali-aggregate reaction will be more than the optimum amount neces-

sary for improvement in strength and workability properties of concrete. Fig. 3.5b illustrates the phenomena 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. 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 alkali-silica reaction in concrete containing fly ash when reactive aggregates are used include: (a) use of a pozzolan meeting ASTM C 618 in

a sufficient amount to prevent excessive expansion, or (b) the use of blended cement demonstrated to control ASR expansion using ASTM C 595 and C 1157 (Portland Cement Association, 1994). Several recent case studies of alkali-silica reactions in concrete suggest that some aggregates that pass the current ASTM limits may cause deleterious reactivity in the course of a number of years, even with low-alkali cement (Farbiaz and Carrasquillo, 1987; Snow, 1991). Therefore, Class F fly ash at 20-25 percent mass replacement may be used as a general preventive measure.

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 hydroxides in concrete to continue to form additional calcium silicate hydrate (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. K. Mather (1982) found that several Class C fly ashes used at 30 percent replacement of several high C₃A cements made the system less sulfate resistant. Tikalsky and Carrasquillo (1992, 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 which 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 C₃A (tricalcium aluminate) 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 concretes made with all types of cement. The cements 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 percent.

The sulfate resistance of fly ash concrete is influenced by the same factors which affect concrete without fly ash: curing conditions, exposure, and water-to-cementitious material ratio. The effect of fly ash on sulfate resistance will be dependent upon 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 percent (CaO percent-5 percent) to the percentage iron oxide (Fe₂O₃) in a fly ash, based

on the bulk chemical analysis. More recent research (Mehta, 1986; Tikalsky and Carrasquillo, 1993) 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 not as strongly influenced by Fe₂O₃ as indicated by the R factor. Generally, ASTM C 618 fly ashes with less than 15 percent 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 water-cementitious materials ratio, sulfate-resisting portland cement, and fly ash which exhibits good sulfate-resistance qualities. In attempting to select the fly ash which 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 blended cement, sets a limit on expansion at 6 months (tested in accordance with C 1012) of 0.10 percent for moderate sulfate resistance and 0.05 percent for high sulfate resistance. Fly ashes with large amounts of chemically active alumina may adversely affect sulfate resistance.

3.2.13 Drying shrinkage—Drying shrinkage of concrete is a function of the fractional volume of paste, the water content, cement content and type, and the type of aggregate. In those cases 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 percent 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 calcium hydroxide and other salts to external concrete surfaces. The leached calcium hydroxide reacts with carbon dioxide in air to form calcium carbonate, the source of the white discoloration on concrete. The use of fly ash in concrete can be effective in reducing efflorescence by reducing permeability. This reduced permeability helps maintain the high alkaline environment in hardened concrete. However, certain Class C fly ashes of high alkali and sulfate contents may increase efflorescence.

3.2.15 Deicing scaling—Scaling of concrete exposed to deicing salts occurs when immature or nonair-entrained concrete pavements are exposed to large quantities of deicing salts in a freezing and thawing environment. Concrete pavements containing fly ash that are exposed to deicing salts should be air entrained and allowed to reach a specified strength or maturity. There is some laboratory research that indicates concrete containing 40 percent fly ash, as a percentage of the total mass of cementitious material, may be more susceptible to scaling (Gebler and Klieger, 1986; Ern-

zen and Carrasquillo, 1992; Johnston, 1994). Additional research is needed in this area.

CHAPTER 4—CONCRETE MIXTURE PROPORTIONING

4.1—General

The most effective method for evaluating the performance of a given fly ash in concrete and establishing proper mixture proportions for a specific application is by use of a trial batch and testing program (ACI 211.1). Because different fly ashes have different properties and concrete requirements differ, proportions for a given fly ash and cement 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 percent by mass of total cementitious material. Larger proportions of fly ash may be used for mass concrete to reduce the likelihood of cracking upon cooling, to improve sulfate resistance, to control alkali-aggregate reaction, or they may be used in other special applications (Malhotra, 1984; Haque et al., 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 within the range provided 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. When fly ash blended cement is obtained under ASTM C 1157 one may order it 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 must be selected, and their relative ratio should be adjusted as appropriate for each job situation.

It is usually possible to proportion concrete mixtures for a particular strength level with a blend of cement and fly ash in which the 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), and others have suggested methods of proportioning concrete containing fly ash with and without chemical admixtures. When fly ash is used, indications are that the total volume of cementitious material used (cement plus fly ash) must exceed the volume of cement used in cement-only mixtures to produce equal early strength and equal slump. The total mass of the cementitious material and the optimum proportion of fly ash selected de-

pend 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; Majko and Pistilli, 1984).

