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Guide for the Use of Silica Fume in Concrete*

Reported by ACI Committee 234

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This report describes the physical and chemical properties of silica fume; how silica fume interacts with portland cement; the effects of silica fume on the properties of fresh and hardened concrete; recent typical applications of silica-fume concrete; how silica-fume concrete is proportioned, specified, and handled in the field; and areas where additional research is needed.

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* The first version of this document was prepared by our predecessor ACI Committee 226, and published in the March-April 1987 issue of the ACI Materials *Journal*. Rather than working to get that version into the *ACI Manual of Conrete Practice*, this committee agreed to revise the document to reflect the increasing body of knowledge and use of silica fume in concrete.

CHAPTER 1—INTRODUCTION

1.1—General

In recent years significant attention has been given to the use of the pozzolan silica fume as a concrete property-enhancing material, as a partial replacement for portland cement, or both. Silica fume has also been referred to as silica dust, condensed silica fume, microsilica, and fumed silica (this last term is particularly incorrect - see Section 1.3). The most appropriate term is silica fume (ACI 116R).

The initial interest in the use of silica fume was mainly caused by the strict enforcement of air-pollution control measures in various countries to stop release of the material into the atmosphere. More recently, the availability of high-range water-reducing admixtures (HRWRA) has opened up new possibilities for the use of silica fume as part of the cementing material in concrete to produce very high strengths or very high levels of durability or both.

Investigations of the performance of silica fume in concrete began in the Scandinavian countries, particularly in Iceland, Norway, and Sweden, with the first paper being published by Bernhardt in 1952. Other early Scandinavian papers included those by Fiskaa, Hansen, and Moum (1971), Traetteberg (1977), Jahr (1981), Asgeirsson and Gudmundsson (1979), Løland (1981), and Gjørv and Løland (1982). In 1976 a Norwegian standard permitted the use of silica fume in blended cement. Two years later the direct addition of silica fume into concrete was permitted by standard in Norway.

In South Africa, Oberholster and Westra published research results on using silica fume to control alkali-aggregate reaction in 1981.

In North America, the first paper published was that of Buck and Burkes (1981). Other early research was conducted by CANMET (Malhotra and Carette 1983; Carette and Malhotra 1983a), Sherbrooke University (Aïtcin 1983), Norcem (Wolsiefer 1984), and the Waterways Experiment Station (Holland 1983). The first major placements of ready-mixed silica-fume concrete in the United States were done by Norcem for chemical attack resistance in 1978. The first publicly-bid project using silica-fume concrete was done by the Corps of Engineers in late 1983 (Holland et al. 1986).

This report describes the physical and chemical properties of silica fume; how silica fume interacts with portland cement; the effects of silica fume on the properties of fresh and hardened concrete; recent typical applications of silica-fume concrete; how silica-fume concrete is proportioned, specified, and handled in the field; and areas where additional research is needed.

As with other concrete constituent materials, potential users of silica fume should develop their own laboratory data for the particular type and brand of cement, aggregates, and chemical admixtures to be used with the silica fume. This testing may be supplemented by observations of silica-fume concrete in the field and by testing of cores taken from such concrete.

1.2—What is silica fume?

Silica fume is a by-product resulting from the reduction of high-purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal or ferrosilicon alloys. The silica fume, which condenses from the gases escaping from the furnaces, has a very high content of amorphous silicon dioxide and consists of very fine spherical particles (Fig. 1.1). The SiO_2 content of the silica fume is roughly related to the manufacture of silicon alloys as follows:

Alloy type	SiO_2 content of silica fume
50 percent ferrosilicon	61 to 84 percent
75 percent ferrosilicon	84 to 91 percent
silicon metal (98 percent)	87 to 98 percent

Ferrosilicon alloys are produced with nominal silicon contents of 61 to 98 percent. When the silicon content reaches 98 percent, the product is called silicon metal rather than ferrosilicon. As the silicon content increases in the alloy, the SiO_2 content will increase in the silica fume. The majority of published data and field use of silica fume have been from production of alloys of 75 percent ferrosilicon or higher. Limited applications have been made using fume from production of 50 percent ferrosilicon alloys.

Fume is also collected as a by-product in the production of other silicon alloys. Few published data are available on the properties of these fumes. The use of these fumes should be avoided unless data on their favorable performance in concrete are available.

1.3—Silica fume versus other forms of synthetic silica

Several other amorphous silica products are occasionally confused with silica fume. These products are purposely made, and while they offer the potential of performing well in concrete, they are typically too expensive for such use. These products are made through three processes:

1.3.1 *Fumed silica*—Fumed silica is produced by a vapor-phase hydrolysis process using chlorosilanes such as silicon tetrachloride in a flame of hydrogen and oxygen. Fumed silica is supplied as a white, fluffy powder.

1.3.2 *Precipitated silica*—Precipitated silica is produced in a finely divided form by precipitation from aqueous alkali-metal silicate solutions. Precipitated silica is supplied as a white powder or as beads or granules.

1.3.3 *Gel silica*—Gel silica is also prepared by a wet process in which an aqueous alkali-metal silicate solution is reacted with an acid so that an extensive three dimensional hydrated silica structure or gel is formed. It is supplied as granules, beads, tablets, or as a white powder.

Additional information on these synthetic silicas may be found in ASTM E 1156 or in the work of Dunnom (1984), Ulrich (1984), or Griffiths (1987).

1.4—Using silica fume in concrete

Silica fume was initially viewed as a cement replacement material; and in some areas it is still used as such. In general applications, part of the cement may be replaced by a much smaller quantity of silica fume. For example, one part of silica fume can replace 3 to 4 parts of cement (mass to mass) without loss of strength, provided the water content remains constant. The reader is cautioned that replacement of cement by silica fume may not affect hardened concrete properties

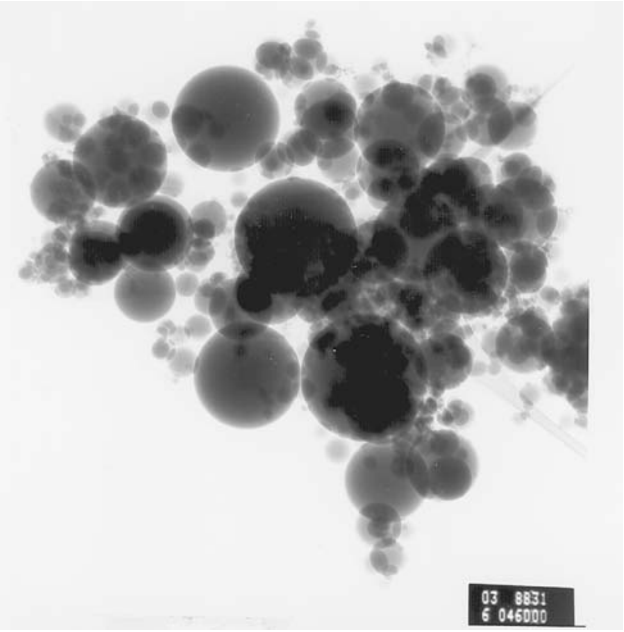

Fig. 1.1 —TEM micrograph of silica fume (courtesy of J. Ng-Yelim, CANMET, Ottawa)

other than strength to the same degree. See Chapter 5 for a discussion of the effects of silica fume on the properties of hardened concrete.

Silica fume addition usually increases water demand. If it is desired to maintain the same water-to-cementitious materials ratio (by mass), water-reducing admixtures or HRWRA or both should be used to obtain the required workability. In order to maintain the same apparent degree of workability, a somewhat higher slump will normally be required for silica-fume concrete because of the increased cohesion.

Because of limited availability and the current high price (relative to portland cement and other pozzolans or slag), silica fume is being used increasingly as a property-enhancing material. In this role silica fume has been used to provide concrete with very high compressive strength or with very high levels of durability or both. In the United States it is currently being used predominantly to produce concretes with reduced permeability for applications such as parking structures and bridge decks. Additional applications of silica-fume concrete are presented in Chapter 6.

1.5—Using silica fume in blended cements

The use of silica fume in blended cements has also attracted interest. Aïtcin (1983) reported that one Canadian cement manufacturer had been making a blended cement since 1982. At present, several Canadian cement companies are selling blended cement containing 7 to 8 percent silica fume. The use of cement containing 6 to 7 percent silica fume to combat alkali-silica reaction in Iceland was described by Asgeirsson and Gudmundsson (1979) and by Idorn (1988). Since 1979, all Icelandic cement is blended with silica fume. Lessard, Aïtcin, and Regourd (1983) have described the use of a blended cement containing silica fume to reduce heat of hydration. Typically, the properties of cements containing silica fume as a blending material may be expected to be the same as if the silica fume were added separately. As with any blended cement, there will be a loss in flexibility in mixture proportioning with respect to the exact amount of silica fume in a given concrete mixture. Unless otherwise stated, the results and information presented in this document were derived from concretes made with separately added silica fume.

1.6—World-wide availability of silica fume

Precise data on the annual output of silica fume in the world are not readily available because of the proprietary nature of the alloys industry. Estimates may be found in publications of the U.S. Bureau of Mines (1990) or in the work of RILEM Technical Committee 73-SBC (1988).

Silica fume generation from silicon-alloy furnaces is typically about 30 percent by mass of alloy produced (Aïtcin 1983). Of the silica fume produced in the world, it is not known what percentage is actually collected.

1.7—Types of silica-fume products available

Silica fume is available commercially in the United States in several forms. All of the product forms have positive and negative aspects that may affect technical performance, material handling, efficiency, and product-addition rate. Material handling methods have been developed in Norway, the United States, and Canada to use silica fume in its as-produced form, densified or compacted form, or slurried form (Jahren 1983; Skrastins and Zoldners 1983). The available forms are described in the following sections.

1.7.1 *As-produced silica fume*—Silica fume as collected is an extremely fine powder. For this report, this material is referred to as "as-produced silica fume." As-produced silica fume may be available in bulk or in bags, depending upon the willingness of the producer to supply this form.

As-produced silica fume has been handled and transported like portland cement or fly ash. However, because of its extreme fineness and low bulk loose density, as-produced silica fume may present serious handling problems. Some as-produced silica fumes will flow with great difficulty. Clogging of pneumatic transport equipment, stickiness, and bridging in storage silos are other problems associated with as-produced silica fume. These problems can be partially overcome with properly designed loading, transport, storage, and batching systems.

Bagged as-produced silica fume has been used by discharging the material directly into truck mixers. However, this approach has not been popular because of the dust generated and the high labor costs. As-produced silica fume has not been used extensively in ready-mixed concrete because of the handling difficulties and higher transportation costs than for other forms of silica fume (Holland 1989).

There is at least one area in the United States near a smelter where as-produced silica fume has been used as a cement replacement. However, elsewhere, very little silica fume in the as-produced state has been used in concrete in the United States.

1.7.2 *Slurried silica fume*—To overcome the difficulties associated with transporting and handling the as-produced silica fume, some suppliers have concentrated on marketing silica fume as a water-based slurry. Slurried silica fume typically contains 42 to 60 percent silica fume by mass, depending upon the supplier. Even when the mass of the water is considered, transportation of the slurry is usually more economical than transportation of the as-produced silica fume.

The slurries are available with and without chemical admixtures such as water reducers, HRWRA, and retarders. The actual amount of chemical admixture in the slurry will vary depending upon the supplier. The admixture dosage typically ranges from that which offsets part of the increased water demand caused by the silica fume to that which provides significant water reduction to the concrete. The slurried products offer the major advantage of ease of use over the as-produced silica fume once the required dispensing equipment is available at the concrete plant. Slurried products are typically available in bulk, 55-gal (208-L) drums, and 5-gal (19-L) pails.

1.7.3 *Densified (compacted) silica fume*—Dry, densified (or compacted) silica-fume products are also available. These products are dense enough to be transported economically. They may be handled like portland cement or fly ash at a concrete plant. The densification process greatly reduces the dust associated with the as-produced silica fume.

One method to produce the densified silica fume is to place as-produced silica fume in a silo. Compressed air is blown in from the bottom of the silo causing the particles to tumble. As the particles tumble, they agglomerate. The heavier agglomerates fall to the bottom of the silo and are periodically removed. Because the agglomerates are held together relatively weakly, they break down with the mixing action during concrete production. The majority of published data and field use of densified silica fume have been from the air-densification process. Unless otherwise stated, the densified silica fume referred to in this report was produced by the air-densification process.

Another method for producing densified silica fume is to compress the as-produced material mechanically. Mechanically-densified silica fume is commercially available in the United States.

The densified (compacted) dry silica-fume products are available with and without dry chemical admixtures. These products are typically available in bulk, in bulk bags [approximately 2000 lb (907 kg)], and in small bags [approximately 50 lb (23 kg)].

1.7.4 *Pelletized silica fume*— As-produced silica fume may also be pelletized by mixing the silica fume with a small amount of water, typically on a disk pelletizer. This process forms pellets of various sizes that can be disposed of in landfills. Pelletizing is not a reversible process — the pellets are too hard to break down easily during concrete production. Pelletized silica fume is not being used as an admixture for concrete; however, it may be interground with portland cement clinker to form a blended cement. The committee is not aware of data comparing the performance of blended cement with interground pelletized silica fume with that of directly added silica fume or blended cement made with as-produced or densified silica fume.

1.8—Health hazards

Until recently, in the United States, the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH), classified silica fume in a general category of "amorphous silica." In 1992 the ACGIH in its publication, "Threshold Limit Values for Chemical Substances and Physical Agents," explicitly listed silica fume with a CAS (Chemical Abstracts Service) number of 69012-64-2. This listing included a Time Weighted Average of 2 mg/m^3 for the respirable portion of the dust. Trace amounts (less than one percent) of crystalline silica (quartz) may be present in silica fume. OSHA (1986) lists amorphous silica and quartz as hazardous materials whereas ACGIH (1992) lists silica fume and quartz as hazardous materials. These listings have apparently been developed based upon exposures of workers in the ferrosilicon industry.

Papers presented at a symposium entitled the "Health Effects of Synthetic Silica Particulates" (Dunnom 1981) indicated that there is little health-hazard potential from the inhalation of amorphous silica fume due to the small particle size and noncrystalline structure. Jahr (1981) stated that experience in Norwegian ferrosilicon manufacturing plants indicated that the risk of silicosis is very small from exposure to this type of amorphous silica.

The committee is not aware of any reported health-related problems associated with the use of silica fume in concrete. There are no references to the use of silica fume in the concrete industry in the publications of either OSHA or ACGIH. The committee recommends that workers handling silica fume use appropriate protective equipment and procedures which minimize the generation of dust. Users should refer to the manufacturer's material safety data sheets for the products being used for specific health and safety information.

CHAPTER 2—PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF SILICA FUME

2.1—Color

Most silica fumes range from light to dark gray in color. Because SiO_2 is colorless, the color is determined by the nonsilica components, which typically include carbon and iron oxide. In general, the higher the carbon content, the darker the color of the silica fume. The carbon content of silica fume is affected by many factors relating to the manufacturing process such as: wood chip composition, wood chip use versus coal use, furnace temperature, furnace exhaust temperature, and the type of product (metal alloy) being produced. The degree of compaction may also affect the color.

2.2—Density

The specific gravity of silica fume is approximately 2.2, as compared to about 194 lb/ft^3 (3100 kg/m^3) for normal portland cement. However, the density of some silica fumes may exceed 137 lb/ft^3 (2200 kg/m^3). Table 2.1 lists silica fume density results from several sources. Variations in density are attributed to the nonsilica components of the various silica fumes.

2.3—Bulk density

2.3.1 *As-produced silica fume*— The bulk density of as-produced silica fume collected from silicon metal and ferrosilicon alloy production usually ranges from 8 to 27 lb/ft^3 (130 to 430 kg/m^3), although it is most common to see values near the middle of this range.

2.3.2 *Slurried silica fume*— Slurried silica fume will typically have a bulk density of about 11 to 12 lb/gal [83 to 90 lb/ft^3 (1320 to 1440 kg/m^3)]. The nominal silica fume content of most slurries is approximately 50 percent by mass. The actual silica fume content may vary depending upon the

Table 2.1—Silica fume density versus alloy type

Silicon alloy type	Silica fume density, Mg/m^3	Reference
Si	2.23	1
Si and FeSi-75 percent	2.26-2.27	2, 3
FeSi-75 percent	2.21-2.23	1
FeSi-50 percent	2.3	1

References:
1. Aïtcin, Pinsonneault, and Roy, 1984.
2. Pistilli, Roy, and Cecher, 1984.
3. Pistilli, Wintersteen, and Cechner, 1984.

particular source and whether chemical admixtures have been added to the slurry.

2.3.3 *Densified (compacted) silica fume*—Densification from an initial bulk density of 12.5 lb/ft^3 (200 kg/m^3) to a densified value of 31.2 lb/ft^3 (500 kg/m^3) has been reported (Elkem 1980; Popovic, Ukraincik, and Djurekovic 1984). The bulk density of commercially available densified silica fume ranges from approximately 30 to 40 lb/ft^3 (480 to 640 kg/m^3). Beyond about the 45 lb/ft^3 (720 kg/m^3) level, it may become increasingly difficult to disperse densified silica fume particles within concrete.

2.4—Fineness, particle shape, and oversize material

Silica fume consists primarily of very fine smooth spherical glassy particles with a surface area of approximately 20,000 m^2/kg when measured by the nitrogen-adsorption method. The extreme fineness of silica fume is best illustrated by the following comparison with other fine materials (note that the values derived from the different measuring techniques are not directly comparable):

Silica fume: 13,000-30,000 m^2/kg, nitrogen adsorption
Fly ash: 400 to 700 m^2/kg, Blaine
Ground granulated blast-furnace slag: 350 to 600 m^2/kg, Blaine
Portland cement: 300 to 400 m^2/kg, Blaine

The nitrogen-adsorption method is currently the most common test used to estimate the surface area of silica fume particles. The Blaine apparatus is not appropriate for measuring the surface area of silica fume because of difficulties in obtaining the necessary 0.50 porosity level to conduct the test. Nitrogen-adsorption surface area results for various silica fumes have ranged from 13,000 to 30,000 m^2/kg (Malhotra et al. 1987). One study of Si and FeSi-75 percent silica fumes reported results between 18,000 m^2/kg and 22,000 m^2/kg (Elkem 1980). Another study (Nebesar and Carette 1986) reported average surface area values of 20,000 m^2/kg and 17,200 m^2/kg for Si and FeSi-75 percent silica fumes respectively. Because the nitrogen-adsorption result is affected by the carbon content of the silica fume (the carbon itself has a high surface area), the carbon content should be reported along with the surface area. Often, the loss on ignition (LOI) is reported in lieu of the carbon content.

