

Use of Fly Ash in Concrete

Reported by ACI Committee 226



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Fly ash from coal-burning power plants is used in concrete primarily because of its pozzolanic and cementitious properties. These properties contribute to strength gain and improved durability when used with portland cement. Other principal reasons for using fly ash include economy and beneficial modification of certain properties of fresh and hardened portland cement concrete.

This state-of-the-art report gives an overview of the properties of fly ash and its proper use in the production of portland cement concrete. 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 the effect of fly ash on properties of concrete, a discussion of quality assurance of fly ash, guidance regarding the handling and use of fly ash in concrete, and the use of fly ash in specific applications. Referenced documents give more information on each topic.

Keywords: admixtures; air entrainment; alkali-aggregate reactions; bleeding (concrete); bonding; concrete blocks; concrete durability; concrete pavements; concrete pipes; creep properties; density (mass/volume); drying shrinkage; fineness; fly ash; grout; mass concrete; mix proportioning; modulus of elasticity; mortars (material); permeability; portland cements; pozzolans; precast concrete; prestressed concrete; pumped concrete; quality assurance; ready-mixed concrete; reinforced concrete; reviews; sampling; setting (hardening); specifications; storage; strength; sulfate resistance; temperature rise (in concrete); tests; workability.

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CHAPTER 1—GENERAL

1.1—Introduction

Fly ash is used extensively in concrete as a separately batched material and as an ingredient in blended cement. It is used for economy and to improve the properties of concrete used for certain applications. This report provides a summary of the technology of the use of fly ash in concrete and a comprehensive list of references concerning the characterization of fly ash, its properties, and its effects on concrete. Guidance is provided concerning the specification and use of both Class F and Class C fly ash, along with information on quality assurance of fly ash and fly ash concrete.

According to ACI 116R, "Cement and Concrete Terminology," fly ash is "the finely divided residue resulting from the combustion of ground or powdered coal which is transported from the firebox through the boiler by flue gases; known in UK as pulverized fuel ash (pfa)." Fly ash possesses pozzolanic properties similar to naturally occurring pozzolanic materials, primarily of volcanic or sedimentary origin, found in many parts of the world. About 2000 years ago the Romans mixed volcanic ash, called "pulvis puteolanus," (later changed to "pozzolana") with lime to produce mortar and concrete (Vitruvius 1960, in translation). A pozzolan is 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" (ACI 116R-85). Pozzolans, such as fly ash, are used as ingredients in portland cement concrete.

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.

Davis and colleagues recognized in subsequent studies the reactivity of fly ash with calcium and alkali-hydroxides in portland cement paste, and therewith the ability of fly ash to act as a preventive measure against deleterious alkali-aggregate reactions. The U.S. Army Corps of Engineers, The Bureau of Reclamation, major U.S. engineering firms, and others recognized the beneficial effects 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).

The oil crisis of the 1970s led to the greater use of coal to fire electric power plants. Fly ash containing higher levels of calcium oxide became available due to the use of coal and lignite containing calcium compounds in their incombustible fractions. Most such coals in the United States are sub-bituminous and lignitic. Concurrent with this increased availability of fly ash, extensive research in the United States, Canada, and elsewhere has led to better understanding of the chemical reactions involved and improved the technology to economically use the large quantities of fly ash now available to the concrete industry (ACI, SP-79).

Fly ash is used in concrete for reasons including economics, improvements and reduction in temperature rise in fresh concrete, workability, and contribution to durability and strength in hardened concrete. Fly ash makes efficient use of the products of the hydration of portland cement: (1) solutions of calcium and alkali hydroxide which exist in the pore structure of the cement paste and (2) the heat generated by hydration of portland cement, an important factor in initiating the reaction of the fly ash.

When fly ash concrete is properly cured, fly ash reaction products help fill in the spaces between hydrating cement particles in the cement paste fraction of the concrete, thus lowering its permeability to water and aggressive chemicals (Manmohan and Mehta 1981). The slower reaction rate of many fly ashes is a real help in limiting the amount of early heat generation and the detrimental early temperature rise in massive structures. Using fly ash in concrete saves energy by reducing the amount of portland cement (an energy intensive product) required to achieve the desired concrete properties.