The optimum use of fly ash and chemical admixtures often requires that adjustments be made in the ratio of cement to fly ash 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 since higher curing temperatures tend to increase the relative strength of fly-ash concrete compared to non-fly ash concrete at all ages, especially if long-term curing is provided.

Because use of fly ash normally contributes additional volume to the concrete, certain adjustments must be made to proportions. When 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-void system. Ordinarily, a small reduction in the mixing water demand can be expected when fly ash is used.

Most specifying agencies and concrete producers compute an equivalent water-cement ratio (w/c) for fly ash concrete by adding the cement + pozzolan by mass to get a water to total cementitious material ratio by mass. This ratio is sometimes called the water to binder ratio (ACI 363R). This is a consistent approach since the fly ash in a blended cement meeting ASTM C 595 will be counted as part of the cement. In those cases where a maximum water-cement ratio 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 water-cementitious material ratio to use in air-entrained concrete to attain frost resistance of concrete, it may be advantageous to specify that a strength level, such as 24 MPa (3500 psi) as stipulated in ACI 308, be obtained prior to exposing the concrete to 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 et al., 1959; Buck and Thornton, 1967). This is the same approach used in the ACI Building Code (ACI 318) for concrete with lightweight aggregate, since it is difficult to calculate accurately the water to cementitious material ratio in such mixtures.

Similar to non-fly ash concrete, the water requirements of concrete containing fly ash may be reduced by 5 to 10 percent by using conventional water-reducing admixtures. Data reported by Vollick (1959) indicate that the amount of water reduction obtained in concrete incorporating fly ash may 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 may lead to water

reductions of 15 to 40 percent. 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. Cementitious material contents in excess of 385 kg/m^3 (650 lb/yd^3) usually are required for 20 percent 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

5.1—Introduction

The ASTM specification for fly ash is ASTM C 618, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland-Cement Concrete, and the standard sampling and test methods are in ASTM C 311, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete. These standards are under the jurisdiction of ASTM Committee C-9. ASTM C 618 was originally published in 1968 to combine and replace C 350 on fly ash and C 402 on other pozzolans for use as mineral admixtures. Standard C 311 for sampling and testing was published originally 1953. It is recommended that specifiers of fly ash use the latest edition of these standards. 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. The Canadian Standards Association has a published standard for fly ash (CAN/CSA - A 23.5 - M 86). This standard is very similar to ASTM C 618, with exceptions which will be noted in the following discussions.

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

ASTM C 618 states that Class F is "normally produced from burning anthracite or bituminous coal;" and Class C is "normally produced from lignite or subbituminous coal." Many power plants blend various types of coals for power generation. Some fly ashes produced from subbituminous coals and lignite meet all the physical and chemical requirements of Class F are thus marketed as Class F. Most Class F fly ashes meet the ASTM C 618 physical and chemical requirements for Class C.

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, ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) (Manz, 1983). The intent is to assure that sufficient reactive glassy constituents are present. A lower requirement is necessary for Class C since the calcium oxide content may be substantial, thus making it impossible in some cases for the sum of ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) to be 70 percent 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 percent range; however, four of the five fly ashes contained more than 70 percent ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) 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 (SO_3) in fly ash. ASTM C 618 has a limit of 5.0 percent for both classes; other specification limits range from 2.5 to 12.0 (Manz 1983). The sulfate in fly ash can affect the optimum amount of fly ash needed for maximum strength development and acceptable setting time 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 which could contribute to harmful sulfate attack.

Limits on moisture content of fly ash are necessary to insure proper handling characteristics. Also, many Class C fly ashes will begin to hydrate in the presence of moisture. ASTM C 618 limits moisture to 3.0 percent.

The maximum allowable loss on ignition in ASTM C 618 is 6.0 percent for both Class C and Class F fly ashes. CAN/CSA-A 23.5-M allows 12 percent for Class F and 6 percent for Class C. Some specifiers modify this limit to a value lower than 6 percent, particularly where air-entrained concrete is involved. The great majority of fly ashes from base-load power plants are well below 6 percent loss on ignition, due mainly 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 Class F fly ash with up to 12 percent loss on ignition when acceptable laboratory or performance data are available.

Specification ASTM C 618 contains an optional chemical requirement on amount of available alkalis, expressed as equivalent Na_2O . This requirement limits the available alkalis in Class F and Class C fly ashes to 1.5 percent maximum. However, fly ash with available alkalis greater than 1.5 percent may be used with reactive aggregate if laboratory tests show that deleterious expansion does not occur. These requirements are not appropriate unless the concrete will be made using reactive aggregates or unless it is known that higher alkali levels interact adversely with chemical admixtures (Halstead, 1981).