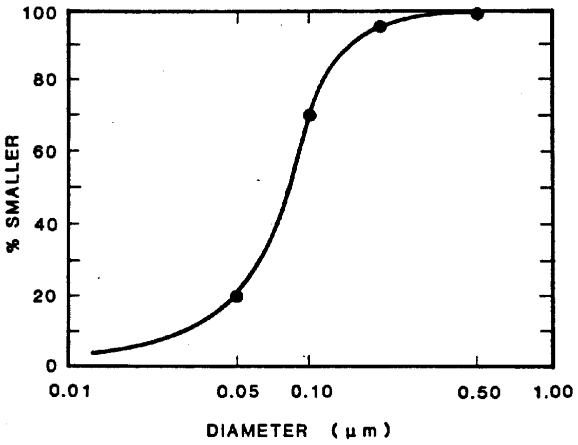

Fig. 2.1—Particle size distribution of silica fume (Fiskaa, Hansen, and Moum 1971)

The particle-size distribution of a typical silica fume shows most particles to be smaller than one micrometer (1 µm) with an average diameter of about 0.1 µm (Fig. 2.1). This is approximately 1/100 of the size of an average cement particle. The particle size distribution of silica fume may vary depending upon the fume type and the furnace gas exhaust temperature.

One of the most common tests conducted upon silica fume is the residue (oversize) on the 45-µm (No. 325) sieve. In this test a sample of silica fume is washed through a 45-µm sieve, and the mass and composition (wood, quartz, carbon, coal, rust, and relatively large silica fume agglomerates) of the oversize particles are reported.

The amount of oversize material is strongly influenced by the silica-fume collection system; and the amount of oversize material may vary considerably from one system to another. Many silica fumes show oversize amounts less than 6 percent, although larger values may be seen. Various values have been reported for the amount of oversize: 0.3 to 3.5 percent (Elkem 1980), 3.7 to 5.6 percent (Pistilli, Rau, and Cechner 1984), and 1.8 percent and 5.4 percent for Si and FeSi-75 percent, respectively (Nebesar and Carette 1986). The Canadian Standard, “Supplementary Cementing Materials” (Canadian Standards Association 1986), limits the maximum amount retained on the 45-µm sieve to 10 percent.

Because many nonsilica components of silica fume are associated with the larger particles, some silica fume suppliers routinely remove oversize particles from the silica fume. Some oversize removal (beneficiating) processes work with the dry fume using various kinds of cyclones or classifiers. Other systems run slurried silica fume through screens, usually after the silica fume has been passed through one or more of the dry beneficiating processes.

2.5—Chemical composition

Table 2.2 gives the chemical composition of typical silica fumes from silicon furnaces in Norway and North America. The silica fumes generally contain more than 90 percent silicon dioxide. The chemical composition of the silica fumes varies with the type of alloy that is being produced (see Section 1.2).

The acid-soluble chloride content of as-produced and densified silica fumes has been found to range between 0.016 to 0.025 percent by mass.* European specifications that address chlorides have established upper limits for chlorides in silica fume of 0.1 to 0.3 percent by mass. Assuming a cement content of 650 lb/yd^3 (390 kg/m^3), a 10 percent addition of silica fume by mass, and an acid-soluble chloride content of 0.20

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* Private communication from Michael Pistilli, member A CI Committee 234.

percent by mass in the silica fume, the silica fume would contribute 0.002 percent chloride ions by mass of cement. In cases where chloride limits are critical, chlorides contributed by the silica fume should be included in the overall calculations.

The pH of silica fume and water slurries may be determined. This test may be performed on a sample prepared by adding 20 grams of silica fume to 80 grams of deionized water. Typical values at one silicon metal source were between 6.0 and 7.0.

The committee is not aware of data describing effects of variations in nonsilicon dioxide components on concrete performance.

2.6—Crystallinity

Testing by X-ray diffraction has shown silica fume to be essentially amorphous (Nebesar and Carette 1986; Aïtcin, Pinsonneault, and Roy 1984). Silicon carbide (SiC), an intermediate compound occurring during the production of silicon and ferrosilicon alloys, has been observed (Popovic, Ukraincik, and Djurekovic 1984). All diffraction patterns exhibit a broad hump centered around the area where crystalline cristobalite would normally be found. The absence of a distinct peak at this location suggests that cristobalite is not present in significant quantities.

2.7—Variability

Although silica fume source-to-source variations and within-source variations have been monitored, only a limited amount of this information has been published. The results of within-source silica-fume variability studies for chemical composition and physical properties are presented in Table 2.2 and Table 2.3. These results indicate that silica-fume uniformity from a single source is reasonably similar to the uniformity associated with ground granulated blast-furnace slags, and the variations are smaller than those associated with fly ashes (Malhotra et al. 1987). This observation is not surprising considering that the production of silicon and alloys containing silicon are well-controlled metallurgical processes.

Seasonal, within-source variations occur in silica fume from a particular furnace. Changes in the materials used to produce silicon or silicon alloys will cause variations in the silica fume collected from these furnaces. If the silicon-alloy type is changed in a furnace, then the silica fume recovered from this furnace will change.

An approach toward minimizing within-source variations has been to blend silica fume from several furnaces or from many days of production or both. One silica fume supplier blends slurried silica fume from four furnaces producing the same alloy in a 400,000-gal (1,520,000 L) tank.

2.8—Relating physical and chemical properties to performance in concrete

Currently, the relationship between variations in physical and chemical properties of silica fume and performance in concrete is not well established.

It is sometimes assumed that the higher the $Si0_2$ content of a silica fume, the more reactive the silica fume will be in concrete. However, the committee does not have data to relate performance directly to SiO_2 content. Higher SiO_2 content implies that there are fewer of the non-SiO_2 components. This concept is reflected in the Canadian Standard (Canadian Standards Association 1986) that limits the use of silica fume in Canada to materials recovered from the production of silicon or ferrosilicon alloys containing at least 75 percent

Table 2.2—Variations in chemical composition of silica fumes from several sources

Silicon alloy type	Si(1)		FeSi-75 percent(1)		Si and FeSi-75 percent(2) blend		FeSi-75 percent(3)		Si(4)	
Number of samples (n)	42		42		32		6		28	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
SiO_2	93.65	3.84	93.22	1.71	92.1	1.29	91.4	0.92	94.22	0.34
Al_2O^3	0 .28	0.13	0.31	0.20	0.25	0.12	0.57	0.03	0.36	0.04
Fe_2O_3	0.58	2.26	1.12	0.86	0.79	0.70	3.86	0.41	0.10	0.01
CaO	0.27	0.07	0.44	0.34	0.38	0.11	0.73	0.08	0.27	0.05
MgO	0.25	0.26	1.08	0.29	0.35	0.10	0.44	0.05	0.20	0.02
Na_2O	0.02	0.02	0.10	0.06	0.17	0.04	0.20	0.02	—	—
K_2O	0.49	0.24	1.37	0.45	0.96	0.22	1.06	0.05	—	—
S	0.20(5)	0.16(5)	0.22(5)	0.06(5)	—	—	—	—	—	—
SO_3	—	—	—	—	0.36	0.10	0.36(6)	0.16(6)	—	—
C	3.62(5)	0.96(5)	1.92(5)	1.15(5)	—	—	—	—	3.05	0.25
LOI	4.36(5)	1.48(5)	3.10(5)	0.90(5)	3.20	0.45	2.62(6)	0.42(6)	3.60	0.33

Note:
(1) From Nebesar and Carette, 1986
(2) From Pistilli, Rau, and Cechner, 1984
(3) From Pistillo, Wintersteen, and Cechner, 1984
(4) From Luther, 1989a
(5) n = 24
(6) n = 30

Table 2.3—Physical properties of several silica fumes

	Silicon alloy type	Si(1)	FeSi-75 percent(1)	Si and FeSi-75 percent(2)	FeSi-75 percent(3)
	Number of samples	24	24	Blend 32	30
Percent retained on 45-µm sieve	Mean	5.4	1.8	5.62	3.73
	Standard deviation	4.0	1.5	1.69	4.48
Specific surface area using nitrogen adsorption method (m^2/kg)	Mean	20,000	17,200	—	—
	Standard deviation	2100	—	—	—
Specific gravity	Mean	—	—	2.27	2.26
	Standard deviation	—	—	0.02	0.08
Pozzolanic activity index with portland cement, percent	Mean	102.8	96.5	91.9(4)	95.3(4)
	Standard deviation	5.1	13.7	10.0	4.0
Pozzolanic activity index with lime (MPa)	Mean	8.9	—	7.0(4)	9.1(4)
	Standard deviation	0.8	—	0.8	0.9
Water requirement, percent	Mean	138.8	139.2	140.1(4)	144.4(4)
	Standard deviation	4.2	7.2	2.6	2.0

Notes:
(1) from Nebesar and Carette, 1986.
(2) From Pistilli, Rau, and Cechner, 1984.
(3) From Pistilli, Wintersteen and Cechner, 1984.
(4) 8 samples.

silicon. Silicon and ferrosilicon (75 percent) silica fumes contain higher amorphous SiO_2 contents than the other silica fumes. This standard, however, does allow the use of silica fume recovered from the production of ferrosilicon alloys containing less than 75 percent silicon if acceptable performance of the material in concrete has been demonstrated.

Among the silica fumes that have been used in North America in concrete to date, it has been possible to achieve desired entrained air contents, although silica fumes having relatively high carbon contents may require increased air-entraining admixture dosages. The Canadian Standard (Canadian Standards Association 1986) limits the loss on ignition, which relates closely to the carbon content, to a maximum of 6 percent.

Although many project specifications have required a surface-area (fineness) range for the silica fume that will be used in the concrete, no data are currently available to relate concrete performance to silica fume fineness. Finer particles will react more quickly or to a greater extent than coarser ones. However, the increased water demand of finer silica fumes may offset, to some degree, the beneficial effects of the increased reactivity of the particles, unless a water-reducing admixture or high-range water-reducing admixture (HRWRA) is used.

It has not been demonstrated to date that the characteristic pH of a silica-fume slurry is associated with significant changes in concrete properties or performance.

Published data relating delivery form of silica fume (as-produced, slurried, or densified) to performance in concrete are lacking. There may be minor differences in the fresh and hardened concrete properties for concretes made with the different available forms. There may also be minor differences in performance resulting from changing sources of silica fume. Laboratory tests to verify performance are recommended when a change in form or source of silica fume is anticipated during a project.

2.9—Quality control

Since there are few published data available to relate particular physical or chemical properties of silica fume to its performance in concrete, quality-control measures should aim at assuring uniformity of properties of a particular silica fume in order to minimize variations in the performance of the concrete. Changes in the silica fume or in the silicon alloy should be reported by the silica-fume supplier. Laboratory testing to verify performance in concrete is recommended if a change occurs.

CHAPTER 3—MECHANISM BY WHICH SILICA FUME MODIFIES CEMENT PASTE

3.1—Physical effects

Cohen, Olek, and Dolch (1990) have calculated that for a 15 percent silica fume replacement of cement, there are approximately 2,000,000 particles of silica fume for each grain of portland cement in a concrete mixture. It is, therefore, no surprise that silica fume has a pronounced effect on concrete properties.

In general, the strength at the transition zone between cement paste and coarse aggregate particles is lower than that of the bulk cement paste. The transition zone contains more voids because of the accumulation of bleed water underneath the aggregate particles and the difficulty of packing solid particles near a surface. Relatively more calcium hydroxide (CH) forms in this region than elsewhere. Without silica fume, the CH crystals grow large and tend to be strongly oriented parallel to the aggregate particle surface (Monteiro, Maso, and Olliver 1985). CH is weaker than calcium silicate hydrate (C-S-H), and when the crystals are large and strongly oriented parallel to the aggregate surface, they are easily cleaved. A weak transition zone results from the combination of high void content and large, strongly oriented CH crystals.

According to Mindess (1988), silica fume increases the strength of concrete largely because it increases the strength of the bond between the cement paste and the aggregate particles. Wang et al. (1986) found that even small additions (2 to 5 percent) of silica fume produced a denser structure in the transition zone with a consequent increase in microhardness and fracture toughness. Detwiler (1990) also found that silica fume increased the fracture toughness of the transition zone between cement paste and steel.

The presence of silica fume in fresh concrete generally results in reduced bleeding and greater cohesiveness, as discussed in Chapter 4. This is a physical effect, the result of incorporating extremely fine particles into the mixture. As Sellevold (1987) pointed out, “The increased coherence (cohesiveness) will benefit the hardened concrete structure in terms of reduced segregation and bleed water pockets under reinforcing bars and coarse aggregate.” Monteiro and Mehta (1986) stated that silica fume reduces the thickness of the transition zone between cement paste and aggregate particles. One reason for this is the reduction in bleeding.

The presence of silica fume accelerates the hydration of cement during the early stages. Sellevold et al. (1982) found that equal volumes of an inert filler (calcium carbonate) produced the same effect. They concluded that the mere presence of numerous fine particles — whether pozzolanic or not — has a catalytic effect on cement hydration.

Monteiro and Mehta (1986) proposed that the minute silica-fume particles provide nucleation sites for CH crystals so that the CH crystals are smaller and more randomly oriented. Wang et al. (1986) also found that the mean size and orientation index of the CH crystals within the transition zone were reduced by the addition of silica fume. At the interface itself, the CH crystals will be oriented parallel to the aggregate surface whether silica fume is present or not. In a study of the texture (preferred orientation) of CH crystals in the transition zone, Detwiler et al. (1988) found that silica fume did not affect the orientation. However, within the transition zone (within 50 µm of the aggregate surface) both the crystal size and amount of CH are reduced, thus leading to a strengthening of this region. The pozzolanic reaction, discussed in the next section, brings about further improvements in strength over time.

In hardened concrete, silica-fume particles increase the packing of the solid materials by filling the spaces between the cement grains in much the same way as cement fills the spaces between the fine-aggregate particles, and fine-aggregate fills the spaces between coarse-aggregate particles in concrete. This analogy applies only when surface forces between cement particles are negligible, that is, when there is enough admixture present to overcome the effects of surface forces. Bache (1981) explained the theory of the packing of solid particles and its effect on the properties of the material. Because it is a composite, concrete is affected not only by the packing of particles in the cement paste, but also by their packing near the surfaces of aggregate particles. Fig. 3.1 illustrates how the minute silica-fume particles can improve packing in the boundary zone. Since this is frequently the weakest part of a concrete, it is especially important to improve packing in this region.

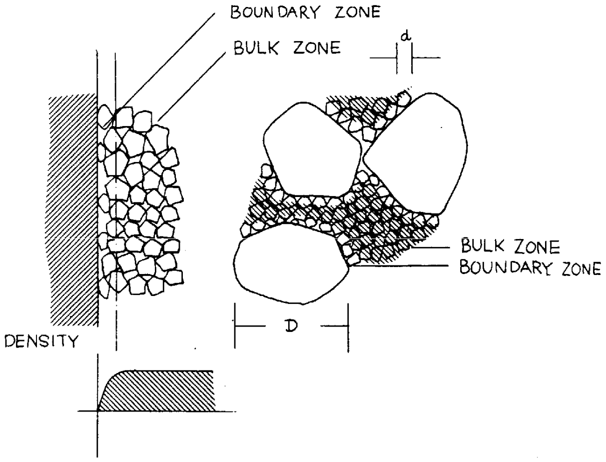


Fig. 3.1—Wall effect and barrier effect are expressions of the fact that particles are packed more loosely in the immediate vicinity of a surface than in the bulk, and of the fact that there is not room for small particles in the narrow zones between big particles

Bache (1981) also showed that addition of silica fume could reduce water demand because the silica-fume particles were occupying space otherwise occupied by water between the cement grains. This reduction only applies for systems with enough admixture to reduce surface forces. Sellevold and Radjy (1983) also reported on a decrease in water demand for silica-fume mixtures and stated that water-reducing admixtures have a greater effect on silica-fume concretes. However, in most concretes used for general construction purposes, the addition of silica fume will result in an increase in water demand because of the high surface area of the silica fume and will require the use of a water-reducing admixture or a high-range water-reducing admixture HRWRA.

It is worth emphasizing here that all of these physical mechanisms depend on thorough dispersion of the silica-fume particles in order to be effective. This requires the addition of sufficient quantities of water-reducing admixture(s) to overcome the effects of surface forces and ensure good packing of the solid particles. The proper sequence of addition of materials to the mixer as well as thorough mixing are also essential (see section 9.2).

3.2—Pozzolanic reactions

In the presence of hydrating portland cement, silica fume will react as any finely divided amorphous silica-rich constituent in the presence of CH — the calcium ion combines with the silica to form a calcium-silicate hydrate through the pozzolanic reaction. The simplest form of such a reaction occurs in mixtures of amorphous silica and calcium hydroxide solutions. Buck and Burkes (1981) studied the reactivity of silica fume with calcium hydroxide in water at 38 C. Silica fume to calcium hydroxide ratios (SF:CH) 2:1, 1:1 and 1:2.25 were included. They found that a well-crystallized form of CSH-I was formed by 7 days of curing. For the 2:1 mixtures, all CH was consumed by 7 days; for the 1:1 mix-

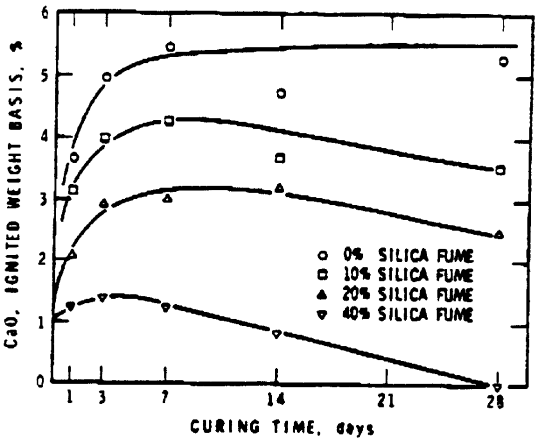


Fig. 3.2—Amount of calcium hydroxide (as CaO) in cement pastes containing different amounts of silica fume (Ono, Asaga, and Daimon 1985; as shown in Malhotra et al. 1987)

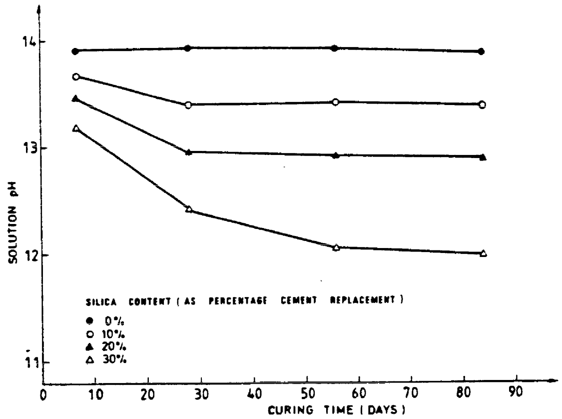


Fig. 3.3—Influence of silica fume on pH values of pore water squeezed from cement pastes. Ordinary portland cement, water-to-cement plus silica fume ratio of 0.50 (Page and Vennesland, 1983)

tures, 28 days was required to consume the CH. Kurbus, Bakula, and Gabrousek (1985) found that reaction rates were dramatically increased at higher temperatures. At 90 C, 95 percent of added CH was reacted after only 2.5 hours in an 4:1 mixture of SF:CH. In cement pastes the reactions are more complex. Grutzeck, Roy, and Wolfe-Confer (1982) suggest a "gel" model of silica fume-cement hydration. According to this model, silica fume contacts mixing water and forms a silica-rich gel, absorbing most of the available water. Gel then agglomerates between the grains of unhydrated cement, coating the grains in the process. Calcium hydroxide reacts with the outer surface of this gel to form C-S-H. This silica-fume gel C-S-H forms in the voids of the C-S-H produced by cement hydration, thus producing a very dense structure.