1.1.1 Effect of fly ash in fresh concrete—Fly ash use in concrete generally causes an increase in setting time—both initial and final set. It normally allows a reduction in the quantity of mixing water in a concrete mixture necessary to produce a target slump. Because of the fineness and rounded shape of the fly ash particles, its use generally improves the cohesion and work-

ability of the concrete at a given slump. Segregation and bleeding are often reduced. Fly ash improves the pumpability of concrete mixtures and improves the ease of flat-work finishing operations. However, the timing of finishing operations may be changed due to changes in setting times. As the concrete hardens, the fly ash makes use of developed heat from portland cement hydration to accelerate pozzolanic reactions and, thereby, promotes the reaction of the fly ash with available calcium and alkali hydroxides. Using fly ash in concrete generally allows a reduction in the required cement content, and therefore reduces the peak temperature developed in the concrete during curing.

1.1.2 Effect of fly ash in hardened concrete—Increased long-term strength through continued pozzolanic reaction is achieved with most fly ashes in concrete, if the concrete is maintained in a moist environment at moderate temperatures (Stodola 1983). Early strength development at three-days' age is normally reduced by the use of Class F fly ashes and may be reduced with Class C fly ashes. However, this can generally be compensated for by proper proportioning of the mixture.

Continued long-term reaction of fly ash reduces the size of the pore spaces in the cement paste phase of the concrete. Permeability and the rate of diffusion of moisture and aggressive chemicals into the concrete is reduced, thereby reducing the danger of damage due to sulfate attack, steel corrosion, and alkali-silica reaction. Some fly ashes reduce the vulnerability of concrete to sulfate attack (Dunstan 1980) and may reduce the severity of alkali-silica reactions by reacting with alkali hydroxides that would otherwise be available to attack reactive aggregate constituents.

The performance of a concrete mixture containing fly ash depends upon the same factors that determine quality in non-fly ash concrete. These factors include: (a) the characteristics of the materials incorporated in the mixture; (b) the proportioning of the mixture; (c) the quality assurance programs for material quality and the quality control exercised over concrete production and placement; (d) the quality of workmanship employed in all facets of the concrete construction; and (e) the extent of curing.

1.2—Source of fly ash

Due to the increased use of pulverized coal to fire electric power generation plants, fly ash is now available in most areas of the United States, Canada, and many other parts of the world. Fly ash is normally produced by burning coals which have been crushed and ground to a fineness of 70 to 80 percent passing a No. 200 (75- μ m) sieve. Specifications for the use of fly ash in concrete are given in ASTM C 618, which defines two classes of fly ash—Class F and Class C. Class F fly ash is usually produced by burning anthracite or bituminous coal while the Class C fly ash is normally produced by burning sub-bituminous coal or lignite.

Bituminous and anthracite coals rarely contain high-calcium mineral matter in significant proportion; the

sub-bituminous coals and lignites may or may not contain a high amount of calcium (Roy, Luke, and Diamond 1984). The separation of fly ash into two classes reflects differences in composition which affect cementitious and pozzolanic properties. Class C fly ash usually has cementitious properties in addition to pozzolanic properties, while Class F fly ash is rarely cementitious when mixed with water alone.

Approximately 50 million tons (45 million Mg) of fly ash is produced annually in the United States. About 10 percent of total fly ash production is used in concrete.

1.3—Chemical and mineral composition

Fly ashes are complex in their range of chemical and phase compositions. They consist of heterogeneous combinations of glassy and crystalline phases. Table 1.3 gives typical fly ash composition and physical properties for a number of Class F and Class C fly ashes.

These reported data include North American fly ashes derived from the burning of bituminous and sub-bituminous coal, lignite, and in some cases mixtures of these in electric power plants. Other references also provide detailed chemical and physical data for a number of Class F and Class C fly ashes (McCarthy et al. 1984; Berry and Hemmings 1983; and EPRI CS-3314). Although the constituents are typically not present as oxides, it is customary to express the results of the chemical analyses of the materials in terms of the oxides of the elements, e.g., silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and sulfur trioxide (SO_3).

Wide ranges exist in the amounts of the three principal constituents— SiO_2 (25 to 60 percent), Al_2O_3 (10 to 30 percent), and Fe_2O_3 (5 to 25 percent). If the sum of these three ingredients is 70 percent or greater, the fly ash is technically considered Class F. (Specifications are discussed in Chapter 3.) Because Class C fly ashes generally contain significant percentages of calcium compounds reported as CaO , the sum of the three constituents just mentioned is required only to be greater than 50 percent. The MgO content of fly ash is generally not greater than 5 percent. The level of alkali oxides expressed as Na_2O equivalent is generally less than 5 percent in Class F fly ashes, but it may range up to about 10 percent in Class C fly ashes.