5.3—Physical requirements

Fly ash fineness is controlled in most cases by limiting the amount retained on the 45- μm (No. 325) sieve by wet sieving. Reactivity of fly ash has been found to be related directly to the quantity passing this sieve since the coarser particles generally do not react rapidly in concrete. ASTM C 618 limits the amount retained to 34 percent for both Class F and Class C fly ashes. 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 the fly ash. It does not necessarily bear any relation to the optimum proportion of fly ash for use in concrete. The alternative strength activity index with hydrated lime at 7 days has recently been dropped from ASTM C 618 because it is not widely regarded as a significant indicator of quality. However, tests conducted on consecutive samples of a given source of fly ash by a single laboratory using a single source of lime correlate well with the results of other qualification tests.

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 Canadian Standard CSA-A23 S-M specifies curing at 65 C (149 F) for 7 days.

Other specified and optional physical properties include:

1. Water requirement of the mortar used in the strength activity test to assure that fly ash does not cause a large increase in mixing water demand.

2. Soundness by measuring autoclave expansion or contraction. A length change of 0.8 percent is the maximum allowed by ASTM C 618 for both fly ash classes. It is required that if the fly ash will constitute more than 20 percent of the cementitious material in the proposed concrete, the paste used for autoclave testing shall contain the anticipated percentage of fly ash. The test protects against the delayed expansion that could 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, SO_3 content, and concrete strength in their laboratory study.

3. Variability limits are given in ASTM C 618. Limits are specified for both Class F and Class C fly ashes to keep the variation of specific gravity and fineness of the fly ash within practical limits for shipments over a period of time. Also, for fly ash used in air-entrained concrete there is an optional limit on the permitted variation of demand for air-entraining admixture caused by variability of the fly ash source. These limits are invoked to restrain the variability of properties of concrete containing fly ash.

Table 5.1—Relationship between particle size and surface area

Mean particle diameter μm	Surface area, m^2/m^3	Equivalent surface area, m^2/kg at various densities			
		2.0 Mg/m^3	2.5 Mg/m^3	3.0 Mg/m^3	3.15 Mg/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

4. The optional Multiple Factor, applicable only to Class F, is calculated as the product of LOI (percent) and amount retained on the 45- μm (No. 325) sieve (percent). The maximum value of 255 restricts sieve residue (less than 34 percent) only when the loss on ignition exceeds 6 percent.

5. Increase in drying shrinkage of mortar bars at 28 days. This limit is 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.

6. Reactivity with alkalis. Optional mortar-bar expansion tests can be requested if a fly ash is to be used with an aggregate regarded to be deleteriously reactive with alkalis. Fly ash has been recommended for use in concrete to reduce the damage from alkali-silica reaction (Snow, 1991). ASTM C 618 limits the actual expansion of potentially reactive aggregate/paste combinations, whereas CSA-A 23.5-M determines the effect of fly ash in reducing expansion as compared to portland cement only samples.

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 and that 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 procedures to be used for sampling and testing fly ash. For a number of test procedures, reference is made to other cement, mortar, or concrete tests for the body of the test procedure, with ASTM C 311 indicating the modifications in proportions, preparation procedures, or test parameters needed to accommodate fly ash testing. The three main divisions of the standard are sampling methods, chemical analysis methods, and physical test procedures.

Either individual grab samples or composite samples may be used depending on the circumstances. The method provides detailed procedures for sampling from: (1) conveyor delivering to bulk storage, (2) bulk storage at points of discharge, (3) bulk storage by means of sampling tubes, and (4) railroad cars or trucks.

Chemical test procedures involve determining moisture content by drying to constant mass and then determining the LOI. The latter requires igniting the dried sample to constant mass in a muffle furnace at 750 ± 50 C using an uncovered porcelain crucible (not a platinum crucible as used for cement testing). Many of the required chemical determinations are then made using procedures which are the same as, or very similar to, those used in testing portland cement.

Physical tests on fly ash include density and amount retained on the 45- μm (No. 325) sieve determined using the test methods developed for portland cement. Soundness and strength activity testing procedures are included in ASTM C 311 with reference to cement testing procedures where appropriate.

Of all the tests conducted, the two which are most difficult to obtain credible, repeatable, results are fineness and strength activity with lime. In the fineness test, test sieves are not precisely manufactured to exactly 45 μm . The standard procedure calls for calibrating sieves using a portland cement reference sample, and computing a correction factor for the sieve. Since the fly ash particles retained on the test sieve tend to be much larger than 45 μm , large correction factors give inaccurate results. Sieves with small correction factors give more accurate results. In the strength activity index test with lime, results are highly dependent on the lime used by the laboratory. Since the performance of the lime 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

A company selling fly ash intended to be in conformance with ASTM C 618 should have 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 six months of testing is recommended. This quality history should include monthly ASTM C 618 certification as well as at least 40 individual test results for loss on ignition, 45- μm (No. 325) sieve residue, specific gravity, and 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, 1981). After the quality history is established, the source should be tested at least monthly to assure continued conformance to ASTM C 618.