Ono, Asaga, and Daimon (1985) studied the cement-silica fume system in low water-cement ratio (0.23) pastes at 20 C. The amounts of CH present after various periods of hydration at portland cement:silica fume ratios of 100:0, 90:10, 80:20, and 60:40 are shown in Fig. 3.2. At very high levels of silica fume, almost all CH is consumed by 28 days. At lower levels of silica fume, e.g., 10 percent, typical of those used in practice, CH is reduced by almost 50 percent at 28 days. These results are supported by those of Huang and Feldman (1985a) who found that while silica fume accelerates early hydration and leads to increased production of CH at times up to 8 hours, at later ages CH is consumed, and for a mixture containing 50 percent silica fume, no CH is detectable after 14 days. Hooton (1986) found that with 20 percent by volume silica-fume replacement, no CH was detectable after 91 days moist curing at 23 C, while 10 percent silica fume reduced CH by 50 percent at the same age. The exact constituents of portland cement or silica fume or both that determine the extent of pozzolanic reaction have not been well defined, although studies by Traetteberg (1978) indicate that alkali and silica contents of the silica fume appear to exert some influence. Silica fumes with lower alkali and higher SiO_2 contents are able to bind more CH and increase the extent of the pozzolanic reaction.

3.3—Pore water chemistry

The Ca-Si ratio of hydration products has been found to decrease with increased silica fume levels; and as a result of the low Ca-Si ratio, the C-S-H is able to incorporate more substitutions such as aluminum and alkalies. Diamond (1983) noted that the alkalies in silica-fume pore solutions were significantly reduced, as did Page and Vennesland (1983).

In cement pastes, Page and Vennesland (1983) found that the pH of pore solutions was reduced by increasing replacements of portland cement by silica fume (Fig. 3.3). The reduction in pH could be due to increased reaction of alkalies and calcium hydroxide with silica fume.

According to Byfors, Hansson, and Tritthart (1986), silica fume causes a much greater reduction in the hydroxyl content of pore solutions than either slag or fly ash. The reduction in hydroxyl concentration was also found by Diamond (1983). There are conflicting data on the chloride-binding capacity of silica fume, with Byfors, Hansson, and Tritthart (1986) finding an increase, while Page and Vennesland (1983) noted a decrease.

Concern is frequently raised regarding a reduction in pH of pore water by the consumption of CH by silica fume and the impact of any such reduction on the passivation of reinforcing steel. At the levels of silica fume usage typically found in concrete, the reduction of pH is not large enough to be of concern. For corrosion protection purposes, the increased electrical resistivity (Section 5.4.1) and the reduced permeability to chloride ions (Section 5.3.3) are believed more significant than any reduction in pore solution pH.

3.4—Reactions in combination with fly ash or blast-furnace slag

A number of researchers have looked at combinations of fly ash and silica fume. The primary research objectives were to offset the reduced early strengths typical of fly ash concretes and to evaluate the durability parameters of concretes with combinations of pozzolans. The committee is not aware of definitive information regarding reaction mechanisms when fly ash and silica fume are both present. See also Section 5.6.

Mehta and Gjørv (1982), during an investigation of compressive strengths of concretes made with combinations of fly ash and silica fume, also examined free CH and pore-size distribution of similar cement pastes. Based on strength development and free CH determinations, they concluded that the combinations of pozzolans showed much greater pozzolanic activity, even at 7 and 28 days than did the fly ash alone. The combination also showed considerable reduction in the volume of large pores at all ages studied.

Carette and Malhotra (1983b) found that the later-age strength development of concrete containing silica fume and fly ash was not impaired, indicating the availability of sufficient CH for fly ash pozzolanic activity.

The commercial use of silica fume in combination with ground granulated blast-furnace slag (GGBFS) has been reported (Bickley et al. 1991). It was found that silica fume helped in obtaining high-early strength and that later-age strength development of portland cement-silica fume concrete was enhanced by the addition of GGBFS. However, the mechanism by which hydration was modified was not studied.

Regourd, Mortureux, and Hornain (1983) found that silica fume and GGBFS competed for the available calcium hydroxide and that the microstructure of pastes and the mechanical strengths of mortars were not very different for the mixtures containing 5 percent silica fume. They did note that the cement paste-aggregate bond seemed better in the presence of silica fume. Sarkar, Aïtcin, and Djellouli (1990) reported on the microstructural development of a high-strength concrete containing 10 percent silica fume and a 30 percent GGBFS replacement of portland cement. They found that the silica fume began to react within one day. The reaction of GGBFS was much slower, probably because of the higher CH consumption of the silica fume.

3.5—Reactions with different types of portland cements

Silica fume, because of its high surface area, accelerates the hydration of alite (Malhotra et al. 1987). The initial heat evolution of alite is intensified in the presence of active silica (Kurdowski and Nocun-Wczelik 1983). Therefore, it might be expected that portland cements with high alite contents would benefit from silica fume; more CH is created which in turn is available to react pozzolanically with silica fume. However, Hooton (1986) used silica fume with Type V portland cement and found a reduced rate of hydration of alite.

3.6—Heat of hydration

Most available data on heat development in portland cement-silica fume systems relate to early age tests. Huang and Feldman (1985a) have studied cement pastes containing 0, 10, 20, and 30 percent silica fume using conduction calori-metry. Two peaks were discernible (Fig. 3.4), one occurring at 5 hr and one at about 6 to 10 hr. The earlier peak, attributable to alite hydration, appears to be shifted to earlier times as the amount of silica fume is increased. The second, more prominent peak, may be due to either aluminate hydration or a pozzolanic reaction. The intensity of this peak also increases as silica fume is increased. Although the rate of heat liberation, expressed on a cement basis, is greater as the amount of silica fume increases, the total heat liberated, expressed on a total solids basis in the mixture, is somewhat decreased as silica fume is substituted for cement. Data by Kumar and Roy (1984) indicate that total heat may be reduced by 15 to 30 percent depending upon the particular cement and amount of silica fume used. Meland (1983) performed isothermal calorimetry on pastes in which portland cement was replaced by 10 or 20 percent silica fume. Except for the combination of 10 percent silica fume and a lignosulfonate water reducer, all of the pastes showed a decrease in the total heat of hydration

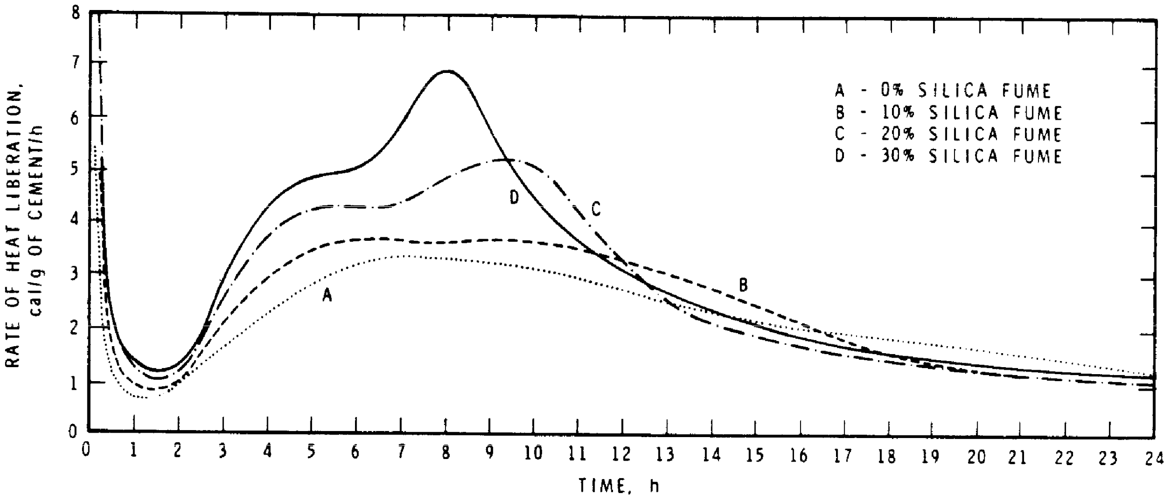


Fig. 3.4—Rate of heat evolution in cement-silica fume pastes (Huang and Feldman 1985a)

when compared to a plain portland cement paste. Meland attributed the one case of increased total heat to a possible interaction between the silica fume and the lignosulfonate material.

3.7—Reactions with chemical admixtures

3.7.1 *High-range water-reducing admixtures (HRWRA)*—Since silica fume has a very high surface area, it will increase the water demand when used in concrete. HRWRA are usually recommended in order to lower the water demand to the appropriate level and to allow for adequate dispersion and proper packing of the silica-fume particles.

The two most common HRWRA are sulfonated melamine formaldehyde condensate and sulfonated naphthalene formaldehyde condensate. It is believed that adsorption of the molecular polymer chain on the surface of cement grains accounts for dispersion of cement (Andersen and Roy 1988). This also accounts for dispersion of silica fume in cement or concrete mixtures. The polymer adsorbs on the surface of the cement and silica fume, producing a negatively charged surface (the negative functional group facing the liquid phase). The resulting repulsion between the cement and silica fume particles prevents flocculation and causes the observed plasticizing effects.

The use of HRWRA in silica-fume concrete exposes more particle surface area for the pozzolanic reaction between calcium ion and silicon dioxide with a potential for increased production of C-S-H gel. This is probably due to dispersion of agglomerated silica fume particles. Rosenberg and Gaidis (1989) showed chemical and physical evidence that silica fume with HRWRA does not densify concrete in the usual sense; it enhances the paste-aggregate bond to produce a strength increase and that strength increase does not appear to be related to reduced porosity. Porosity is primarily controlled by the water-cementitious materials ratio which can be lowered by use of a HRWRA.

There is disagreement as to whether the mechanisms underlying improved mechanical properties of concrete containing both silica fume and HRWRA are physical or pozzolanic in nature. According to Bache (1981), when sufficient HRWRA is present to overcome surface forces, silica fume in concrete can fit into spaces between cement grains in the same way that fine aggregate occupies the space between particles of coarse aggregate and as cement grains occupy space among the fine aggregate.

Recent data (Detwiler and Mehta 1989) show that at age 7 days, the influence of silica fume on the compressive strength may be attributed mainly to physical effects. By an age of 28 days, both physical and chemical effects become significant. Testing was conducted by comparing silica fume with a non-pozzolanic material (carbon black) having a similar surface area. Both concretes contained HRWRA.

Malhotra et al. (1987) reported extensive information on chemical reactions in the cement-silica fume water system. The authors compiled all known published information regarding the most important aspects of the hydration reactions in this system.

An option when using silica fume in concrete is to increase the dosage of lignosulfonates, instead of using high amounts of HRWRA. Lignosulfonates are less expensive and more readily available in some parts of the world. However, the use of lignosulfonates is often limited because of extensive retardation of setting time and excessive air-entraining effects. Investigations by Helland and Maage (1988) and by Berg (1989) show that retardation is much less in concrete where silica fume has replaced cement (mass by mass). The mixtures made by Helland and by Berg do not have the same proportions; thus the results from the two series cannot be compared directly. The retardation may diminish in the presence of silica fume because of the large surface area of the material and consequent adsorption of a portion of the chemical admixture.

3.7.2 *Calcium chloride*—At this time the committee is not aware of published data on the interaction of calcium chloride and silica fume.

3.7.3 *Nonchloride accelerators*—The addition of silica fume to concrete containing nonchloride accelerator does not appear to influence the accelerating effect. The combination of the two has been used successfully in commercial applications, including high-strength concrete and concrete required to have a high degree of durability.

3.7.4 *Corrosion inhibitors*—Calcium nitrite is used as a corrosion inhibitor in reinforced concrete. Calcium nitrite in combination with silica fume has been successfully used in several commercial applications (Berke, Pfeifer, and Weil 1988; Berke and Roberts 1989). Calcium nitrite is also a set accelerator. However, it is usually used along with a retarder to offset this accelerating effect. The biggest benefit is in the area of corrosion protection, where it has been shown that silica fume reduces chloride ingress, while calcium nitrite will inhibit corrosion once the chloride ions reach the reinforcing steel.

3.7.5 *Air-entraining admixtures*—Experience indicates that the use of silica fume requires that the amount of air-entraining admixture generally must be increased in order to produce a specified air content in the concrete. However, once a proper air content is achieved in the fresh concrete, the air-void distribution is good (Pigeon, Plante, and Plante 1989).

The production of air-entrained, high-strength, flowing concrete using a HRWRA based on a combination of sulfonated melamines and sulfonated naphthalenes showed that the addition of two percent silica fume did not affect the size distribution of the air-voids. The air-entraining admixture was based on a sulfonated alkyl polyglycol ether (Ronneberg and Sandvik 1990). The dosage of the air-entraining admixture was the same whether or not silica fume was present, probably because of the small amount of silica fume used. See also Section 4.8.

3.7.6 *Compatibility with admixture combinations*—There are no published data describing incompatibility of silica fume with admixture combinations normally used in concrete. However, it is advisable to conduct laboratory testing of concrete using the proposed admixtures to assure that all materials are compatible.

CHAPTER 4—EFFECTS OF SILICA FUME ON PROPERTIES OF FRESH CONCRETE

4.1—Water demand

The water demand of concrete containing silica fume increases with increasing amounts of silica fume (Scali, Chin, and Berke 1987; Carette and Malhotra 1983a). This increase is due primarily to the high surface area of the silica fume. In order to achieve a maximum improvement in strength and permeability, silica-fume concrete should generally be made with a water-reducing admixture, a high-range water-reducing admixture (HRWRA), or both. The dosage of the HRWRA will depend upon the amount of silica fume and the type of water reducer used (Jahren 1983).

4.2—Workability

Fresh concrete containing silica fume is more cohesive and less prone to segregation than concrete without silica fume. As the silica-fume content is increased, the concrete may appear to become sticky. To maintain the same apparent workability, industry experience has shown that it is necessary to increase the initial slump of the concrete with silica fume by about 2 in. (50 mm) (Jahren 1983) above that required for conventional portland-cement concretes.

4.3—Slump loss

The presence of silica fume by itself will not significantly change the rate of slump loss of a given concrete mixture. However, since silica fume is typically used in conjunction with water-reducing admixtures, or HRWRA, or both, there may be a change in slump-loss characteristics which is actually caused by the chemical admixtures selected. Different chemical admixtures produce differing rates of slump loss. Trial batches using project materials are recommended to establish slump loss characteristics for a particular situation.

4.4—Time of setting

Silica-fume concrete usually includes chemical admixtures that may affect the time of setting of the concrete. Experience indicates that the time of setting is not significantly affected by the use of silica fume by itself. Practical control of the time of setting may be achieved by using appropriate chemical admixtures.

4.5—Segregation

Concrete containing silica fume normally does not segregate appreciably because of the fineness of the silica fume and the use of HRWRA. Segregation may occur in many types of concrete (with and without silica fume) with excessive slump, improper proportioning, improper handling, or prolonged vibration. The use of silica fume will not overcome poor handling or consolidation practices.

4.6—Bleeding and plastic shrinkage

Concrete containing silica fume shows significantly reduced bleeding. This effect is caused primarily by the high surface area of the silica fume to be wetted; there is very little free water left in the mixture for bleeding (Grutzeck, Roy, and Wolfe-Confer 1982). Additionally, the silica fume reduces bleeding by physically blocking the pores in the fresh concrete.

Plastic shrinkage cracks generally occur when the water evaporation rate from the concrete surface exceeds the rate at which water appears at the surface due to bleeding, or when water is lost into the subgrade. Since silica fume concrete exhibits significantly reduced bleeding, the potential for plastic shrinkage cracking is increased. Both laboratory and field experience indicate that concrete incorporating silica fume has an increased tendency to develop plastic shrinkage cracks (Aïtcin, Pinsonneault, and Rau 1981). Therefore, care should be exercised to prevent early moisture loss from freshly placed silica-fume concrete, particularly under conditions which promote rapid surface drying from one or more factors such as high concrete temperature, low humidity, low ambient temperatures combined with higher concrete temperatures, and high wind. Thus, it is necessary to protect the surfaces of freshly placed silica-fume concrete to prevent rapid water evaporation (Jahren 1983). Fogging, using evaporation retarders, erecting windbreaks, and immediate curing have been used successfully to eliminate plastic shrinkage cracking during placing of silica-fume concrete flatwork. See the reports prepared by ACI Committees 305 and 308 as well as Section 9.5.1 of this report for additional information regarding prevention of plastic shrinkage cracking.

4.7—Color of concrete

Fresh and hardened concretes containing silica fume are generally darker than conventional concrete. This is particularly apparent for concretes containing higher percentages of silica fume as well as those silica fumes that have a high percentage of carbon. The color difference may lessen and virtually disappear after some time (Gjørv and Løland 1982).

4.8—Air entrainment

The dosage of air-entraining admixture to produce a required volume of air in concrete usually increases with increasing amounts of silica fume due to the very high surface area of silica fume and to the effect of carbon when the latter is present (Carette and Malhotra 1983a).

4.9—Unit weight (mass) of fresh concrete

The use of silica fume will not significantly change the unit weight of concrete. Any changes in unit weight are the result of other changes in concrete proportions made to accommodate the use of the silica fume. It is frequently stated that silica fume will increase the “density” of concrete. Silica fume will produce a much less permeable concrete, but it will not produce a concrete with a higher mass per unit volume.