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 over 10 percent. Fly ashes used in concrete typically have less than 6 percent loss on ignition. The principal active constituent of Class F fly ash is siliceous or aluminosilicate glass. The principal active constituent in Class C fly ash is calcium aluminosilicate glass (Diamond 1983; Roy, Luke, and Diamond 1984).

Minor elements that may be present in varying amounts, depending on the origin of the coal from which a particular fly ash is derived, include titanium, iron, magnesium, phosphorus, sulfur, oxygen, potassium, sodium, carbon, and others as traces. Some fly ashes also have trace amounts of organic compounds

Table 1.3 — Typical chemical and physical properties of fly ash from different coal burning power plant sources

Fly ash I.D. (Reference no.)	Chemical properties, percent								Physical properties		
	LOI	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	No. 325 seive retention, percent	Blaine fineness m ² /kg	Specific gravity
Less than 10 percent CaO (nominal Class F)											
FA-4*	1.0	6.7	58.5	19.9	5.6	1.7	1.5	1.3	17	379	2.31
FA-5*	0.9	0.7	60.1	27.8	3.8	1.0	0.3	2.8	18	262	2.18
FA-7*	1.8	1.7	56.0	25.7	8.3	1.1	0.3	2.8	22	282	2.28
FA-8*	2.6	2.4	49.0	21.8	17.9	1.0	0.4	2.7	20	282	2.45
FA-13*	4.2	1.7	45.0	19.6	23.9	0.9	0.4	2.3	24	236	2.45
FA-14*	3.0	1.9	47.7	29.5	9.7	0.7	0.3	1.9	28	287	2.30
FA-15*	2.5	1.3	52.7	28.6	5.8	1.0	0.3	2.4	17	351	2.38
FA-16*	4.0	1.6	50.6	27.6	8.2	1.0	0.4	2.5	4	508	2.49
FA-17*	0.4	7.5	49.8	21.6	7.0	1.7	2.8	0.7	24	316	2.27
FA-18*	4.3	2.2	43.6	26.0	16.6	0.9	0.3	1.9	17	337	2.24
No. 3 [†]	7.2	3.2	64.4	24.7	3.9	1.5	—	—	2	—	—
D-Precip. [‡]	3.9	1.0	52.9	30.1	7.3	1.1	0.4	2.9	8	643	2.33
D-Mech. [§]	6.4	1.0	54.9	27.6	10.4	0.9	0.3	2.4	30	333	2.15
More than 10 percent CaO (nominal Class C)											
FA-1*	0.9	25.5	36.3	17.7	6.7	4.6	1.6	0.6	15	417	2.65
FA-2(a)*	1.9	15.5	38.8	13.4	22.5	1.5	0.5	1.9	16	355	2.74
FA-9(a)*	0.5	11.6	50.5	17.7	6.6	3.4	3.5	1.2	11	315	2.44
FA-10(a)*	0.5	28.2	35.9	17.1	5.6	5.1	1.8	0.5	16	390	2.70
FA-11(a)*	0.4	16.9	51.4	16.9	5.8	3.5	0.6	0.8	21	288	2.52
A [‡]	0.4	17.3	35.7	20.3	5.8	4.3	6.5	0.8	11	418	2.67
F [‡]	0.7	24.9	23.1	13.3	9.6	7.5	7.3	0.6	12	324	2.86
G [‡]	0.6	11.7	48.9	21.3	3.7	2.7	6.4	0.9	38	318	2.31
I [‡]	0.3	29.0	31.1	17.0	5.6	3.8	3.2	0.4	15	604	2.74

*Collins and Emery 1982.

†Burns, Guarnashelli, and McAskill 1982.

‡Rose, Lowe, and Floyd 1979.

§Gebler and Klieger 1983.

other than unburned coal. Section 3.7 of this report, "Start-up oil and stack additives," discusses some of the materials which when used in the coal-burning or ash-collection process may affect fly ash properties.

Carbon content is not usually determined directly, but is often assumed to be approximately equal to the loss on ignition (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.