A quality control program should be established for each individual source. Such programs may vary with coal type, collection systems, and other factors. The important characteristics of the particular source of fly ash should be determined and a quality control program established for that source taking into account those characteristics and the requirements of specifications for its use in concrete. Testing for critical requirements may be needed more frequently

than prescribed in ASTM C 311. For example, critical characteristics of fly ashes may include: loss on ignition, fineness, color, or SO_3 . However, all fly ashes may not have the same critical characteristics nor may all these characteristics need to be included in regular testing programs. Samples may also be taken periodically and stored in the event that future testing and evaluation is desirable.

An effective quality control program allows the fly ash supplier to maintain test reports on the fly ash for demonstration of product compliance with regard to the physical, chemical, and variability requirements of ASTM or other special project performance requirements, as well as to monitor variability of critical characteristics. Statistical evaluations of the test data provide the supplier with information on long-term variations.

ASTM C 311 provides for tests to be conducted on fly ash samples representing not more than 360 Mg (400 tons) for certain tests and not more than 1800 Mg (2000 tons) for others. 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 determining its suitability for a desired end use or directing it to waste disposal (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 may influence fly ash quality. The chemical composition and fineness of fly ash from one source 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 its properties and the variation of these 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, loss on ignition, and autoclave expansion (Minnick, Webster, and Purdy, 1971). Significant properties of Class C fly ash that affect performance in concrete include fineness, loss on ignition, autoclave expansion, and the amounts of SO_3 , CaO, and alkalis present. Variability of fly ash color should also be monitored since changes in color may be of importance for architectural concrete applications. Fly ash color may also indicate changes in carbon content or power plant burning conditions, which may alter the performances of the fly ash, especially in air-entrained concrete.

McKerall, Ledbetter, and Teague (1981) have developed regression equations for fineness and specific gravity of fly ashes produced in Texas from subbituminous coal and lig-

nite. 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 μm (No. 200) sieve test and a CaO heat evolution test described in the Appendix.

5.7—Start-up, oil, and stack additives

The fly ash distributor and user should be aware of changes in the ash properties that may 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 start-up (Ravina, 1981). Changes in burning and fly ash collection procedures at the power station may 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 may 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 to divert questionable quality fly ash to waste disposal. When a coal-boiler unit is first fired, oil is often used to help initiate combustion, and the ash may contain hydrocarbon residues from the oil. In power plants where this is done during start-up 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 concrete which is not air-entrained 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 SO_3 emissions, reduce corrosion and fouling, and to 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” (EPRI FP-910). 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, alkalies, or SO_3 . Prior to the use of 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 must be made fairly rapidly concerning the probable quality of the fly ash so that material that does not meet requirements may be designated for other uses or directed to waste disposal. Some of the properties specified

in ASTM C 618 as well as 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, if needed.

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. Depending on the objective of the testing they may be used by the fly ash marketer 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
2. Carbon content
3. 45- μm (No. 325) sieve fineness
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. Hydrocarbons
12. Ammonia

CHAPTER 6—FLY ASH IN CONCRETE CONSTRUCTION

6.1—Ready-mixed concrete

A survey of the ready-mixed concrete industry in the United States in 1989 indicated that, of the companies who responded to the questionnaire, 92 percent use at least some fly ash compared to 31 percent in 1983 (Justman, 1991). Approximately 55 percent of the concrete produced contained fly ash; as compared to 46 percent in 1983. Some of the 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 industry standards in the United States 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. This takes advantage of the capacity of concrete containing fly ash to pump higher and further at faster rates, and with less segregation. Ready-mixed concrete containing Class C fly ash was successfully pumped on a 75-story office tower in Houston, Texas (Cook, 1982).

Very high strengths, up to 100 MPa (14,000 psi) in the field and higher in the laboratory, have been used with cer-

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

Albinger (1984) has stated that the decision to use or not use fly ash should be based on four factors: fly ash properties; effectiveness of the quality control program of the supplier; ability to adjust to concrete changes, such as delayed finishability and increased air-entraining admixture demand; and cost effectiveness. The cost of additional equipment to store and batch fly ash is an expense which 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 control and logistic problems relating to the use of fly ash in concrete. 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 United Kingdom considering the incorporation of fly ash in pavement concrete. In the United States, the use of increased amounts of fly ash in highway construction is being 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 was 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; K. 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.

6.3—Mass concrete

Mass concrete was one of the first applications in which fly ash was used in the United States. Hungry Horse Dam, Montana, completed in 1953, contains over 2.3 million m³ (3 million yd³) 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 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 been used in roller-compacted concrete dams (Schradler, 1982).

Use of fly ash can reduce the 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 in 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; i.e., 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 concrete mixture are other important considerations in the construction of mass concrete.