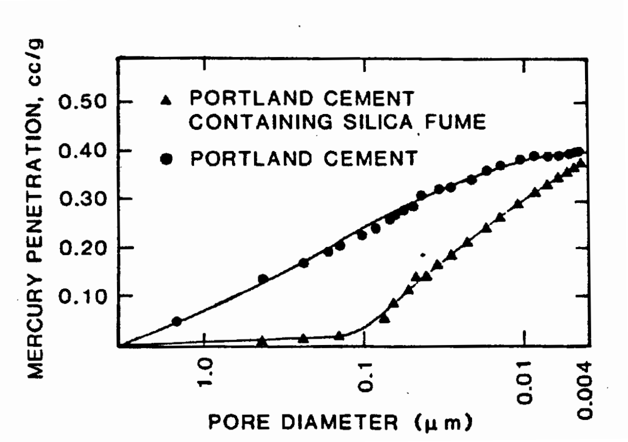


Fig. 5.1—Pore size distribution in pastes of neat portland cement with silica fume (Mehta and Gjørv 1982)

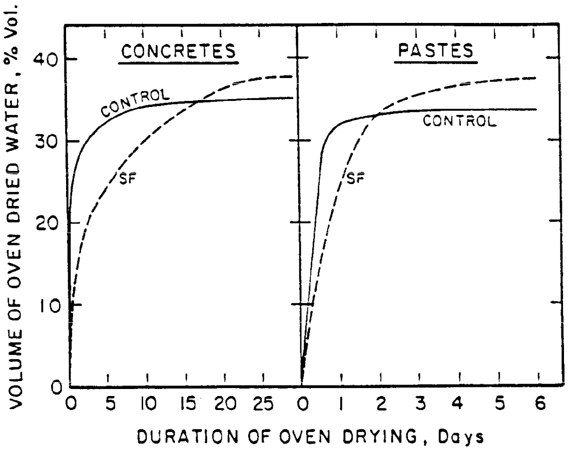


Fig. 5.2—Water loss curves during drying of pastes and concretes with and without silica fume at a water-cementitious materials ratio of 0.33. Water loss is presented as volume of water lost relative to paste volume (Bentur, Goldman, and Cohen 1988)

4.10—Evolution of hydrogen gas

Buil, Witier, and Paillere (1988) have reported on the evolution of hydrogen gas from a mixture of silica fume and lime. The reaction involves free silicon which may be present in very small quantities in some silica fumes and is similar to that which takes place when aluminum is placed in concrete. Research on this phenomenon is currently underway. Because hydrogen gas rather than atomic hydrogen is produced, this reaction does not indicate a risk of hydrogen embrittlement for prestressing steel (Warren 1987).

The evolution of hydrogen gas has raised concerns over possible explosion hazards. One case involving hydrogen gas trapped in the voids of extruded hollow core elements which were cured under accelerated conditions has been reported. The committee believes this reaction may be a concern only in confined areas with extremely poor ventilation. For typical construction applications, it will not be possible to develop a situation with enough hydrogen gas present in the atmosphere to cause an explosion.

CHAPTER 5—EFFECTS OF SILICA FUME ON PROPERTIES OF HARDENED CONCRETE

5.1—Microstructure modification

5.1.1 *Porosity*—Mercury intrusion porosimetry has shown that silica fume makes the pore structure of paste (Mehta and Gjørv 1982) and mortar (Huang and Feldman 1985b, Yamato, Emoto, and Soeda 1986) more homogeneous by decreasing the number of large pores, Fig. 5.1. Total porosity, however, appears to remain largely unaffected by silica fume.

Bentur, Goldman, and Cohen (1988) illustrated this refining effect of silica fume by the slower rate of water loss during drying of paste and concrete, Fig. 5.2. Here too, the total porosity remained nearly the same for pastes and concretes with and without silica fume. Tazawa and Yonekura (1986) reported that under the same drying conditions, water will evaporate more rapidly from large pores than small pores. The slower evaporation rate from paste and concrete containing silica fume is due to their having a larger proportion of fine pores than do conventional paste and concrete.

5.1.2 *Permeability*—The permeability of concrete is determined by the measurement of the liquid or vapor flow rate through the medium. High concrete permeability is closely linked to poor durability. These types of concretes have pore structures that allow freezing and thawing damage by water, cement paste deterioration due to the penetration of aggressive chemicals, and corrosion of embedded steel reinforcement by ingress of chloride ions.

The reduction in the size of capillary pores, as explained in Section 5.1.1, increases the probability of transforming the continuous pores into discontinuous ones (Philleo 1986). Since capillary porosity is related to permeability (Powers et al. 1954), the permeability to liquids and vapors is reduced by silica fume addition. Hooton's (1986) data for cement pastes of 0.25 water-to-cementitious materials ratio indicated water permeability of 0.9×10^{-13} m/s and $< 0.1 \times 10^{-13}$ m/s for 28-day cured pastes containing 10 and 20 percent by volume of silica fume respectively. When no silica fume was added, permeability was higher, 3.8×10^{-13} m/s.

Data for mortar and concrete show a similar trend in that silica fume reduces permeability (Sheetz, Grutzek, and Strickler 1981; Mehta and Gjørv 1982; Delage and Aïtcin 1983) by about one order of magnitude (Maage 1984; Maage and Sellevold 1987). Measurement of the water permeability for high-strength concrete [>40 MPa (5,800 psi)] is often impossible because of the measuring equipment limitations and leakage around the permeability cells (Hustad and Løland 1981; Hooton 1986; Hooton 1993). Sellevold and Nilsen (1987) concluded that silica fume is more effective in reducing permeability than it is in enhancing strength and suggested that it is the improved quality of the cement paste-aggregate transition zone (see Section 5.1.4) which is largely responsible.

The committee believes that the low permeability characteristics of silica-fume concrete and the corresponding improvements in long-term durability will provide the single

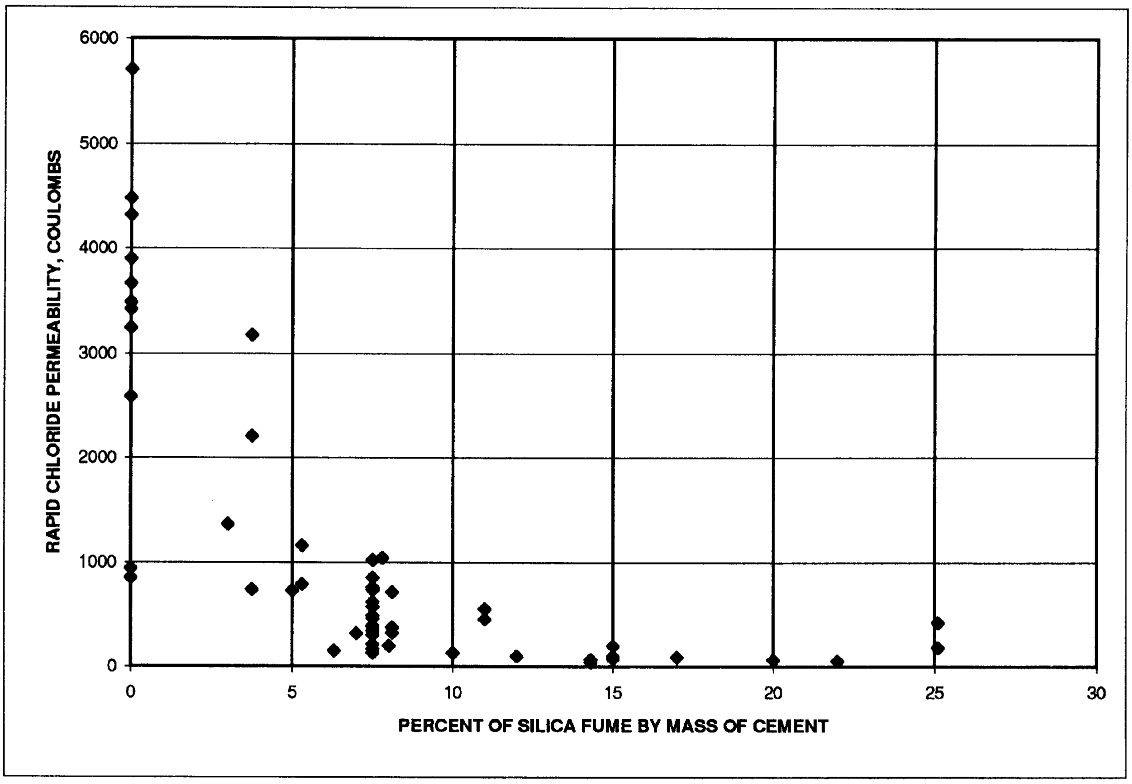


Fig. 5.3—Relationship between rapid chloride permeability as determined by the AASHTO T 277 (ASTM C 1202) test method and silica fume content. Scatter in the data is caused by differences in the mixture proportions, water-cementitious materials ratio, total cementitious materials content, specimen curing method and duration, age at testing, inherent variability of the test method, and laboratory-to-laboratory variations. Data are from Perraton, Aïtcin, and Vezina (1988); Berke (1989); Plante and Bilodeau (1989); Ozyildirim and Halstead (1988); and Wolsiefer (1991)

most significant improvement to the concrete construction industry. The resistance of silica-fume concrete to the penetration of chloride ions is discussed in Section 5.3.3.

5.1.3 *Water absorption*—Data on water absorption of silica-fume concrete are scarce. Ramakrishnan and Srinivasan (1983) reported that the water absorption coefficient of silica-fume fiber-reinforced concrete is lower than that of an ordinary fiber-reinforced concrete. Similarly, Morgan (1988a) has shown that the water absorption of silica-fume shotcrete is lower than that of ordinary shotcrete when tested using ASTM C 642.

Sellevold and Nilsen (1987) reported from work by Virtanen (1985) that the absorption of water in concretes containing silica fume was much lower than that in a reference concrete. They also reported on the work of Lehtonen (1985) regarding the wetting behavior of reference and silica-fume concretes. The silica-fume concrete showed a more gradual rate of water absorption despite the fact that both types of concrete had attained a similar degree of saturation.

5.1.4 *Cement paste-aggregate transition zone*—The microstructure of the cement paste-aggregate transition zone in concrete is significantly different from that of the bulk paste (Hadley 1972; Barnes, Diamond, and Dolch 1978, 1979; Winslow and Liu 1990; Bentur and Cohen 1987; and Bentur 1988). Carles-Giburgues, Grandet, and Ollivier (1982) wrote that the transition zone is about 50 μm thick. They described the hydration process in this zone for pastes with fly ash, slag, or silica fume. They conclude that all of these materials affect the morphology of the transition zone and particularly decrease the thickness and degree of orientation of calcium hydroxide crystals that form adjacent to aggregate particles. Further data suggest that the performance of high quality concretes achieved with the use of silica fume is, at least in part, the result of interfacial effects (Regourd 1985; Bentur, Goldman, and Cohen 1988; Sellevold and Nilsen 1987; Sarkar, Diatta, and Aïtcin 1988).

Bentur, Goldman, and Cohen (1988) have shown that silica fume does not show the same strengthening effects in paste that it exhibits in concrete, Fig. 5.4. For the same water-to-cementitious materials ratio, pastes, with and without silica fume, have the same strength. This paper concludes that only in concrete does the addition of silica fume lead to an increase in strength.

Bentur and Cohen (1987), working with portland cement-mortars, found that the microstructure of the transition zone is characterized by a massive calcium hydroxide layer engulfing the sand grain and by some channel-like gaps as shown in Fig. 5.5. When silica fume was added, the transition zone had a homogeneous and dense microstructure much more similar to that of the bulk paste; the massive

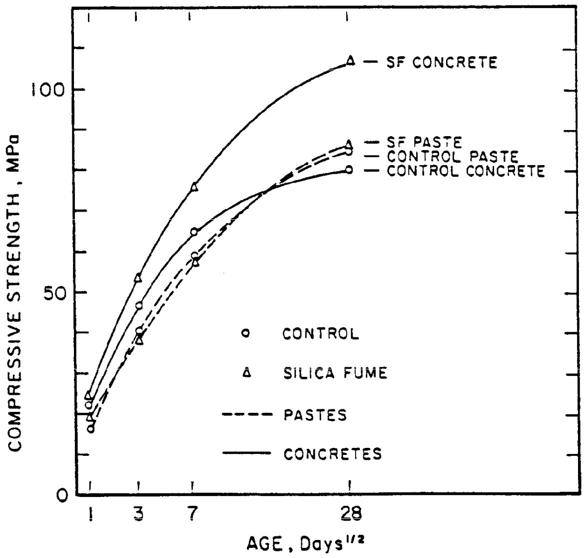


Fig. 5.4—Compressive strength of pastes and concretes with and without silica fume at the same water-cementitious materials ratio (Bentur, Goldman, and Cohen 1988)

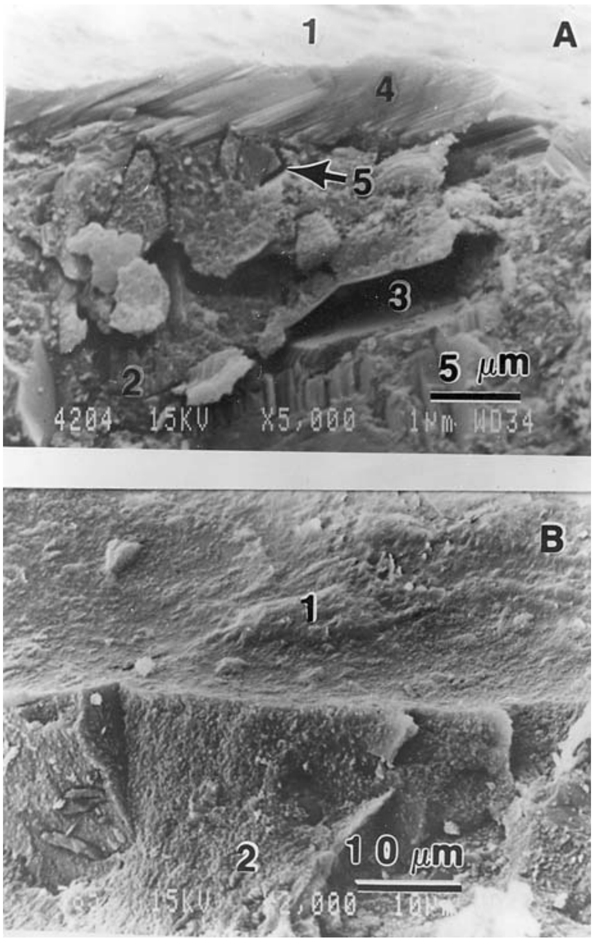


Fig. 5.5—Typical structure of transition zone between the cement paste matrix and aggregate, characterized by scanning electron microscopy (Bentur and Cohen, 1987) a) 28-day system without silica fume; b) 28-day system with silica fume. 1) aggregate surface; 2) cement paste; 3) voids; 4) calcium hydroxide; and 5) microcracks

calcium hydroxide layer was absent and there were no gaps. Quantitative measurements by back scattered electron microscopy have confirmed the reduction in porosity in the transition zone due to silica fume addition (Scrivener, Bentur, and Pratt 1988).

Much of the improvement in concrete properties is thus attributed to interfacial modification caused by the addition of silica fume. Because of their small size, the silica fume particles, when there is enough high-range water-reducing admixture (HRWRA) present to overcome the effects of surface forces, are better able to pack around the aggregate particles during mixing and placing, thus reducing bleeding (Bentur and Cohen 1987). The weak-link effect is apparently eliminated and the improved bond may facilitate a true composite effect where the aggregate particles act as reinforcing fillers rather than inert fillers. This may lead to an increase in the concrete strength over that of its paste matrix, Fig. 5.4 (Bentur, Goldman, and Cohen 1988; Bentur 1989).

5.2—Mechanical properties

Since silica fume improves the bond between the paste and aggregate (see Section 5.2.6), the influence of the quality of the aggregate on the mechanical properties of concrete becomes more important in silica-fume concrete. The dimensions, durability, and engineering properties (strength, modulus of elasticity, Poisson's ratio) become important factors to be considered in selecting the appropriate aggregate for the concrete.

5.2.1 *Modulus of elasticity and Poisson's ratio*—Wolsiefer (1984) reported, for a high-strength silica-fume concrete cured for 28 days, a static modulus of 6.25 x 10^6 psi (43.1 GPa) and a compressive strength of 14,220 psi (98 MPa). The static modulus of elasticity of silica-fume concrete is apparently similar to that of portland-cement concrete of similar strength (Luther and Hansen 1989; Loland 1983). Sellevold et al. (1982) found the dynamic modulus of elasticity increases with increasing silica-fume content in pastes. Helland, Hoff, and Einstabland (1983) concluded that the stress-strain behavior of silica-fume concrete was similar to that of portland-cement concrete.

Wolsiefer (1984) reported a Poisson's ratio of 0.21 for a 14,220-psi (98-MPa) silica-fume concrete. Saucier (1984) studied five silica-fume concretes and found Poisson's ratio ranging in value from 0.208 for 13,350-psi (92-MPa) concrete to 0.256 for 16,440-psi (113-MPa) concrete. These variations in Poisson's ratio are not believed by the committee to be significant.

5.2.2 *Creep*—Saucier (1984) tested concretes with compressive strength in the 11,600 to 14,500 psi (80 to 100 MPa) range. He found essentially no difference in creep between mixtures with and without silica fume (up to 15 percent by mass of cement). The same conclusion was reached by Buil and Acker (1985) for cement replacement of 25 percent (i.e., 33.33 percent silica fume by mass of cement) and compressive strength of 7250 to 11,600 psi (50 to 80 MPa).

Luther and Hansen (1989) found a negligible change in creep when silica fume was added in high-strength mixtures, whereas Tomaszewicz (1985) found a reduction of 27 percent

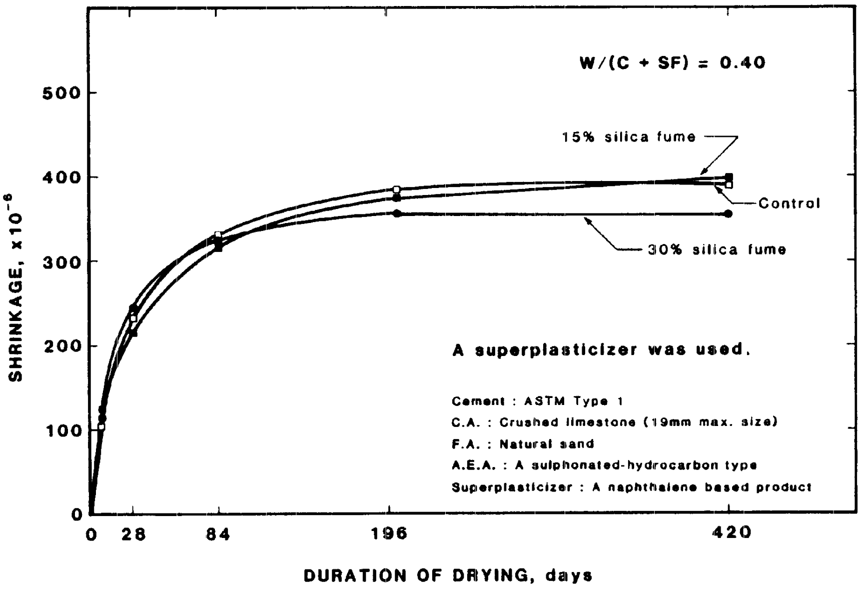


Fig. 5.6—Drying shrinkage of silica-fume concrete with a water-cementitious materials ratio of 0.40 (Malhotra et al. 1987)

when comparing normal-strength concrete without silica fume and high-strength concrete with 15 percent silica fume.

Limited published data and the different nature of the creep tests used by various investigators makes it difficult to draw specific conclusions on the effect of silica fume on the creep of concrete. The only statement that can be made with certainty is that creep of silica-fume concrete is not higher than that of concrete of equal strength without silica fume.