Rapid cooling of the ash from the molten state as it leaves the flame causes fly ash to be predominantly noncrystalline (glassy) with minor amounts of crystalline constituents, such as mullite, quartz, magnetite (or ferrite spinel), and hematite. Roy, Luke, and Diamond (1984) indicate that 60 to 90 percent of most fly ashes are glass phases. Other constituents which may be present in high-calcium fly ashes include periclase, anhydrite, alkali sulfate, melilite, merwinite, nepheline, sodalite, C₃S, C₃A, and others. (McCarthy et al. 1984).

1.3.1 Class C fly ash—Active compounds in addition to calcium aluminosilicate glass that may be present in Class C fly ash are free lime (CaO), anhydrite (CaSO₄), tricalcium aluminate (3CaO·Al₂O₃), calcium sulfoaluminate (4CaO·3Al₂O₃·SO₄), and rarely, calcium silicates (Mehta 1983). The strength-related properties of concrete containing Class C fly ash, as compared to Class F fly ash, are influenced by the cementitious calcium aluminosilicate glass and, in many instances, by the presence of crystalline phases which contribute to the hydration of Class C fly ashes (Diamond 1981 and EPRI CS-3314).

High-calcium (Class C) fly ashes often react directly with water to form cementitious phases such as C-S-H (calcium-silicate-hydrate), calcium hydroxide, and ettringite. In addition, the glassy phase in these fly ashes, while still predominant, is often less abundant but more reactive than in Class F fly ashes. These glassy materials are reactive with the calcium and alkali hydroxides released from the cement-fly ash system.

1.3.2—Class F fly ash—Low-calcium (Class F) fly ashes characteristically contain a large proportion of silicate glass of high silica content plus crystalline phases of low reactivity, typically mullite, magnetite (or ferrite spinel), and quartz. On an equal weight basis high-calcium fly ashes (normally from lignite and subbituminous coals) gain more early strength than low-calcium fly ashes (normally from bituminous coal) due both to chemical and physical factors.

The chemical composition of the glass in fly ashes varies considerably, affecting its activity. Also, the corresponding structure of the glass varies from that of the strongly interlinked network characterizing highly siliceous glass in many Class F fly ashes, to a more substituted structure which contains a larger proportion of network modifiers in the Class C fly ashes. These constituents may include alkaline earth, alkali, and aluminosilicate glasses similar to the glassy structures of blast-furnace slag. It has also been proposed that calcium aluminate glasses are present. The high-silica glass is intrinsically less reactive with water than the other glasses. Therefore, Class F fly ashes are more effective in concrete as Class C fly ashes (Roy, Luke, and Diamond 1984).

High-silica glasses react generally more slowly with the hydroxyl, alkali, and calcium ions from alkali and calcium hydroxides present. Although the pozzolanic reaction tends to deplete the residual calcium hydroxide, the continuing hydration of C_2S and C_3S releases more calcium hydroxide. The reactivity of a glass is also influenced by the characteristics of the particular cement with which it is used and by its alkaline constituents.

1.4—Physical properties

The shape, fineness, particle-size distribution, density, and composition of fly ash particles influence the properties of freshly mixed, unhardened concrete and the strength development of hardened concrete as previously indicated.

Fly ashes produced at different power plants or at one plant with different coal sources may have different colors. Fly ash color and the amount used can influence the color of the resulting hardened concrete in the same way as changes in cement or fine-aggregate color. Fly ash color is generally not an engineering concern except that 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, loss on ignition, iron content, or burning conditions.

1.4.1 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, bag filters, or electrostatic precipitators. Lane and Best (1982) reported that the shape of fly ash particles is also a function of particle size. The major-

ity of fly ash particles are glassy, solid or hollow, and spherical in shape. Hollow empty spheres are called cenospheres. Spheres that contain smaller particles of ash are known as plerospheres (Lauf 1982). The remaining fly ash particles are translucent to opaque, slightly to highly porous, and vary in shape from rounded to elongated. Examples of fly ash particle shapes are shown in Fig. 1.4.1 (a) and (b).

It has been shown in Europe that the intergrinding of fly ash with cement in the production of blended cement has improved its contribution to strength (EPRI SC-2610-SR). Grinding further reduces particle size, breaks up cenospheres, and releases smaller particles contained in plerospheres. However, if the mixture of fly ash and cement clinker is ground too fine, water requirement can be increased.