6.4—Bulk handling and storage

Since fly ash is normally of lower density than portland cement, its bulk density should be considered when ordering or taking inventory. Fly ash storage typically requires about 30-40 percent more volume per unit mass than does portland cement; a 100 Mg (or tons) portland cement bin will hold about 70 to 75 Mg (or 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/m³ (55 and 80 lb/ft³); whereas cement in bins and silos is generally between 960 and 1500 kg/m³ (60 and 94 lb/ft³). Both fly ash and cement may have lowered bulk density immediately after conveying (Strehlow, 1973). Rail cars can not carry as much mass of fly ash as 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. Occasionally, fly ashes with very low bulk density may reduce the load that can be carried.

The spherical particle shape of fly ash, as well as significant quantities of very fine grains mean that fly ash will require handling and storage facilities slightly different from portland cement. When aerated, fly ash tends to exhibit very fluid handling characteristics, with an aerated angle of repose of 10 to 15 deg. As a result, bins for storage of fly ash, as well as transport systems (pneumatic or mechanical) must be well sealed to prevent leakage. This characteristic increases the possibility of leakage of fly ash from bins and silos.

Bins and silos intended for cement may 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 may require slightly different unloading techniques than 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 must also be taken to clearly identify which storage compartments contain fly ash, and to establish proper materials-management procedures (Gaynor, 1978). Bins should be completely cleaned when they are being converted to handle a different type of material. As with cement from



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

different mills, fly ash from different sources should not be mixed in the same bin.

Since 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 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 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 must be stored in different compartments of the same bin or silo and are separated by a common dividing partition, frequent inspections of the partition must 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 may 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.

6.5—Batching

When batching fly ash and cement at a concrete plant, it is usually not necessary to install separate weigh batchers. Fly ash and cement may be weighed cumulatively in the same weigh batcher. Due to the lower density of fly ash, weigh batchers must be sized adequately to handle larger volumes of cementitious material. Cement should be weighed first so that accidental overbatching of fly ash will not cause underbatching of cement (Gaynor, 1978). However, care must be taken to accurately batch the correct amounts of both cement and fly ash, since overbatching or underbatching may result in unacceptable variations in the properties of the plastic and hardened concrete.

To transport fly ash from bin to weigh 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 weigh hopper. Fly ash

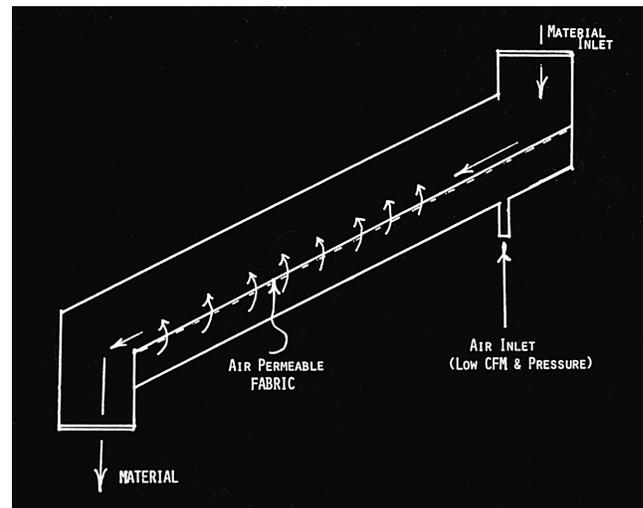


Fig. 6.2(a)—Schematic of an air slide



Fig. 6.2(b)—Screw conveyor for transporting 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 weigh batcher, an air slide or a screw conveyor can be used (see Figs. 6.2a and b). Since fly ash flows very easily, a positive shut-off valve should be installed to insure 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.

CHAPTER 7—FLY ASH IN CONCRETE PRODUCTS

7.1—Concrete masonry units

The manufacture of concrete masonry units typically involves the use of a dry, harsh concrete mixture compacted into 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 mate-

rial and aggregate mineral filler.

Curing methods for masonry units include autoclave curing and atmospheric-pressure steam curing. Manufacturers using both curing systems are able to 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 reportedly gives added plasticity to the relatively harsh mixtures used in concrete masonry units (Belot, 1967). Autoclave curing, though not as common as in the past, is still used to manufacture high quality masonry units. Concrete masonry units cured in autoclaves show 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 typically allow for the use of fly ash in amounts up to 35 percent for Class C and 30 percent of the cementitious material for Class F fly ashes. Percentages greater than this 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 insure that the fly ash meets the soundness requirement of ASTM C 618, especially when the fly ash will constitute more than 20 percent of the total cementitious material in the product.