5.2.3 *Drying shrinkage*—Data shown in Fig. 5.6 indicate that the drying shrinkage of silica-fume concrete (after 28 days of moist curing) is generally comparable to that of the control concrete for a water-cementitious materials ratio of 0.40 and silica fume contents of 15 and 30 percent. Carette and Malhotra (1983a) reported that the drying shrinkage of silica-fume concrete after 28 days of moist curing is generally comparable of the control concrete regardless of the water-to-cementitious materials ratio ($w/c + m$).

The amount of silica fume and duration of curing prior to drying are important factors in the drying shrinkage of concrete. Sellevold and Nilsen (1987) reported that concrete shrinkage is influenced little by silica-fume content up to 10 percent by mass of cement. Early drying increases shrinkage for lean silica-fume mixtures (w/cm greater than 0.60) and for high silica-fume contents (greater than 10 percent by mass of cement) because early drying inhibits pozzolanic reaction.

Hansen (1987) and Luther and Hansen (1989) reported that drying shrinkage of high-strength silica-fume concrete is either equal to or somewhat lower than that of concretes of equal strength without silica fume. Tazawa and Yonekura (1986) also found reduced shrinkage, but for equal strength, the shrinkage per unit volume of paste was similar.

Drying shrinkage data on concrete containing 20 percent silica fume and a HRWRA and having a water-to-cementitious materials ratio of 0.22 have been published by Wolsiefer (1984). This concrete achieved a 28-day compressive strength of 16,170 psi (111.4 MPa). Shrinkage specimens moist cured for 1 and 14 days showed shrinkage of 0.073 percent and 0.053 percent, respectively. The shrinkage values for the specimens moist cured for 14 days were 24.3 percent lower than those of high-strength [11,000 psi (79 MPa)] concrete made without silica fume.

5.2.4 *Compressive strength*—The main contribution of silica fume to concrete strength development at normal curing temperatures (i.e., other than accelerated curing conditions) takes place from about three to 28 days. Typical strength development characteristics of silica-fume concrete are shown in Fig. 5.7 and 5.8. Fig. 5.7 shows data for concrete with silica fume as a direct replacement by mass for portland cement, and Fig. 5.8 refers to concrete with silica fume as an addition to portland cement-fly ash concrete. The one-day compressive strength of silica-fume concrete is about equal to that of the control concrete when the silica fume is used as a direct replacement. When silica fume is used as an addition to the portland cement-fly ash blend, the one-day strengths may be substantially higher than the control, depending upon the amount of silica fume added. At 28 days the compressive strength of silica-fume concrete is always higher and in some instances significantly so, as shown in Fig. 5.7 and 5.8.

The contribution of silica fume to strength development after 28 days is minimal. This situation is unlike concrete made with ASTM C 618 class F fly ash in which case the pozzolanic reactions are very slow at early ages, and the contributions to concrete strength development are usually evident after 28 days and then continue for more than one year.

A limited amount of data suggest there is a retrogression of strength at later ages (91 days to 2 years) (Carette, Malhotra, and Aïtcin 1987); however, more recent data (Aïtcin and Laplante 1990) indicated no tendency for long-term (4 to 6 years) strength loss in silica-fume concrete. Based upon its review of the available data, the committee does not believe that

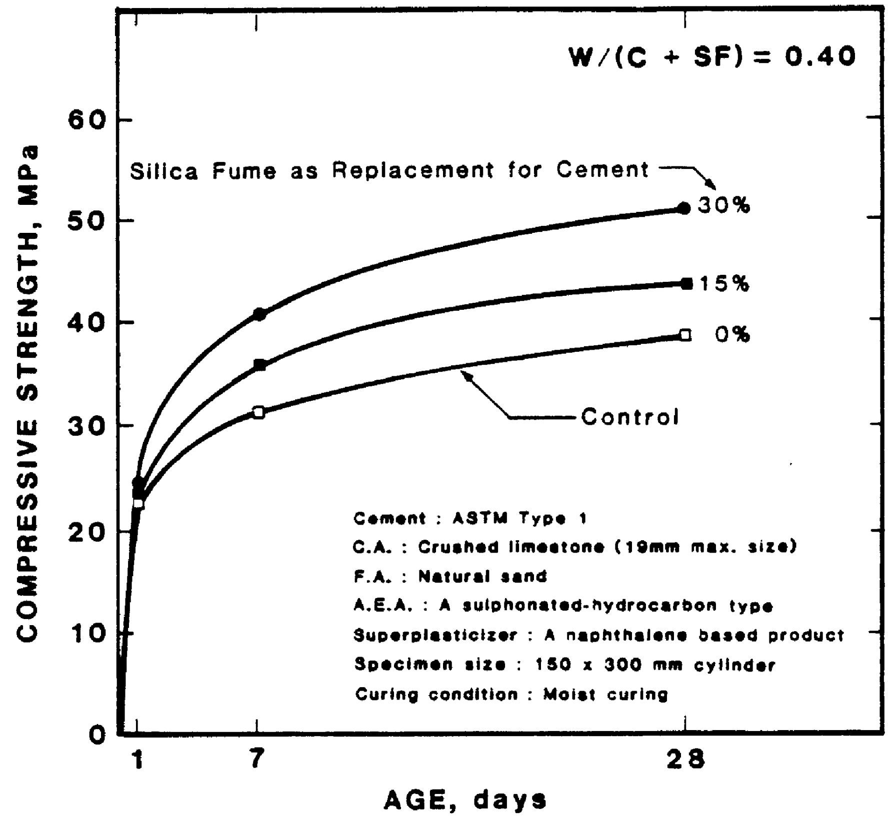


Fig. 5.7—Effect of silica fume on compressive strength of concrete (Malhotra et al. 1987)

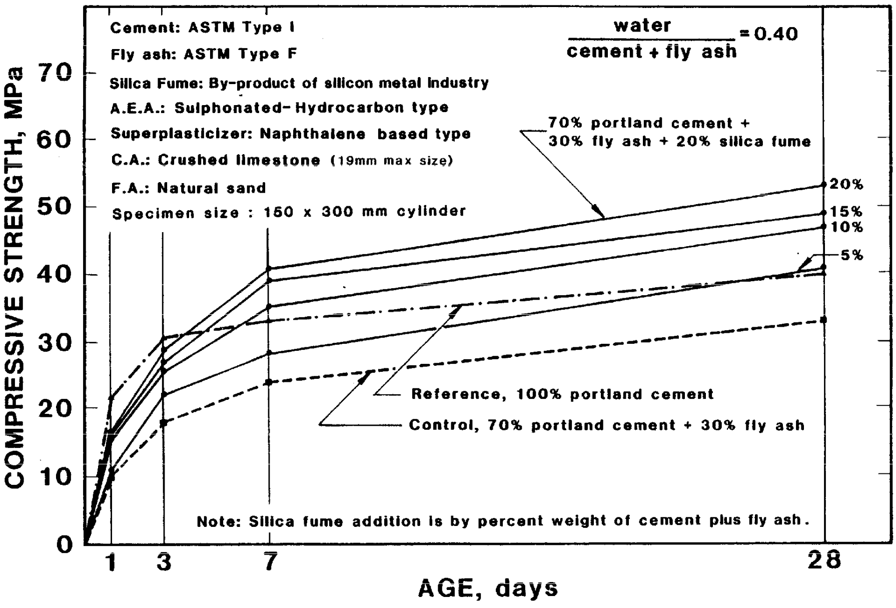


Fig. 5.8—Effect of silica fume on compressive strength of concrete containing fly ash (Carette and Malhotra 1983b)

strength retrogression is a concern with silica-fume concrete.

The effects of temperature on compressive strength have been studied by several investigators. Yamato, Emoto, and Soeda (1986) reported that when concrete is cured at 10 C (50 F), the presence of silica fume did not essentially improve the strength of concrete at 7 days; however, it did at both 28 and 91 days. With higher curing temperatures, 20, 30, and 65 C (68, 86, and 149 F), the presence of silica fume substantially improved the 7-day strength, as well as strengths after longer curing periods. Maage (1986) reported that the pozzolanic action in general is very temperature sensitive, but less so for silica fume than for fly ash.

5.2.5 *Flexural and splitting tensile strengths*—The development of flexural and splitting tensile strengths of concrete incorporating silica fume is similar to that observed in concretes without silica-fume addition. For both types of concrete, as the compressive strength increases the tensile strength also increases, but at a gradually decreasing rate (Goldman 1987). However, because in hardened concrete the ratio of tensile to compressive strength is strongly affected by the properties of the materials used, a unique relationship among the various types of strengths does not exist. If tensile strength is important for design, it must be tested for individual concretes.

Wolsiefer (1984) reported that for 14,220-psi (98-MPa) concrete containing 1000 lb/yd^3 (593 kg/m^3) of cement and 20 percent silica fume, the ratio of flexural to compressive strength varied between 0.13 to 0.15. Luther and Hansen (1989) found the modulus of rupture of silica-fume concrete made with dolomite coarse aggregate and having compressive strength between 7400 and 15,500 psi (51 to 107 MPa) to be about 12.3 times the square root of compressive strength (psi) [1.02 times the square root of compressive strength (MPa)].

McDonald (1991) reported that splitting tensile strength at various ages ranged from 5.8 to 8.2 percent of the compressive strength at the same age. The higher percentages, 8.2 and 8.0 percent, were at ages of 1 and 3 days, respectively. Splitting tensile strength ranged from 500 psi (3.4 MPa) at an age of 1 day [compressive strength 6080 psi (42 MPa)] to a maximum of 1015 psi (7.0 MPa) at the age of 90 days [compressive strength 14,280 psi (98 MPa)]. Luther and Hansen (1989) found the splitting tensile strength of fly ash and silica-fume concretes to be similar, ranging between 9.7 and 10.6 percent of the compressive strength. One 15,500-psi (107-MPa) silica-fume concrete developed a splitting tensile strength of 1110 psi (7.7 MPa).

5.2.6 *Bond strength*—Using silica fume as a component of concrete has been shown to improve bond strength at three types of interfaces: cement paste to aggregate, cement paste to steel reinforcement, and new to old concrete.

Chen and Zhang (1986a) have studied the effect of silica-fume addition on the properties of a transition zone between marble and cement paste. An addition of 5 percent silica fume increased the 28-day splitting-bond strength approximately twice that of a sample without silica fume. Odler and Zurz (1988) measured the splitting-bond strength between five different kinds of rocks and cement paste containing up to 10 percent silica fume. The results showed that in every case the bond strength of the samples containing silica fume was higher than that of samples without silica fume. The improved cement-aggregate bond resulting from the use of silica fume was also reported by other investigators. Chen and Wang (1988) found that the splitting-bond strength increased from 2.0 MPa (290 psi) for cement paste without silica fume to 2.4 MPa (345 psi) for cement paste containing 30 percent silica fume. Wu and Zhou (1988) also reported increased splitting bond strength, but the data in this paper are presented in such a way that it is impossible to provide a single numerical value to solely characterize the bond improvement.

Wang et al. (1986) reported that adding 5 percent or more silica fume by mass of cement to concrete significantly increases the effective fracture energy of the paste-aggregate transition zone. The improved fracture energy was also reported by Wu and Zhou (1988).

The cleavage strength of pure zinc plate-to-cement paste boundary was studied by Chen and Zhang (1986b). The results showed that by adding 5 percent silica fume, the 28-day cleavage strength was increased by about 50 percent. Burge (1983) showed that concrete-to-steel reinforcement bond strength in a high strength, lightweight concrete containing silica fume increased 3 to 5 times, depending upon the proportion of cement replaced by silica fume. A similar improvement in ultimate bond strength for lightweight aggregate concrete containing silica fume was reported by Robins and Austin (1986).

The improved bond strength of silica-fume concrete to steel reinforcing bars is reported in numerous papers in the review by Sellevold and Nilsen (1987). Ezeldin and Balaguru (1989) performed a reinforcing bar pull-out test on concretes containing up to 20 percent silica fume. They concluded that the addition of silica fume resulted in bond strength increases which were proportional to the square root of compressive strength, but the use of silica fume led to more brittle behavior.

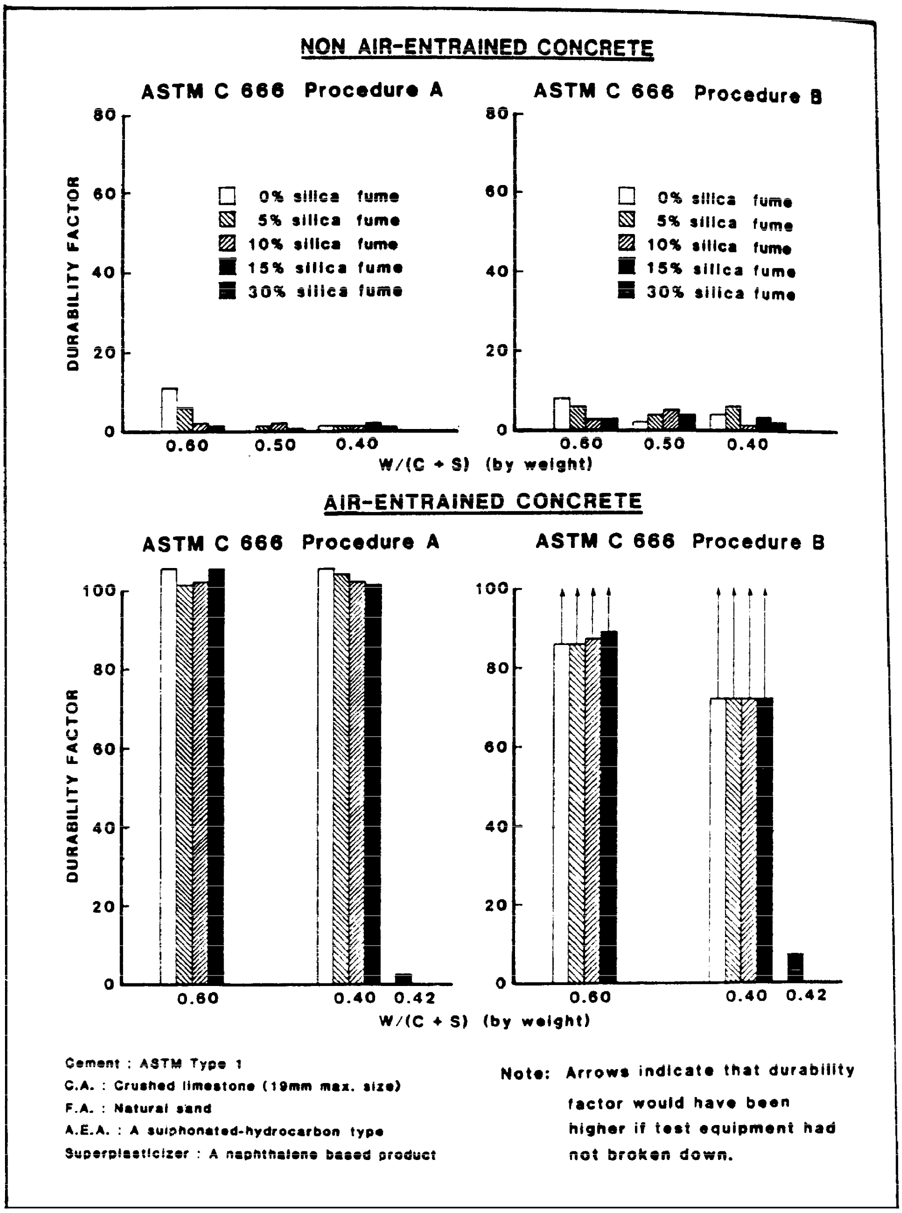
The positive influence of silica fume on a concrete-to-concrete bond strength was reported by Sellevold and Nilsen (1987) who based their conclusions on work by Johansen and Dahl (1983). The improvements were attributed to modification of the transition zone.

5.3—Durability aspects

5.3.1 *Freezing and thawing resistance and scaling resistance*—For properly air-entrained concretes, silica fume should have no detrimental effects on resistance to freezing and thawing and related scaling (Sorensen 1983; Aïtcin and Vezina 1984; Malhotra 1986) (Fig. 5.9). One exception was reported (Malhotra, Painter, and Bilodeau 1987) but in this study, unsatisfactory air-void spacing factors were obtained (0.269 to 0.502 mm). They suggest that for very low water-to-cementitious materials ratios, it is difficult to entrain air in silica-fume concrete, particularly with high dosages of silica fume.

Pigeon, Pleau, and Aïtcin (1986) reported that critical values of spacing factor for good freezing and thawing resistance are smaller for silica-fume concretes. Procedure A of ASTM C 666 was used, but durability factors were not determined. Surface scaling was less severe for silica-fume concretes. In a test program following ASTM C 672, scaling resistance was reduced as silica fume replacement exceeded 5 percent (Pigeon, Perraton, and Pleau 1987). Other scaling tests showed similar results for silica-fume contents exceeding 10 percent, if the water-cementitious materials ratio was greater than 0.38 (Sorensen 1983).

For non-air-entrained concrete, the data are mixed. Traetteberg (1980) found improved frost resistance of silica-fume mortars, which was attributed to altered pore size distributions, that reduced the frequency of large pores capable of accommodating freezable water. Similar results were



Cement : ASTM Type 1
C.A. : Crushed limestone (19mm max. size)
F.A. : Natural sand
A.E.A. : A sulphonated-hydrocarbon type
Superplasticizer : A naphthalene based product

Note: Arrows indicate that durability factor would have been higher if test equipment had not broken down.

Fig. 5.9—Summary of durability factors for air-entrained concretes (Malhotra 1986)

reported by Huang and Feldman (1985c). Good results were obtained with a low water-cementitious materials ratio (0.38) in non-air-entrained concretes with 10 and 20 percent silica fume (Sorensen 1983). Hooton (1993) also obtained good results at a water-to-cementitious materials ratio of 0.35. His results were explained by self desiccation resulting in reductions in internal relative humidity (McGrath and Hooton 1991).

Saucier (1984) found that non-air-entrained, high-strength concrete with 15 percent silica fume and cured for 28 days, gave a durability factor of 95 percent when tested according to ASTM C 666, Procedure A. Hooton (1993) found similar results for 10, 15, and 20 percent silica fume, high-strength concretes at water-to-cementitious materials ratio of 0.35 and cured for 14 days. Although the control concrete failed in 56 cycles, the durability factor of the silica-fume concretes exceeded 90 percent. Yamato, Emoto, and Soeda (1986) showed that for non-air-entrained silica-fume concrete with a water-to-cementitious materials ratio of 0.25, there was good resistance to freezing and thawing regardless of the silica-fume content (up to 30 percent). For a water-to-cementitious materials ratio of 0.35, 0.45, and 0.55, the frost resistance was poor. Luther and Hansen (1989) found the durability factor to be 98 and 96 percent for non-air-entrained 10,000-psi (69-MPa) fly ash and silica-fume concretes, respectively. On the other hand, Malhotra, Painter, and Bilodeau (1987) found that all non-air-entrained concretes failed at less than 50 cycles regardless of water-to-cementitious materials ratio or silica-fume content when moist cured 14 days prior to freezing.