1.4.2 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 collectors. In fly ash suitable for use as pozzolan in concrete the majority of the particles pass the No. 325 ($45\text{-}\mu\text{m}$) sieve. The particle-size distribution 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.

Fineness of the fly ash has a significant influence on its performance in concrete. Lane and Best (1982) used results of tests by ASTM C 430, No. 325 ($45\text{-}\mu\text{m}$) sieve fineness, as a means to correlate the fineness of Class F fly ash with certain concrete properties. Their data indicate that concrete strength, abrasion resistance, and resistance to freezing and thawing are direct functions of the proportion of the fly ash finer than the No. 325

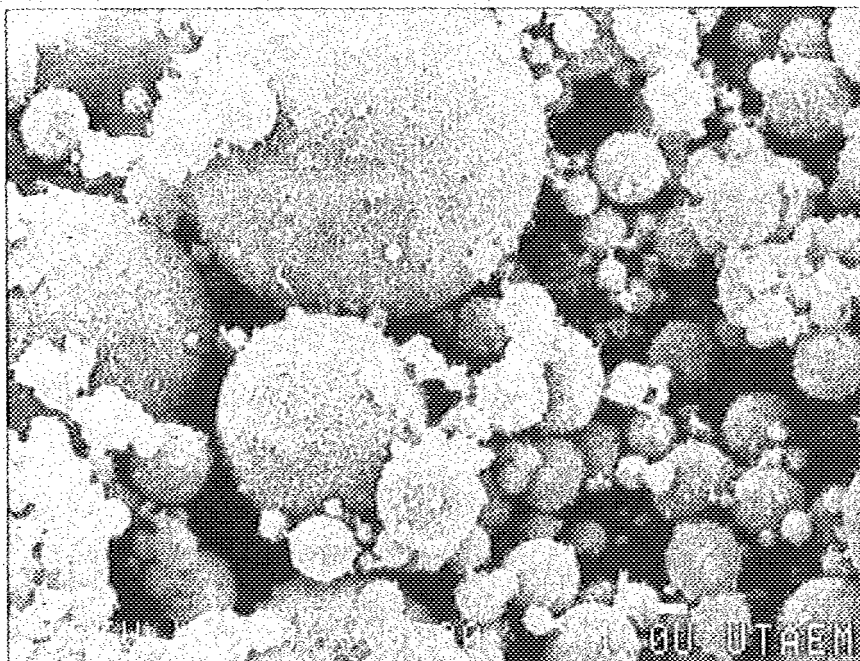


Fig. 1.4.1(a)—Fly ash at 400 magnification

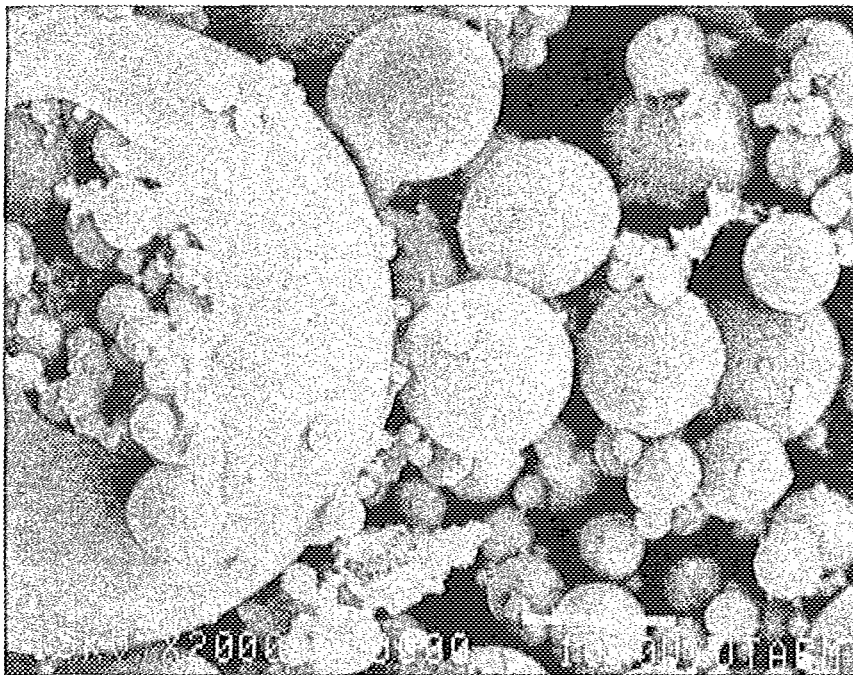


Fig. 1.4.1(b)—Fly ash showing plerospheres at 2000 magnification

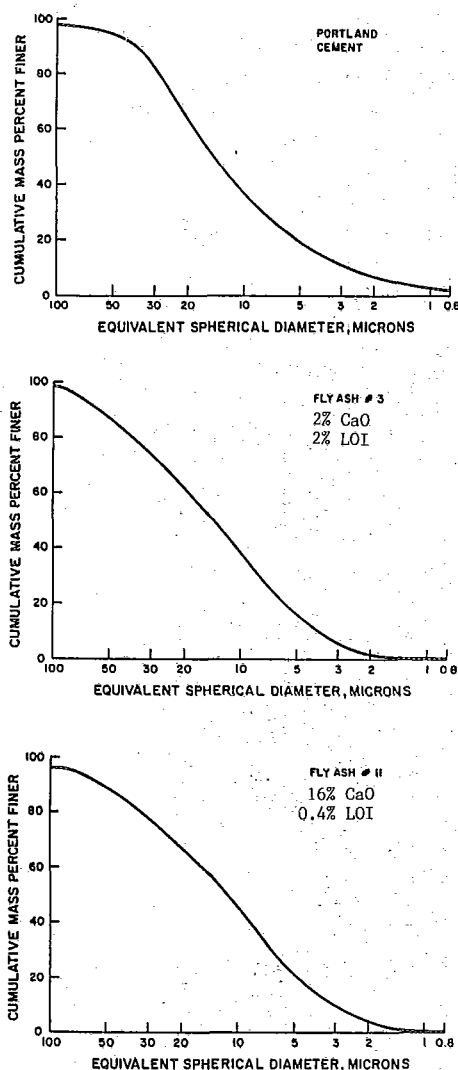


Fig. 1.4.2—Particle-size distribution of portland cement and fly ashes (EPRI CS-3314)

(45- μ m) sieve. They concluded that fineness is a more 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 No. 325 (45- μ m) sieve procedure are the air-permeability test (ASTM C 204), the turbidimeter method (ASTM C 115), and the hydrometer method. Fineness 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 high-carbon ashes which tend to have high fineness values which may be misleading. Useful information on particle size distribution finer than No. 325 (45- μ m) 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 μ m had a positive influence on strength (EPRI CS-3314). In that study nitrogen adsorption and x-ray sedimentation methods were used to measure surface area and particle size distribution, respectively (see Fig. 1.4.2).