Atmospheric-pressure steam curing is typically carried out in insulated kilns. The exact temperature used is a function of the materials and the amount of fly ash used. Up to 35 percent for Class C and 25 percent for Class F fly ashes by mass of total cementitious material has 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. Where fly ash is used in conjunction with cement, this preset period may be longer. If so, it must be used or damage to the product may result.

Proportioning of mixtures for the manufacture of concrete masonry units is not carried out as an exact science. Conditions may 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 using extremely dry concrete mixtures and the other using more fluid concrete mixtures. Dry-cast concrete pipe is produced utilizing mechanical compaction, vibration or both to consolidate the dry concrete mixture into a form which 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 typically used to obtain early age performance.

Wet-cast concrete uses more fluid concrete placed and compacted in a form which 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 density and low permeability.

Fly ash has found widespread use in the manufacture of concrete pipe as a cementitious material and as an aggregate mineral filler to enhance quality and economy. Because properly proportioned mixtures containing fly ash make the concrete less permeable, pipe containing fly ash may be more resistant to weak acids and sulfates (Davis, 1954; K. 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 compacted into a vertical pipe form using a revolving compaction tool. Vibratory pipe processes use mechanical vibration to compact 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 mineral filler to provide added workability and plasticity. Equipment used in pipe production may last longer due to the lubricating effect of the fly ash. 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 very 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 per ASTM C 595 containing a maximum of 25 percent fly ash by mass. Where fly ash is used separately, it is limited to between 5 and 25 percent of total cementitious material. The cementitious materials content for concrete for pipe production shall not be less than 280 kg/m³ (470 lb/yd³). The concrete mixture shall also have a maximum water-cementitious materials ratio of 0.53.

7.3—Precast/prestressed concrete products

Precast concrete products can be produced with or without reinforcement. Reinforcement typically includes the use of 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 enables the use of reusable forms which, for economy, are cycled as rapidly as possible. For this reason, these concrete products generally achieve their competitive position

in the marketplace by using a limited number of forms with a rather short production cycle. Normal production schedules allow for one use of forms per day, however, 10 to 12-hr schedules are common. Accelerated curing is typically employed 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 34.5 MPa (3500 to 5000 psi) are typically required at the time of form removal or stripping. These early concrete strengths are generally achieved with cement contents of 355 to 445 kg/m³ (600 to 750 lb/yd³). 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 percent indicated that they were currently using fly ash in their products, 9 percent had used fly ash but had stopped, and 58 percent 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 percent with the lowest being 12 percent and the highest being 30 percent. Of the respondents who have discontinued the use of fly ash, 86 percent stated low initial strength gain as a problem. Other problems experienced in using fly ash were: 1) lack of consistency of fly ash, 2) slump loss, and 3) 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: 1) early strength gain, 2) creep, 3) shrinkage, 4) permeability, and 5) elastic modulus.

Favorable results were obtained by Dhir et al., (1988) in investigations on concrete containing fly ash at ages from 18 hours to 1 year measuring: 1) strength development (compressive and tensile) and 2) 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 percent, and the ratio (by mass) of Class F fly ash added versus cement replaced ranged from 1.23:1 to 1.59:1. It was concluded that concretes containing fly ash perform as well as, or better than, concretes containing only rapid-hardening cement.

Another investigation was conducted with Class C fly ash to determine the extent of strength gain obtainable (Naik and Ramme, 1990). Cement replacements of 10 to 30 percent 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 is using fly ash as 20 percent 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. However, proportions and curing procedures used must 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 has been added to increase the workability of these dry, harsh mixes (Juvas, 1987).

CHAPTER 8—OTHER USES OF FLY ASH

8.1—Grouts and mortars

According to ACI 116R, grout is “a mixture of cementitious material and water, with or without fine aggregate, proportioned to produce a pourable consistency without segregation of the constituents.” 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 alkali-silica reaction, 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 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 voids 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 the 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 cracks or fissures in rock foundations, (e) soil stabilization, to fill voids in the 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 bags or blankets which are flexible enough to conform to the surrounding contour to completely fill the void and provide complete contact.

8.2—Controlled low-strength material (CLSM)

These materials are discussed in ACI Committee Report 229 “Controlled Low Strength Materials,” and are 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’s normally consist of fly ash, cement, water and fine aggregate. On occasion they may include coarse aggregate, lightweight aggregate, and admixtures such as air-entraining admixtures, water-reducers and high-range water-reducers.

CLSM’s can be proportioned to flow like liquids; no tamping or compaction is needed to achieve strength or density. They are ideal for trench backfilling, pipe bedding and protection, foundation subbase, spread footings, paving base, floor fills, culvert backfill, and for filling abandoned tanks, manholes, steam lines, and sewer lines. Large voids such as sink-holes, basements, and mines have been filled with CLSM. Failing bridges have often been replaced by culverts for 25 percent of the cost of replacing the bridge (Larsen, 1988). Voids under bridges, culverts, slabs, and pavements are filled with no compactive effort using CLSM to achieve stability without replacement. Wash-outs of all types are commonly filled with CLSM. Rip-rap has been grouted with CLSM to protect it from erosion, and revetment mats on river banks have been filled with CLSM to protect them from erosion (Larsen, 1990).