The quality of the silica fume and cement, the mixture proportions, and the curing time to first freezing may account for the wide difference in results between the studies. Further research is required (Philleo 1986; Philleo 1987). The critical dilation test, ASTM C 671, may be a more realistic alternative test to ASTM C 666 (Philleo 1987). At this time, it is recommended that currently recommended values of air entrainment be used to provide adequate resistance to freezing and thawing.

5.3.2 *Chemical attack resistance*—Because of its low permeability, the resistance of silica-fume concrete to attack by various chemicals has been investigated by several researchers.

Feldman and Huang (1985) investigated the resistance of mortars to attack by 4 percent $MgC1_2$ solution for 150-170 days followed by exposure to solution containing a mixture of magnesium, calcium, and sodium chlorides. The water-to-cementitious materials ratio of the mortars was of 0.45 and 0.60, and they contained silica fume at 0, 10 and 30 percent by mass of cement. The properties measured included stiffness, pore-size distribution, $Ca(OH)_2$ content, and non-evaporable water content. The results showed that addition of silica fume substantially increased the durability of the mortars.

Mehta (1985) tested the chemical resistance of low water-to-cement ratio concretes to 1 percent hydrochloric acid solution, 5 percent acetic acid solution, 1 percent lactic acid solution, and 1 percent sulfuric acid solution. The specimens were seven weeks old before the exposure and included plain concrete with a water-to-cement ratio of 0.35, latex-modified concrete with a water-to-cement ratio of 0.33, and silica-fume concrete containing 15 percent of silica fume by mass of cement with a water-to-cementitious material ratio of 0.33. Mehta concluded that concrete containing silica fume showed better resistance to the chemical attack than did the other two types of concrete.

The improved resistance of silica-fume concrete to a number of other aggressive chemicals, including nitrates and acids, has been reported in various papers presented in a review by Sellevold and Nilsen (1987).

5.3.3 *Chloride ion penetration resistance*—Concrete structures in hostile chloride environments are some of the most logical candidates for silica-fume concrete. A great amount of testing to determine the resistance of silica fume concrete to chloride ion penetration has been performed.

Byfors (1987) reported that addition of silica fume up to 20 percent by mass of cement considerably reduced the diffusion rate of chloride ion compared with the performance of ordinary portland-cement paste of the same water-cementitious materials ratio. By increasing the water-to-cementitious materials ratio, the resistance to chloride ion diffusion decreases.

While testing such as that described above is valuable, design engineers and specifiers have required a faster and more practical method of specifying and evaluating the resistance of concrete to chloride ion penetration. The use of ASTM C 1202 (AASHTO T 277), for evaluating the resistance of concrete to chloride ions, has become a standard and routine test. This test measures the electrical charge passed through the concrete, which is then related to the chloride penetration. The method is fast, low in cost, and is becoming widely used by design engineers in the specifications of concrete structures in chloride environments. Work by Whiting (1981, 1988) has shown that this rapid test does correlate with traditional tests of concrete permeability.

Table 5.1—Chloride permeability according to AASHTO T 277 or ASTM C 1202 (silica-fume concrete added by committee for this report). (Table originally appeared in Whiting 1981)

Charged passed (coulombs)	Chloride permeability	Typical of
Greater than 4000	High	High water-cement ratio (0.6) conventional concrete
2000 to 4000	Moderate	Moderate water-cement ratio (0.4 to 0.5) conventional concrete
1000 to 2000	Low	Low water-cement ratio (0.4) conventional concrete
100 to 10000	Very low	Latex-modified concrete, low water-cementitious materials ratio silica-fume concrete (5 to 15 percent), and internally sealed concrete
Less than 100	Negligible	Polymer impregnated concrete; polymer concrete; low water-cementitious materials ratio, high silica-fume content concrete (15 to 20 percent)

The permeability of all concrete and its resistance to chloride ion penetration, especially that of silica-fume concrete depends upon the curing method and the length of time cured (Whiting and Khulman 1987), as well as other factors. Permeability decreases with time, and this decrease is proportional to the degree of cement hydration. As the ambient curing temperature has great influence on the rate of cement hydration, field cores taken in winter conditions will not become resistant to chloride ion penetration until adequately cured. Typical values obtained using the ASTM C 1202 for various types of concretes are shown in Table 5.1. When tested using ASTM C 1202 (AASHTO T 277), the electrical charge passed through concrete was reduced with increasing silica fume replacement levels, as shown in Fig. 5.3 (Hooton 1993).

5.3.4 *Abrasion-erosion resistance*—The excellent resistance of silica-fume concrete to abrasion-erosion damage was reported by Holland (1983, 1986a, 1986b) and McDonald (1991) based upon work done at the Waterways Experiment Station. Testing was done using an underwater procedure (CRD-C 63) which simulates the abrasion erosion which occurs in a hydraulic structure. High-strength silica-fume concrete with limestone aggregate was shown to have abrasion-erosion resistance similar to that of a conventional concrete with a water-cement ratio of 0.40 and containing hard chert aggregates. The improved abrasion-erosion resistance was attributed to the very high compressive strength of the paste fraction of the concrete.

Neely (1988) has also reported on abrasion-erosion resistance of silica-fume concrete used for underwater placements. He found insufficient data to reach a conclusion concerning the effects of silica fume on the abrasion-erosion characteristics of the concrete. There was some evidence that silica fume improved the washout resistance, but since only a small number of concretes tested did not include silica fume, the evidence was not conclusive.

5.3.5 *Fire resistance*—Shirley, Burg, and Fiorato (1988) reported a silica-fume concrete that exploded from heat, as reported by Hertz (1982), was an isolated specialized mortar

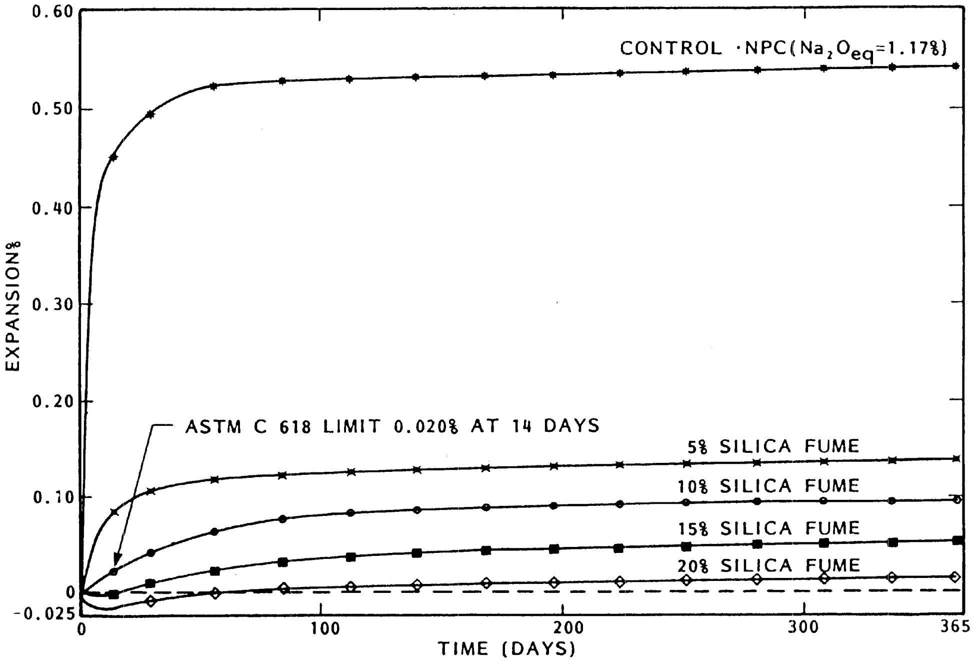


Fig. 5.10—Expansion of ASTM C 441 pyrex mortar bars with various volume replacements of silica fume, made to a flow of 110 ± 15, with HRWRA (Hooton 1993)

mixture that had over 20 percent silica fume by weight of cement, had a water-to-cement ratio less than 0.35, a unit weight in excess of 165 lb/ft^3 (2640 kg/m^3), and a strength in excess of 25,000 psi (170 MPa). They reported on the results of fire tests of two more typical silica-fume structural mixtures, as compared with two fly-ash mixtures and a conventional concrete, and found little difference in performance. The two silica-fume mixtures contained about 140 fl oz/yd^3 (5.46 L/m^3) of a HRWRA and each had approximately a 9-in. (230-mm) slump. No air-entraining admixture was used in any of the concretes tested. All concrete slabs were moist cured 7 days at room temperature and then air dried to a mid-depth relative humidity of 80 percent before test time. Test results showed that the silica-fume concretes had a slightly longer fire endurance than the others; all slabs sustained only random hairline cracks; and all slabs performed very well. Malhotra et al. (1987) reviewed the paper by Sellevold (1984) reporting on the high-temperature exposure tests of plain concrete elements and concrete elements containing silica fume according to ISO standards. These elements were 3 months old and had compressive strengths ranging from 4640 psi (32 MPa) to 5075 psi (35 MPa). All elements met the test temperature requirements for the unexposed face, but more extensive spalling was noticed on the exposed face for the elements containing silica fume.

The committee is aware of concerns regarding the fire safety of high-strength, low-permeability concretes (particularly those containing lightweight aggregates) in applications where the concrete may not be dry in service. Explosive spalling may occur during rapid fire loadings such as a hydrocarbon fire as might be experienced in an offshore oil production structure. The spalling is believed to be the result of the low permeability of the concrete that prevents the escape of steam. Testing to simulate project conditions is recommended in these cases.

5.3.6 *Alkali-aggregate reaction expansion*—The beneficial effects of silica fume on alkali-silica reactivity (ASR) are thought to be largely due to the ability of silica fume to rapidly combine with alkalies in the pore solutions (Diamond 1983; Page and Vennesland 1983) and incorporate the alkalies as substitutes for calcium in the CSH matrix. The alkalies in solution are then not of sufficient concentration to raise the pH of the pore solution high enough to cause deleterious expansion by attacking the reactive silica in the aggregates. Uchikawa, Uchida, and Hanehara (1989) showed that 10 percent by mass replacement with silica fume ties up almost three times more alkali in the CSH than did plain portland cement. They also found that the diffusion rates of alkalies through the pores of concretes incorporating silica fume have been found to be approximately an order of magnitude lower which would restrict the ability of dissolved alkalies to migrate to reactive aggregate sites.

Reduction in expansion of ASTM C 441 Pyrex mortar bars is shown in Fig. 5.10 (Hooton 1993). A 10-percent replacement by mass of the high-alkali cement with silica fume was required to reduce expansion to 0.020 percent at 14 days. Buck (1988) reported expansion values at 14 days of 0.43 percent, 0.12 percent, 0.01 percent, and 0.01 percent for 0 percent, 5 percent, 10 percent, and 15 percent silica fume replacements, respectively. At 365 days the corresponding expansion values were 0.51, 0.21, 0.05, and 0.04 percent.

Reductions in expansion of a reactive rhyolitic sand to less than 10 percent at one year were obtained with 5 percent silica fume (Fig. 5.11, Asgeirsson and Gudmundsson 1979). Less positive results were obtained elsewhere (Soles, Malhotra, and Suderman 1987), but the experimental results are suspect since the aggregates known to be reactive did not approach 0.10 percent expansion in one year in the ASTM C 227 test. Perry and Gillott (1985), working with Beltane opal, concluded that silica fume is effective in controlling expansion but that relatively high amounts, on the order of 20 percent by mass replacement, were required. They also found that small additions of silica fume (5 percent by mass) increased expansion with this highly reactive aggregate. Further, they found that the chemical type of the HRWRA used played a role in determining the amount of expansion.

In another study Davies and Oberholster (1987) compared the effectiveness of various mineral admixtures for reducing alkali-silica reaction expansion using several different testing methods. First, they tested in accordance with ASTM C 227 using a South African Malmesbury graywacke/hornfels aggregate and a cement with a total alkali content of 0.97 percent. A 5 percent by volume silica-fume replacement was not sufficient to control expansion below 0.05 percent. A 10 percent by volume silica-fume replacement resulted in approximately 0.05 percent expansion at 365 days. Higher silica-fume replacements maintained the expansion below the 0.05 percent limit for the entire test period. Next, they used the same aggregate with a cement with a total alkali content of 1.12 percent in concrete cubes in field trials. Here, a 5 percent by volume silica-fume replacement delayed expansion above the 0.05 percent limit for approximately 1250 days whereas a 10 percent by volume replacement showed essentially no expansion through 1500 days. Of all of the mineral admixtures tested, they found silica fume to be the most effective in controlling expansion.

Kawamura, Takemoto, and Hasaba (1987) found that four silica fumes varied widely in their effect on alkali-silica expansion of mortars containing a reactive aggregate (Beltane opal). They found that the addition of relatively small amounts of these silica fumes increased expansion while addition of larger amounts of some of these silica fume completely prevented expansion of the mortars. They also concluded that the ability of the silica fumes did not necessarily correlate with their pozzolanic activity as measured by the amount of calcium hydroxide consumed in paste samples.

In summary, silica fume in sufficient quantity and properly dispersed in concrete will likely be effective in ameliorating the deleterious effects of alkali-silica reactivity. However, it is recommended that each source of silica fume be tested with the particular reactive aggregate before use.

Perry and Gillott (1985) reported that silica fume was much less effective in controlling expansion caused by alkali-carbonate reaction (ACR) than that caused by alkali-silica reaction. However, neither low-alkali cement or other mineral admixtures are effective in combating ACR (Rogers and Hooton 1992).

5.3.7 *Sulfate resistance*—The reduced permeability of silica-fume concrete would be expected to reduce the transport of sulfate ions into concrete. Since silica fume replacement levels are generally 15 percent or less, the dilution effect on C_3A would be small. Sellevold and Nilsen (1987) cite 20-year field performance results from Norway. Specimens were placed in a tunnel in alum shale where ground water sulfate ion concentrations reach 4 g/L with pH 2.5 to 7.0. In this case, the performance of concrete with a conventional portland cement and a 15 percent silica-fume addition with a water-to-cementitious materials ratio of 0.62 was equal to that of a sulfate-resistant portland cement concrete with a water-cement ratio of 0.50.

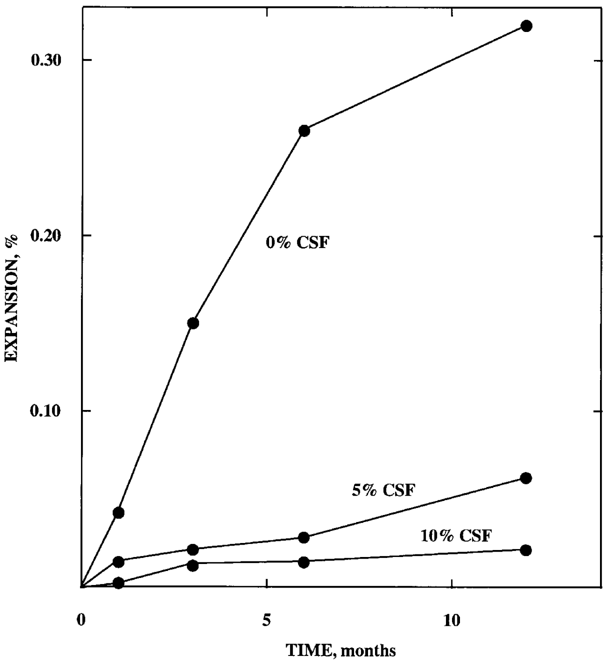


Fig. 5.11—Expansion of mortar prisms made with high-alkali cement, reactive sand, and three silica fume contents (Asgiersson and Gudmundsson 1979)

When exposed to sodium sulfate solution, durability of concrete is enhanced by addition of silica fume (Mather 1982, Mehta 1985, Hooton 1993, Cohen and Bentur 1988). Mather (1982) reported tests using mortar bars exposed to sodium sulfate. Three high C_3A cements (14.6, 13.1, and 9.4 percent C_3A) were used alone and with 30 percent replacement of various pozzolans. The greatest sodium sulfate resistance was obtained with silica fume. Use of silica fume with ASTM type I portland cement has the effect of improving its performance to levels similar to those of ASTM type V portland cement (Mather 1982, Hooton 1993, Cohen and Bentur 1988). In Fig. 5.12, mortar bars containing 10 percent silica fume tested using ASTM C 1012 employing sodium sulfate as the sulfate source are shown to be as resistant as those containing a sulfate resistant portland cement even though the C_3A content of the cement was 11.8 percent (Hooton 1993). Similar results were obtained by Buck (1988) for a cement containing 15 percent C_3A.

Carlsson, Hope, and Pedersen (1986) examined the use of 5 percent silica fume in concrete mixtures intended for use in pipes. They exposed the specimens to a 10-percent sodium sulfate solution for 92 weeks. The silica fume concrete exhibited less mass loss leading the authors to conclude that pipes made from the silica-fume concrete would have 2 to 3

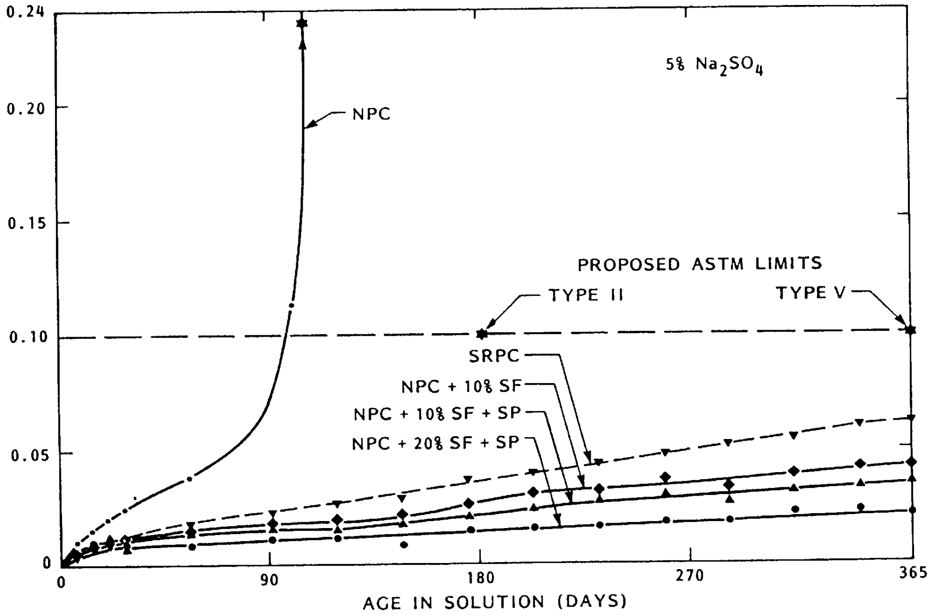


Fig. 5.12—ASTM C 1012 sulfate resistance of silica fume mortar bars, flow 115 ± 5 [(Hooton 1993), SRPC = sulfate resisting portland cement; NPC = normal portland cement; SF = silica fume; SP = superplasticizer HRWRA]

times the life expectancy of the same concrete without silica fume.