1.4.3 Specific gravity—According to Luke (1961), the specific gravity of solid fly ash particles ranges from 1.97 to 3.02, but is normally in the range of 2.2 to 2.8. Some fly ash particles (cenospheres, for example) are capable of floating on water, indicating a specific gravity less than 1.0. High specific gravity is often an indication of fine particles. Roy, Luke, and Diamond

(1984) indicate that fly ashes high in iron tend to have higher specific gravity and that those high in carbon have lower specific gravity. Class C fly ashes tend to have finer particles and fewer cenospheres; thus their specific gravities tend to be higher—in the range of 2.4 to 2.8.

1.5—Chemical activity of fly ash in portland cement concrete

The principal product of the reactions of fly ash with alkali and calcium hydroxide in concrete is essentially 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 heat mobilized 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 liquid 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 hydroxides 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 as a portion of the cementitious material in the concrete. The rate of early heat evolution is reduced in these cases and the time of maximum rate of heat evolution is retarded (Mehta 1983; Wei, Grutzeck, and Roy 1984). However, when the quantity of portland cement per unit volume of concrete is kept constant, the heat evolved (and the compressive strength) 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 more than a proportionate increase in the reaction rate.

However, the activation energy of fly ash is different from the activation energy of portland cement (EPRI SC-2610-SR). The concept of activation energy needed for the reaction to take place involves energy from the chemical reactants, mechanical energy from fine grinding, and thermal energy from heat of hydration or an

outside heat source. Therefore, calculations of rates of strength development in concrete during the early curing phase require calorimetric-based determinations of the rate of heat development with the particular fly ash-portland cement combinations (Owens and Butler 1980; Idorn and Henriksen 1984).