Compressive strengths ranging from 0.35 to 8.25 MPa (50 to 1200 psi) are commonly achieved in CLSM to provide rigidity for volume stability. Self-leveling CLSM can be proportioned to support normal loads. At strength levels less than 1.0 MPa (150 psi), it can be readily excavated. If CLSM is used where future excavation is anticipated then an effort is made to keep strengths low for easy excavation.

Economy is achieved because backfill compaction crews and equipment are not necessary. Excavations for sewer pipe and other conduits can be smaller because compaction equipment is not needed. Pavements, bridges, and culverts can be repaired with minimal interruption of traffic and use of detours. However, the amount of subsidence of these very wet mixtures must be provided for in some applications.

8.3—Soil cement

Soil cement is “a mixture of soil and measured amounts of portland cement and water compacted to a high density” (ACI 116R). Soil cement is explained in detail by a “State-of-the-Art Report on Soil-Cement” by ACI Committee 230. 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 may be used in soil cement as a cementitious material. Usually the cementitious material content is 4 to 16 percent of the dry weight of soil of which any portion of the cementitious material may be fly ash.

8.4—Roller compacted concrete

Roller-compacted concrete is used principally in mass concrete and pavements. ACI Committee 207 has developed a report, “Roller Compacted Mass Concrete” (ACI 207.5R), that discusses its use in the construction and repair of dams. This economical 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 compacted by rollers. Final compaction is normally done by vibrating roller. Construction time is very fast, the mixture is economical and it achieves the strength of richer conventional mixes.

ACI Committee 325 is preparing a state-of-the-art report on roller compacted concrete pavements. Roller-compacted concrete for pavement is a low-slump concrete with a 19-mm (3/4-in.) maximum aggregate size, low water content and not less than 11 percent by mass of cementitious materials, of which 70 percent 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 compact the lifts. The pavement then receives a water cure or curing compound. Control joints are not normally provided. Successful uses include military vehicle, car, truck, and aircraft parking areas as well as log sorting and storage yards, forestry and mine haul roads, and railroad unloading yards.

8.5—Waste management

“Wastecrete” is the name that has been given to solidification and stabilization of hazardous wastes with fly ash or with various combinations of cementitious materials. Fly ash is typically used to solidify many types of hazardous waste such as manufacturing waste streams, incinerator ash, landfill waste, mine tailings, radioactive wastes, and superfund wastes. The advantages and properties that may be associated with this use of fly ashes are:

1. reduction in permeability
2. pH adjustment
3. pozzolanic activity
4. self-cementing
5. economy

- 6. free water reduction
- 7. 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 waste and decrease leachability of various organic compounds. The benefits of stabilization are solidification and limiting the solubility or mobility of the hazardous contaminants. When solidifying and stabilizing hazardous waste with fly ash it is essential to conduct treatability studies 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 that has been used to describe solidification and stabilization of various oil wastes with fly ash and other solidifying agents. The oil wastes to be treated are 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 plains states.

In-situ 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 harden 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 can be covered and the natural grade restored.

CHAPTER 9—REFERENCES

9.1—Specified and/or recommended references

The various standards or reports referred to in this document are listed below with their serial designation.

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
 212.3R Chemical Admixtures in Concrete
 212.4R Guide for Use of High-Range Water-Reducing Admixtures in Concrete
 229R Controlled Low-Strength Materials (CLSM)
 230.1R State-of-the-Art Report on Soil Cement
 304 Guide for Measuring, Mixing, Transporting and Placing concrete
 308 Standard Practice for Curing Concrete
 318 Building Code Requirements for Reinforced Concrete
 363R State-of-the-Art Report on High-Strength Concrete