The results are conflicting for ammonium sulfate. Popovic, Ukraincik, and Djurekovic (1984) showed improved resistance of silica-fume mortars whereas Mehta (1985) showed no improvement in concrete.

In very high concentrations of magnesium sulfate (equivalent to a 4.5 percent SO_3 solution), silica fume impaired the performance of the pastes made with both ASTM type I and type V portland cements (Cohen and Bentur 1988). Calcium silicate hydrate (CSH) was found to have decomposed and there was an absence of magnesium hydroxide which tends to block pores and give protection to CSH from further attack. There was not much of a difference between the extent of damage in the two types of cements. In both instances, addition of silica fume reduced the strength and increased mass loss by a factor of 5 to 10.

5.4—Miscellaneous properties

5.4.1 *Electrical resistivity*—Electrical resistivity and alternating current (AC) resistance are measures of the ability of concrete to resist corrosion currents. Corrosion currents are encountered in steel-reinforced concrete under chloride attack in deicing and marine environments. An increased electrical resistivity makes reinforced concrete more resistant to galvanic corrosion currents by reducing the rate of corrosion.

Electrical resistivity (expressed in ohm-cm) has been measured in non-standard laboratory tests, and also during the ASTM C 1202 (AASHTO T 277) rapid chloride permeability test. Data have shown that resistivity is inversely proportional to the ASTM C 1202 (AASHTO T 277) permeability values (Berke and Roberts 1989). The resistivity values are calculated by determination of the cell constant of the test setup, and calibrations with the 4-pin platinum wire test method. Fig. 5.13 shows electrical resistivity data, as measured by the rapid chloride permeability test, for a silica-fume concrete at 11 percent and 20 percent addition of silica fume by mass of cement. The 20 percent silica fume dosage showed a resistivity of 110,000 ohm-cm (Wolsiefer 1991).

Data indicate that silica-fume concrete has high electrical resistance to the passage of corrosion current (Berke and Roberts 1989; Berke 1989; Berke and Weil 1988). Berke et al. (1991) presented resistivity data for concrete containing silica fume or silica fume and fly ash. At 28 days, a concrete with 600 lb/yd^3 (355 kg/m^3) of cement, 75 lb/yd^3 (44.5 kg/m^3) of silica fume (12.5 percent) and a water-to-cement ratio of 0.47 had a resistivity of 51.75 kohm-cm. They also presented data on resistivity changes over 3 years of ponding with a 3 percent sodium chloride solution. From corrosion testing they concluded low rapid chloride permeability test readings and high resistivity are indicators of good corrosion resistance performance.

Vennesland and Gjørv (1983) measured electrical resistivity by embedding an isolated steel plate in the middle of an insulated concrete cylinder. The test cylinder was immersed in water with counter electrodes and an AC bridge was employed to measure electrical resistivity. Fig. 5.14 shows the resistivity data for three concrete mixtures each with 0, 10 and 20 percent silica fume addition by mass of cement. Correlation with Vennesland and Gjørv's data is seen with an electrical resistivity of 127,000 ohm-cm for a comparable mixture [675 lb/yd^3 (400 kg/m^3) cement, 143 lb/yd^3 (85 kg/m^3) silica fume; 21 percent by mass of cement.] Electrical resistivity is improved and the increased resistivity is more pronounced at high strengths. The improvement is due

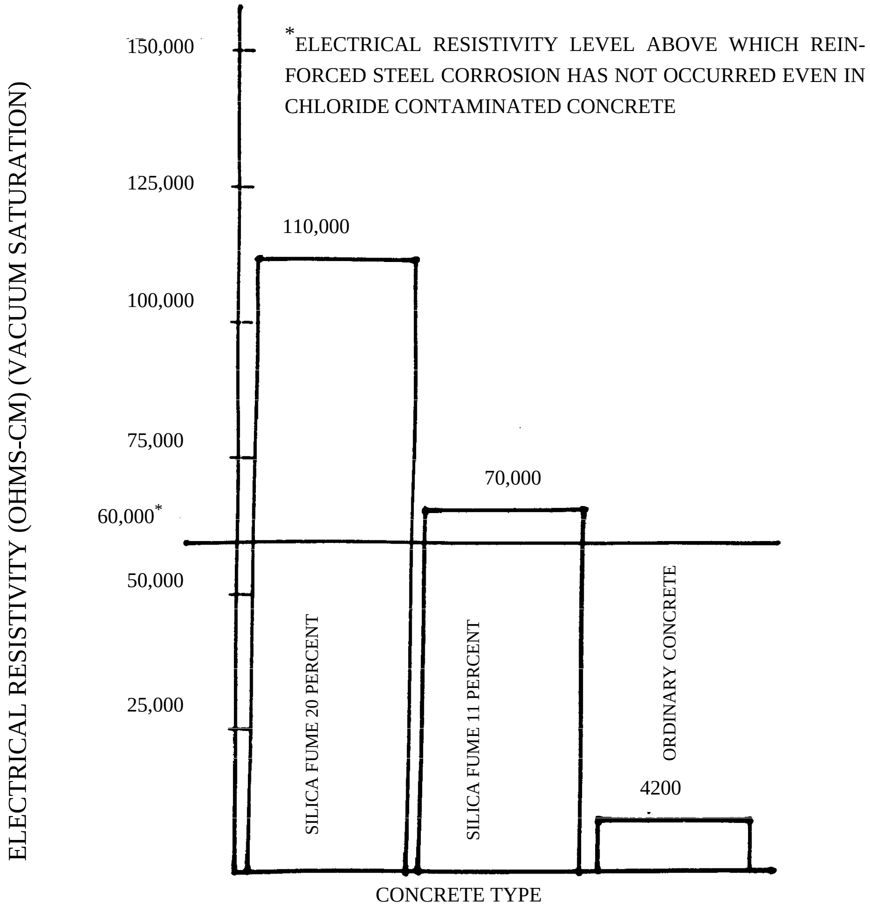


Fig. 5.13—Electrical resistivity as measured during AASHTO T 277 (ASTM C 1202) testing for various silica fume contents (Wolsiefer 1991)

to the effect of silica fume in lowering the ion concentration in the pore solutions and providing a more discontinuous capillary pore structure (Sellevold and Nilsen 1987).

AC resistance, in ohms, has been measured in the FHWA time-to-corrosion NCHRP Southern Exposure Slab test. This laboratory test is a scaled down steel reinforced deck in which macro cell (mat to mat) AC resistance, corrosion current, half-cell potential, and chloride absorption are measured, during 48 weeks of sodium chloride (15 percent solution) ponding in alternate soak/dry cycles. Fig. 5.15 shows that the AC resistance for a silica-fume concrete sample (prepared with a dry silica-fume admixture, at 20 percent addition by mass of cement), increased from 5000 ohms to 25,000 ohms during the course of the test. The corresponding control concrete was flat at 890 ohms. These data, along with simultaneous corrosion current measurements, tend to indicate that the silica-fume concrete was not a conductor of corrosion current (Wolsiefer 1991).

5.4.2 *Thermal properties*—Published data on thermal properties are scarce. The committee is not aware of any effect of silica fume on thermal properties, since such properties depend primarily on the thermal characteristics of the aggregate. The committee is not aware of data on thermal resistivity. Heat of hydration is covered in Chapter 3.

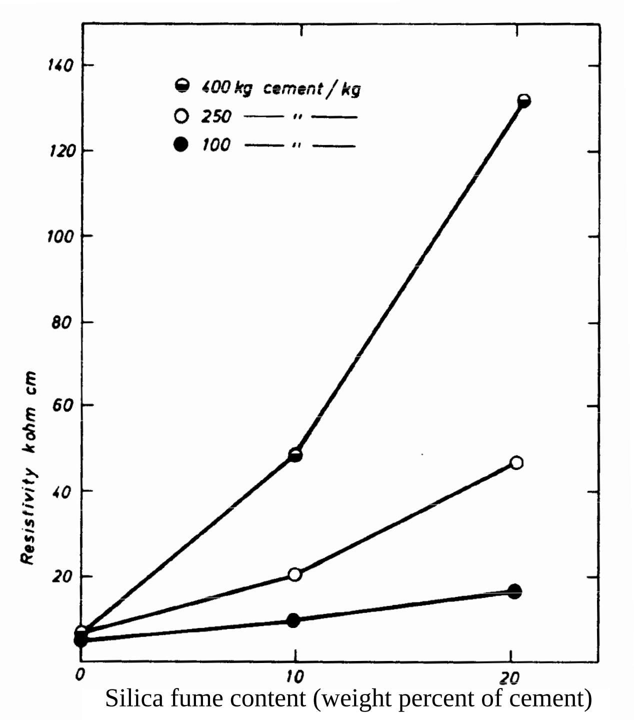


Fig. 5.14—Effect of silica fume on the electrical resistivity of concrete (Vennesland and Gjørv 1983)

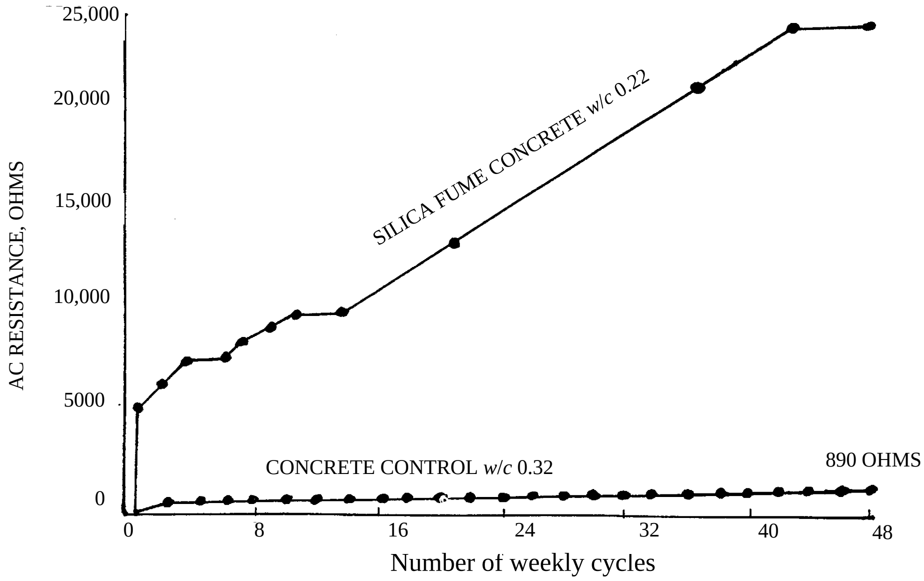


Fig. 5.15—Alternating-current resistance of concrete containing 20 percent addition of silica fume (Wolsiefer 1991)

5.5—Use of silica fume in combination with fibers

The use of silica fume in combination with various types of fibers has been studied by several researchers. This work has covered bonding characteristics of the paste to the fibers, the influence of a combination of fibers and silica fume on the bond strength to reinforcing steel, and the use of silica fume in glass-fiber reinforced concrete.

The improved bond strength of silica fume concrete to various types of fiber reinforcement is reported in numerous papers in the review by Sellevold and Nilsen (1987). Paillere, Buil, and Serrano (1989) examined the use of steel fibers to reduce autogenous cracking of low water-cement ratio silica-fume concretes. Bayasi and Soroushian (1989) showed that replacement of cement with silica fume at 5 to 20 percent enhanced the effectiveness of steel fibers in concrete. This improvement was attributed to the improved fiber interfacial bond strength.

Ezeldin and Balaguru (1989) looked at the bond to reinforcing steel behavior of normal-strength and high-strength steel-fiber reinforced concrete using a pullout test method. They found that silica fume increased bond strength but resulted in brittle bond failure. Use of the steel fibers increased ductility. Horiguchi, Saeki, and Fujita (1988) have shown that the pullout strength of reinforcing steel in steel-fiber reinforced concrete with 30 percent silica fume was about 2.1 times that of conventional concrete.

Krenchel and Shah (1985) have described using silica fume and high volumes (2 to 5 percent) of polypropylene fibers together in Scandinavia. They reported that the reinforcing performance of polypropylene fibers can be substantially improved by using silica fume in the matrix. Ohama, Amano, and Endo (1985), working with carbon fibers, reported that adding silica fume and water-reducing admixtures was very effective for dispersing the carbon fibers. They also reported that the use of silica fume improved the physical properties of the composite by increasing the paste-to-fiber bond.

Various studies have shown that addition of silica fume to glass-fiber-reinforced concrete (GFRC) made with alkali-resistant glass fibers and sometimes high-alumina cement can reduce or eliminate the loss of ductility and strength associated with increasing age (Bentur and Diamond 1985; Hayashi, Sato, and Fujii 1985; Bijen 1985).

5.6—Use of silica fume in conjunction with fly ash

A number of researchers have looked at combinations of fly ash and silica fume. The primary research objectives have been to offset the reduced early strength typical of fly-ash concretes and to evaluate the durability of concretes with combinations of pozzolans. The committee is not aware of definitive information regarding reaction mechanisms when fly ash and silica fume are both present. See also Section 3.4.

Mehta and Gjørv (1982), during an investigation of compressive strength of concretes made with combinations of fly ash and silica fume, also examined CH and pore-size distribution of similar cement pastes. Based on strength development and CH determinations, they concluded that the combination of pozzolans showed much greater pozzolanic activity, even at 7 and 28 days than did the fly ash alone. The combination also showed considerable reduction in the volume of large pores at all ages studied.

Carette and Malhotra (1983b), also during a strength investigation, found that the later-age strength development of concrete containing silica fume and fly ash was not impaired, indicating the availability of sufficient CH for fly ash pozzolanic activity.

Mehta and Gjørv (1982) and Carette and Malhotra (1983b) found that the combination of pozzolans could offset the reduction of early strength caused by the use of fly ash alone. Seabrook and Wilson (1988) reported on work using combinations of fly ash and silica fume in lightweight-aggregate concrete for offshore applications in the Arctic. They achieved 91-day compressive strength of 9400 psi (65 MPa) at unit weight of 125 lb/ft^3 (2000 kg/m^3.)

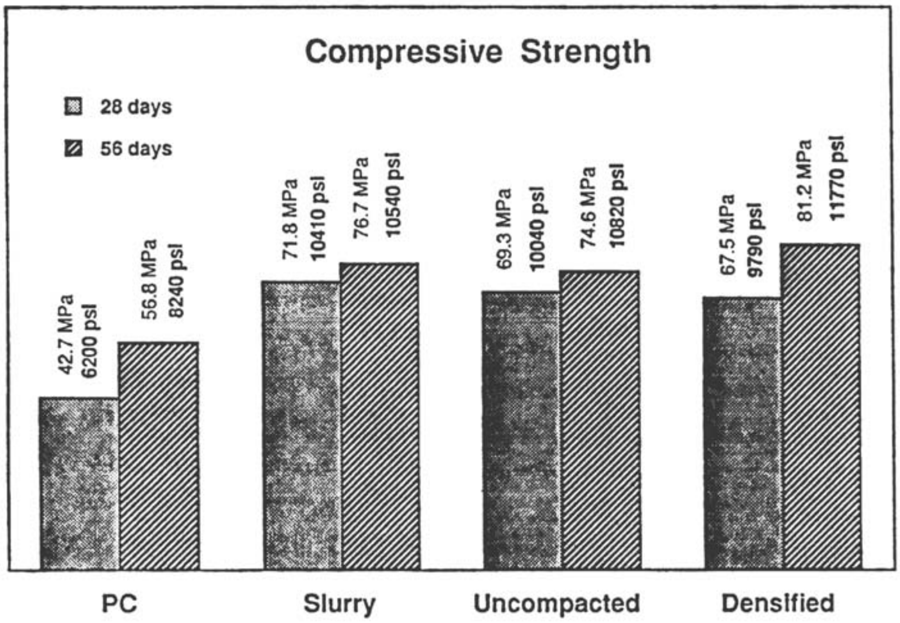


Fig. 5.16—28- and 56-day compressive strengths of plain concrete and concretes containing various forms of silica fume (Cohen and Olek 1989)

Maage (1986) examined combinations of portland cement, fly ash, and silica fume for influence on strength and heat development. He also investigated the effect of these combinations on the maturity functions of the concretes. Silica fume was used as a replacement material in concretes in which the cement content was reduced to maintain essentially constant 28-day compressive strengths. He reported that the early-age strength of the concretes containing silica fume was reduced with increasing fly ash contents resulting in greater early-age strength reductions. For concretes with silica fume, heat generation per kilogram of cement plus silica fume was higher than without silica fume. For concretes cured at 20 C, maturity calculations were found to be valid for up to 2 to 3 days of equivalent curing time. Concerning the durability of these concretes, Maage (1987) investigated water permeability, frost resistance, sulfate attack, carbonation, chloride diffusion, pH-level of pore water, and electrical resistivity. He concluded that silica fume worked in combination with the blended cements in approximately the same manner as with concretes containing only portland cement.

Gautefall (1986) examined the chloride-diffusion rates in pastes made from ordinary portland cement and a blended cement containing 10 percent fly ash, both with silica fume contents ranging from 0 to 15 percent. He found that the addition of silica-fume led to a marked decrease in chloride diffusivity, more so for the ordinary portland cement than for the blended cement.

Wakeley and Buck (1986) examined grouts containing Class H cement, an expansive agent, fly ash (a Class C and a Class F ash were tested), and silica fume. They examined compressive strength, volume change, phase composition, and microstructure. They found some differences in performance with the different ashes, but concluded that the properties of the grouts were markedly similar. Seabrook (1987) has described the use of fly ash and silica fume in a grout for use in ducts in post-tensioned concrete. He developed a grout which was superior in absorption, shrinkage, bleeding, and corrosion resistance over the neat cement grout.

5.7—Property variations with respect to type, source, and form of delivery of silica fume

Effects of the form of silica fume (as-produced, slurried, densified) on properties of unreinforced concrete have been studied for concretes containing 9 percent silica fume (Cohen and Olek 1989) and 11 and 15 percent silica fume (Fidjestøl et al. 1989) by mass of portland cement. Results from both studies indicated that at the age of 28 days, the slurried and as-produced silica fumes provided somewhat more compressive strength than did the densified material. The 56-day compressive strength of the concrete containing the densified silica fume somewhat exceeded those of the concretes containing the other forms of silica fume as shown in Fig. 5.16 (Cohen and Olek 1989).

Results from rapid chloride permeability measurements made in accordance with ASTM C 1202 (AASHTO T 277) indicate that all forms of silica fume tend to increase resistance to chloride permeability to about the same level as shown in Fig. 5.17 (Cohen and Olek 1989; Fidjestøl et al. 1989).

In the investigation by Cohen and Olek (1989) the frost resistance of air-entrained concrete did not seem to be affected by the form of silica fume used. In that investigation all silica-fume concrete specimens performed well when tested using ASTM C 666, Procedure A.