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

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

1.5.1 Research—Many opportunities exist for the use of fly ash, and continuing research into the nature and reactivity of the glassy and crystalline phases will expand applications. Methods used to characterize fly ash include chemical analyses, particle size, surface area, and phase determination made by x-ray diffraction (Mings et al. 1983; Pitt and Demirel 1983). Lauf (1981) and others have performed leaching and selective dissolution experiments to determine the insoluble phase content and the nature of the microstructure after dissolution of most of the glassy phase. The phases of Class F ashes tend to be less soluble (Halse et al. 1984), while those of calcium-rich fly ashes are generally more soluble. Buck, Husbands, and Burkes (1983) reported work on six fly ashes, four from lignite and one each from sub-bituminous and bituminous coal, that yielded 57 to 75 percent glass in dissolution studies. Also, 25 to 42 percent crystalline material was found, of which 4 to 30 percent was water soluble, 6 to 17 percent acid insoluble, and 2 to 14 percent was magnetite. In all, 20 different crystalline phases were detected. No simple technique has yet been found to separate crystalline and glassy phases for all types of fly ashes (Scheetz et al. 1981; EPRI SC-2610-SR).

CHAPTER 2—FLY ASH CONCRETE PROPERTIES AND PROPORTIONS

2.1—Effect on properties of fresh concrete

2.1.1 Workability—The absolute volume of cement plus fly ash normally exceeds that of cement in similar non-fly ash concrete mixtures. This is because the mass of fly ash used to replace cement is usually equal to or greater than that replaced and the fly ash normally is of lower density. 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 of the SiO_2 concentration over CaO produces an improved stability of the dispersion of the cement and fly ash particles in the highly alkaline fresh paste. (Roy, Skalny, and Diamond 1982; Young 1982, and others).

Fly ash changes the flow behavior of the cement paste (Rudzinski 1984); also, the generally spherical shape of fly ash particles normally permits the water in the concrete to be reduced for a given slump (Brown 1980). Water reduction by fly ash further increases the solids-to-liquid ratio with additional beneficial results. However, coarse high-carbon fly ash, which will not meet typical specifications for pozzolan, usually increases the water requirement slightly (Abdun-Nur 1961). 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 $10\ \mu\text{m}$ (EPRI CS-3314), which favorably influence concrete workability.

2.1.2 Bleeding—Using fly ash in air-entrained and nonair-entrained concrete mixtures usually reduces bleeding by providing greater fines volume and a lower water content for a given workability (Idorn and Henriksen 1984). The fines present from fly ash can compensate for a deficiency in aggregate fines and help block bleed-water channels (Lane 1983).

2.1.3 Pumpability—Improved pumpability of concrete is usually achieved when fly ash is used. For mixtures deficient in the smaller sizes of fine aggregate or lean in cement, the addition of extra fly ash as an aggregate supplement will make concrete or mortar more cohesive and less prone to segregation and bleeding. Further, the spherical shape of the fly ash particles serve to increase workability and pumpability by decreasing friction between aggregate particles and between the concrete and the pump line (Best and Lane 1980).

2.1.4 Time of setting—The use of fly ash may retard the time of setting of the concrete. Class F fly ash generally extends the time of setting, while Class C fly ash may extend, reduce, or have no significant effect on the time of setting. 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; soluble alkalies; use of other admixtures; the amount of fly ash; and the fineness and chemical composition of the fly ash (Plowman and Cabrera 1984). 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 with fly ash concrete due to improved workability, slower slump loss, and retarded setting characteristics (Gardner 1984).

2.1.5 Finishability—Since fly ash concrete typically 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 chances 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.

2.2—Effect on properties of hardened concrete

2.2.1 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). There is no known special effect on the relationship of tensile strength to compressive strength for the use of fly ash compared to non-fly ash concrete. Compared with non-fly ash concrete 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); however, if equivalent 3-day or 7-day strength is desired, it can be provided by using accelerators or changing the mix 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 hydroxide 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 (superplasticizers) to reduce the water to cementitious material ratio to 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, fly ash concrete with equivalent or lower strength at early ages may have equivalent or higher strength at later ages than concrete without fly ash (Bloem 1954). 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 fly ash concrete as compared with 30 percent for concrete without fly ash. Other tests, **Documents** with and without fly ash, showed significantly higher performance for the fly ash concrete at ages up to 10