ASTM

C 14 Specification for Concrete Sewer, Storm Drain, and Culvert Pipe
 C 76 Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe
 C 109 Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)
 C 115 Test Method for Fineness of Portland Cement by the Turbidimeter
 C 151 Test Method for Autoclave Expansion of Portland Cement
 C 157 Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete
 C 185 Test Method for Air Content of Hydraulic Cement Mortar
 C 188 Test Method for Density for Hydraulic Cement
 C 204 Test Method for Fineness of Portland Cement by Air Permeability Apparatus
 C 227 Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
 C 289 Test Method for Potential Reactivity of Aggregates (Chemical Method)
 C 311 Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete
 C 361 Standard Specification for Reinforced Concrete Low-Head Pressure Pipe
 C 412 Specification for Concrete Drain Tile
 C 430 Test Method for Fineness of Hydraulic Cement by the 45-µm (No. 325) 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 478 Specification for Precast Reinforced Concrete Manhole Sections
 C 505 Specification for NonReinforced Concrete Irrigation Pipe with Rubber Gasket Joints
 C 506 Reinforced Concrete Arch Culvert, Storm Drain, and Sewer Pipe
 C 507 Specification for Reinforced Concrete Elliptical Culvert, Storm Drain, and Sewer Pipe
 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 654 Specification for Porous Concrete Pipe
 C 789 Specification for Precast Reinforced Concrete Box Sections for Culverts, Storm Drains, and Sewers
 C 850 Specification for Precast Reinforced Concrete Box Sections for Culverts, Storm Drains, and Sewers with Less Than 2 ft of Cover Subjected to Highway Loadings

- C 989 Specification for Ground Iron Blast-Furnace Slag for Use in Concrete and Mortars
- C 1012 Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
- C 1157 Performance Specification for Blended Hydraulic Cements

Electric Power Research Institute

SC-2616-SR, Special Report, 1982 Workshop Proceedings: *Research and Development Needs for Use of Fly Ash in Concrete*

CS-3314, Jan. 1984, *Testing and Correlation of Fly Ash Properties with Respect to Pozzolanic Behavior*

Highway Research Board

HRB Special Report 127, 1972, *Guide to Compounds of Interest in Cement and Concrete Research*

HRB Special Report, 119, 1971, *Pozzolans in Highway Concrete*, "Admixtures in Concrete," pp. 21-32

American Coal Ash Association

How Fly Ash Improves Concrete Block, "Ready-Mix Concrete, and Concrete Pipe," 1978-1979, reprinted from the *Concrete Industries Yearbook*

Tennessee Valley Authority

Technical Report CR-81-1, 1981, *Properties and Use of Fly Ash in Portland Cement Concrete*

United States Bureau of Reclamation

4908 Length Change of Hardened Concrete Exposed to Alkali Sulfates

Canadian Standards Association

A23.5M Standard Specification for Fly Ash in Concrete

These publication may be obtained from the following organizations:

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

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

Electric Power Research Institute
Box 50490
Palo Alto, CA 94303

Transportation Research Board
2101 Constitution Avenue
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Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Proceedings of the Second International Conference — Madrid, Spain, American Concrete Institute SP-91, 1601 p., 1986, editor, V. M. Malhotra.

Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Proceedings of the Third International Conference — Trondheim, Norway, American Concrete Institute SP-114, 1706 p., 1989, editor, V. M. Malhotra.

Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Proceedings of the US-Turkey Workshop, Istanbul, Turkey, 184 p., 1992, editor, V. Ramakrishnan and M. Suheyl Akman.

Fly Ash and Coal Conversion By-Products: Characterization, Utilization and Disposal VI, Symposium Proceedings, V. 178, Materials Research Society, 1989, Boston, Massachusetts, editors, Robert L. Day and Fredrik P. Glasser.

Controlled Low-Strength Materials, American Concrete Institute SP-150, 110 p., 1994, editor, Wayne S. Adaska.

Helmuth, Richard, *Fly Ash in Cement and Concrete*, Portland Cement Association, 196 p., 1987.

Supplementary Cementing Materials for Concrete, CANMET, Ottawa, Ontario, Canadian Government Publishing Centre, 1986, editor, V. M. Malhotra.

APPENDIX—RAPID QUALITY CONTROL TESTS

A.1—Loss on ignition

The test, in accordance with ASTM 311, involves drying to constant mass for moisture content. However, if the moisture content is known to be low, a quick loss on ignition 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 loss on ignition, 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 loss on ignition, but the correlation between the two test values was very good.

A.3—Material retained on 45- μm (No. 325) sieve

The ASTM C 311 procedure generally involves at least two hours of drying of the residue on the sieve after the wet-sieving operation. However, a hot plate or higher oven temperature 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 which react rapidly with water.

A.4—Air-jet sieving

Alpine air-jet sieve equipment is available that will provide a faster test since 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 the ATM sonic sieve equipment) are also available which can be employed to indicate changes in the particle size distribution of the 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 which 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 controlled light source. If necessary, a piece of clear glass can be placed over the fly ashes for the comparison. A change in color 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 is another fairly rapid procedure which may be useful 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

(Meininger, 1981; Gebler and Klieger, 1983.) Foam-index values 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. 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

(Meininger, 1981; Gebler and Klieger, 1983.) 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. 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 which 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 as described by McKeerall, 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 (start-up 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 which includes cement or other alkaline material. Cover the bottle and mix. Open the bottle to detect ammonia odor (Ravina 1981).

ACI 232.2R-96 was submitted to letter ballot of the committee and was approved in accordance with ACI balloting requirements.