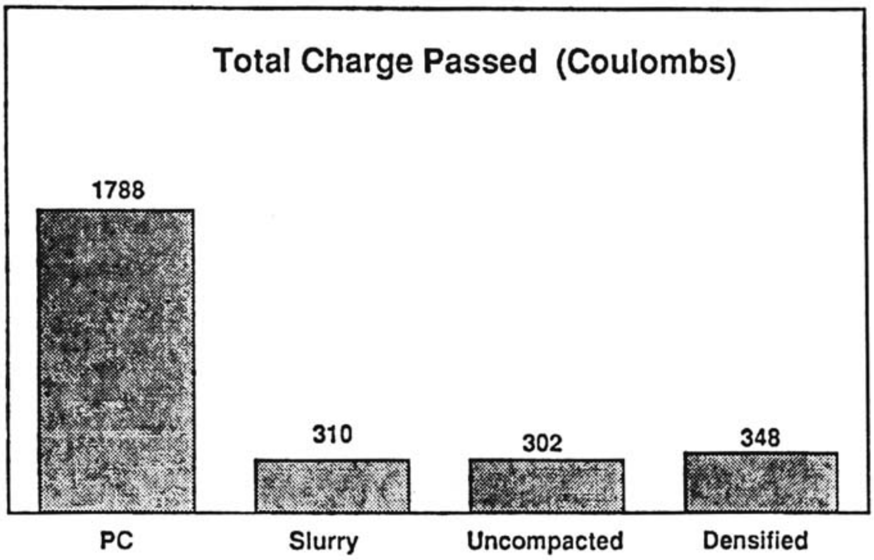


Fig. 5.17—Total electrical charge passed during AASHTO T-277 (ASTM C 1202) testing of plain concrete and concretes containing various forms of silica fume (Cohen and Olek 1989)

CHAPTER 6—APPLICATIONS OF SILICA FUME

6.1—Introduction

This chapter describes the uses of silica fume, primarily in concrete. Other applications in grout or mortar are also mentioned. Many different types of projects that have been accomplished since silica fume has been commercially available are included.

6.2—Abrasion resistance

Silica-fume concrete has been used in industrial floors in North America and Europe to provide increased abrasion resistance. Silica-fume concrete was placed in an abrasion-resistant application for the floor of Fire Station 16 in Pittsburgh, Pennsylvania, in 1986.

One dry-bagged silica-fume concrete product that achieves a 28-day compressive strength of 20,000 psi (138 MPa) was used to provide increased abrasion resistance against the action of arresting-gear cables at the ends of runways at two United States Air Force bases.

Use of silica-fume concrete to resist abrasion in pavements is described in Section 6.13.

6.2.1 *Abrasion-erosion resistance*—The first major application of silica-fume concrete in the United States was for repair of hydraulic structures subjected to abrasion-erosion damage.

The concrete in the stilling basin slab of Kinzua Dam in western Pennsylvania was severely damaged by abrasion erosion. After extensive laboratory testing at the Waterways Experiment Station, the Corps of Engineers specified silica-fume concrete as the repair material. The project required over 2000 yd^3 (1530 m^3) of concrete with a compressive strength of 12,500 psi (86 MPa) at 28 days. The 18-percent silica-fume concrete achieved a compressive strength over 13,000 psi (90 MPa) at 28 days (Holland et al. 1986) and over 16,000 psi (110 MPa) at three years. This concrete was placed in late 1983. Divers' inspections in the summer of 1990 indicated that a small amount of abrasion-erosion wear had occurred—significantly less than seen in concretes used in the stilling basin previously.

The Corps of Engineers also specified silica-fume concrete as the repair material for the concrete in the invert of the Los Angeles River Channel. The existing concrete had been damaged primarily by abrasion erosion. Almost 27,000 yd^3 (20,600 m^3) of silica-fume concrete were placed in the invert during 1983, 1984, and 1985. Various mixture proportions and repair approaches were used over the life of the project. Compressive strength of 8000 to 10,500 psi (55 to 72 MPa), depending upon the mixture used, was achieved (Holland and Gutschow 1987). As of the writing of this Guide, this concrete has performed well.

The Corps of Engineers also specified 8000-psi (72-MPa) silica-fume concrete to line a 150-ft (46-m) section of the Lowell Creek Tunnel, located near Seward, Alaska. The tunnel invert had experienced severe abrasion-erosion damage. Hard igneous coarse aggregate was used in the repair concrete, and tests upon the same mixture that was placed achieved a 2.8 percent mass loss during the Corps of Engineers abrasion-erosion test method (CRD-C 63). A mass loss below 7 percent was specified. The concrete achieved an 8950-psi (62-MPa) compressive strength (Luther 1989b). After one year, an estimated 1/8 in. (3 mm) of wear had occurred, less than had been observed for previously used repair materials.

The Bureau of Reclamation used 13,000-psi (90-MPa) silica-fume concrete in 1985 during a spillway repair for the American Falls Dam, located near American Falls, Idaho. As of summer 1988, the concrete has performed well. In November 1987, the Bureau of Reclamation used silica-fume concrete to repair portions of the spillway and sidewall for the Navajo Dam, located near Farmington, New Mexico.

As part of an erosion control system, in 1987 over 2700 high-strength precast silica-fume concrete dolosses were placed along a portion of the Lake Erie shoreline owned by Diamond Shamrock Corporation. The 7.7 percent silica-fume concrete was used for improved durability in the abrasive coastal environment.

6.3—Alkali-silica reaction

As described in Section 5.3.6 of this Guide, silica fume has been shown, in some instances, to prevent deleterious expansion due to the alkali-silica reaction in concrete. No scientifically documented case histories in the use of silica fume to control alkali-silica reaction in concrete in North America are available. Silica fume has been used in blended cement to prevent excessive expansion caused by the alkali-silica reaction in Iceland. Olafsson (1989) reported that since 1979, no serious expansion due to alkali-silica reaction has been found in the concrete. No other long-term data on the performance of silica fume in this role are available.

6.4—Cement replacement

Because of its high pozzolanic activity, silica fume can replace portland cement while maintaining essentially the same level of concrete performance. Skrastins and Zoldners (1983) provided some data on cost savings in Canada where silica fume was substituted for cement in concretes of different strength levels. Their work was based upon using as-produced silica fume with a cost of about $65/ton ($70/Mg) in 1982. However, since silica fume is usually significantly more expensive than cement, its use as a replacement for portland cement is governed by transportation costs and the location of a source of silica fume readily accessible to users. Silica fume has also been used as a cement replacement material in Norway (Løland 1984), Australia (Tasmania), the United States (Alabama), Canada (Quebec), and South Africa.

6.5—Heat reduction

Silica fume has been used to replace cement for the purpose of reducing the amount of heat generated in concrete. This was one motive for using silica-fume concrete in the Tjorn bridge, near Gothenburg, Sweden, and the Alta Dam in northern Norway (Fidjestøl 1987). In January 1988, the Maine Department of Transportation also used silica fume for this reason in piers for the Fairfax Bridge near Farmington, Maine.

6.6—Chemical attack resistance

The reduced permeability of silica-fume concrete provides protection against a variety of forms of chemical attack. While the use of silica fume does not eliminate deterioration caused by chemical attack, it may lengthen the time between repairs. Typically, such placements have been relatively small and the concretes have contained high silica fume dosages (10 to 18 percent by mass of cement). In July 1986, silica-fume concrete was used by the U.S. Borax Company for an industrial floor in Death Valley, California. The floor is exposed to 5 percent sulfuric acid and borax. As of 1989, the field performance of this concrete has been acceptable. In another example, the Redwing Company, Dunkirk, New York, used silica-fume concrete in a floor in a tomato processing area where the concrete is exposed to organic acids and routine floor cleaning. This floor has also performed satisfactorily. In an application for Union Carbide, Columbus, Ohio, an underground chemical storage tank was fabricated from 72-in. (1.8-m) diameter precast pipe elements made with silica-fume concrete (Holland and Luther 1987).

6.7—Corrosion resistance

One of the largest uses of silica-fume concrete is in applications where the intent is to reduce the permeability of the concrete to the intrusion of chloride ions. In recent years, concrete bridge decks and parking structures in many countries have shown distress and damage due to the effects of chloride-based deicing chemicals. Because of its low permeability, silica-fume concrete offers possible benefits by reducing the rate of penetration of chloride ions (Sorensen 1983).

One of the largest applications of silica fume for corrosion protection has been in parking structures, both for cast-in-place and precast concrete. By 1991, over 200 parking structures had been constructed using silica-fume concrete. In many cases, the specifications for these structures have been written to include a requirement for a given level of performance on the rapid chloride ion permeability test (Whiting 1981; ASTM C 1202; AASHTO T 277). Typical mixture proportions for these projects have included 650 lb/yd^3 (385 kg/m^3) cement, an addition of 7.5 to 10 percent silica fume by mass of portland cement, and a maximum water-to-cementitious materials ratio of 0.40.

Silica-fume concrete is also being used for rehabilitation of parking structures. One such project at O'Hare Plaza, Chicago, involved restoration of four parking areas. After removal of the deteriorated concrete, silica-fume concrete was used as a bonded overlay material with an average thickness of 3 in. (76 mm).

Silica fume has also been used to provide corrosion protection for marine structures. This application is discussed in Section 6.12.

6.8—Grout

A grout consisting of portland cement, silica fume, water, and water-reducing admixtures was used to anchor post-tensioned tie-back cables in Baltimore during 1985. The silica-fume grout exhibited longer pot life, the grout pumped more easily, and the cables were tensioned significantly earlier (by several days) and with fewer failures (tendon pullouts) than with the non-silica-fume grout that was used earlier during the project.

During 1987, a 20-percent silica-fume grout mixture was used to provide improved corrosion protection of tie-back anchors for the Virginia Department of Transportation King's Highway retaining wall project, located in Fairfax County, Virginia.

Silica-fume bonding grouts have been used by several state transportation agencies that have placed silica-fume overlays (Luther 1988). The Illinois Department of Transportation uses silica-fume bonding grout even for non-silica-fume concrete bridge deck overlays (Illinois Department of

Transportation 1988). Several manufacturers offer prepackaged nonshrink grouts containing silica fume.

6.9—High early-strength concrete

Use of silica fume can improve the early-age strength of concretes containing fly ash and blast-furnace slag cement (Mehta and Gjørv 1982; Carette, Malhotra, and Aïtcin 1984).

The Tennessee Department of Transportation used silica-fume concrete as a bridge deck overlay material to take advantage of the high-early strength of the concrete to allow rapid reopening of the Landen B. Hassler Memorial Bridge. The specified compressive strength at three days was 4500 psi (31 MPa) and a strength of 5220 psi (36 MPa) was achieved (Luther 1988).

In May 1987, the Massachusetts Bay Transit Authority used silica-fume concrete to repair pile caps for a railroad bridge in Sandwich, Massachusetts. The specified compressive strength at three days was 5000 psi (34 MPa), and the concrete achieved 6000 psi (41 MPa), even though the air temperature was unseasonably cool and the concrete was partially submerged in cool seawater when the tide was in (Luther 1988).

Eighteen-hour compressive strength between 3000 psi (21 MPa) and 7000 psi (48 MPa) depending on ambient temperatures, has been reported when silica-fume concrete was used to produce high-strength [up to 10,000 psi (69 MPa)] precast elements (Luther and Bauer 1987).

6.10—High-strength concrete

6.10.1 *Cast-in-place*—Silica fume with high-range water-reducing admixture (HRWRA) has been used to produce very-high-strength concrete. Compressive strength as high as 20,000 psi (138 MPa) has been reported.

The Gallery Project, an office structure in Baltimore required approximately 4000 yd^3 (1200 m^3) of 10,000-psi (69-MPa) silica-fume concrete for use in columns and in post-tensioned beams. For the 225 West Wacker project in Chicago, 14,000-psi (97-MPa) concrete was used in the lower level columns (Moreno 1990). Silica-fume concrete was used to provide 12,000-psi (83-MPa) specified compressive strength concrete for the 959-ft (292-m) tall 311 South Wacker Drive office building in Chicago and some of the 10,000-psi (69-MPa) concrete used silica fume also (Robison 1988). The 62-story Two Union Square building in Seattle used silica-fume concrete in the 10-ft (3-m) diameter circular columns. The specified compressive strength was 12,000 psi (83 MPa) and the specified modulus of elasticity was 7,000,000 psi (48 GPa). In order to meet the modulus requirement, the compressive strength averaged 19,000 psi (131 MPa) with some values exceeding 20,000 psi (138 MPa) (Bauer 1988).

6.10.2 *Precast*—Precast elements containing silica-fume concrete were used for a 21-story condominium structure in Wilmington, Delaware. By using 10,000-psi (69-MPa) silica-fume concrete, the precaster was able to reduce section size for some elements, making transportation and erection simpler (Halmos 1986; Luther and Bauer 1987). In another precast application, the Montreal Airport Parking Structure, silica-fume concrete was used for 3000 elements subjected to accelerated curing. Here, the precaster took advantage of the rapid strength gain of heat-cured silica-fume concrete to achieve rapid reuse of forms. Precast parapet wall elements have been used routinely since 1984 by one parking garage designer (Holland 1987a).

Bank-vault manufacturers have used very high strength silica-fume concrete in precast vault panels (Bauer 1988; Luther 1989b). Bank-vault panel concretes typically use hard specialty aggregates, and they develop compressive strength ranging between 12,000 psi (83 MPa) and 20,000 psi (138 MPa), or higher, depending upon the mixture.

Some artists have used silica-fume concrete. One sculpture which was made using ferrocement is located in the courtyard of the Waterfront Office Tower in Stockton, California (Ernst 1987; Hatch 1987).

Precast parking curbs have been made in northeastern United States since 1986. One precaster offers a 15 percent silica-fume concrete curb that achieves compressive strengths of approximately 14,000 psi (97 MPa). This product looks like and competes with granite curb (Blaha 1987).

6.11—Lightweight concrete

Lightweight concrete containing silica fume to provide higher compressive strength has been evaluated extensively for use in offshore concrete structures. To date, a silica-fume mixture has been used on one structure, the Super CIDS structure located in the Beaufort Sea. For this structure, lightweight silica-fume concrete with a unit weight of 110 lb/ft^3 (1760 kg/m^3) and a compressive strength of 8200 psi (57 MPa) was used for the exterior walls (Anon. 1986).

After an extensive laboratory investigation, 6000 psi (41 MPa) specified compressive strength lightweight silica-fume concrete was used in a parking deck overlay on the roof of Cobo Hall Convention Center, Detroit.

Lightweight silica-fume concrete roof tiles are being made in Norway and the United States.

6.12—Offshore and marine structures

The resistance of silica-fume concrete to the penetration of chloride ions is also attracting interest for marine applications. The Southern Pacific Railroad used silica fume in concrete for 192 precast, prestressed elements for three bridges over the Great Salt Lake. Shotcrete containing silica fume has been used for repairs in a marine environment.

During 1986 and 1987, two 755-ft (230-m) long precast silica-fume concrete segments were constructed in dry dock, floated into place, sunk into position, and connected underwater to form an underwater tunnel connecting Lolland and Falsten Islands, in Denmark (Fidjestøl 1987). The Karstø Shore Approach subsea tunnel was also constructed with silica-fume concrete. This tunnel, built using similar construction techniques as the previously mentioned sub-sea tunnel, houses pipelines that bring offshore oil to the mainland near Karstø, Norway (Fidjestøl 1987).

In western Norway, portions of the Norwave electrical generating power plant were constructed with silica-fume concrete. Silica-fume concrete walls that are mostly submerged in ocean water redirect wave motion energy such that water is lifted and deposited into reservoirs. As water from the reservoirs returns to the sea, it is used to generate power. An adjacent power plant also used silica-fume concrete (Fidjestøl 1987).

The first offshore structure using normal weight silica-fume concrete extensively was the Gulfaks C platform, located in the North Sea (Fidjestøl 1987).

State agencies and other owners along the eastern seaboard of the United States have investigated using silica-fume concrete in marine environments. The Florida Department of Transportation made silica-fume concrete piles that showed significantly better corrosion protection of the reinforcing steel than the conventional concrete previously used (Anon. 1987). Reportedly, the Texas State Department of Highways and Public Transportation has conducted experimental work with silica-fume concrete piles, and the Alabama Department of Highways has used silica-fume concrete in portions of the Perdido Pass Bridge, located near Mobile, Alabama, that are exposed directly to seawater (Luther 1988). The Maine Department of Transportation has also used silica-fume concrete in bridges and piers, and precast silica-fume concrete sea wall elements have been placed along the oceanfront in New Jersey. Precast floating dock modules made with fiber-reinforced silica-fume concrete and having a mass as great as 6500 lb (3.0 Mg) have been made and used in Scituate, Massachusetts (Blaha 1987).

A marine terminal for the New York Department of Sanitation was rehabilitated in 1986. This project included the encapsulation of piles and pile caps underwater by tremie, overlaying of a bridge to the marine structure, and the construction of new piles and bridge beam supports using silica-fume concrete. The compressive strength of the concrete averaged over 11,000 psi (76 MPa) at 56 days and the rapid chloride permeability measurements averaged less than 200 coulombs.

6.13—Overlays and pavements

Several state transportation agencies have tested and approved silica-fume concrete for use as a bridge deck overlay material. In this type of application, the silica-fume concrete is used as an alternative to latex-modified concrete or low-slump concrete. Objectives for using silica-fume concrete include retarding access of chlorides to the deck reinforcing steel, achieving a more abrasion-resistant surface, developing good bond strength to the base, and increasing both early and ultimate strength (Luther 1988).

The first bridge deck overlay using silica fume was placed in the United States by the Ohio Department of Transportation in October 1984 (Bunke 1988). Over 100 silica-fume bridge deck overlays have been placed, including in Alabama, Kentucky, Illinois, Ohio, Maine, Michigan, New York, Tennessee, Virginia, and Wisconsin (Luther 1988; Ozyildirim 1988).

The wearing surface of the truck scale weighing platform at the Aalborg Portland Cement plant in Aalborg, Denmark was constructed with silica-fume concrete. This concrete has performed well. In January 1983, silica-fume concrete overlays were placed on approach lanes to a weighing platform at the New Enterprise Stone and Lime Co., located in Roaring Spring, Pennsylvania. This concrete has already lasted over four times as long as that previously used.

Full-depth decks or approach slabs for at least eight bridges have been constructed in the United States with silica-fume concrete (Luther 1988), and in Norway several bridges have been constructed with full-depth silica-fume concrete decks (Fidjestøl 1987).

In Norway, silica-fume concrete pavements have been placed in areas where steel-studded tires abrade conventional concrete quickly. These silica-fume pavements have lasted significantly longer than previously-used materials. Experimental silica-fume concrete roadway pavements placed in more than 12 miles (20 km) of the European highway network in Norway have performed well, showing wear resistance between two and three times better than that of reference high-quality asphaltic cement pavements. Other silica-fume roadway pavements have been placed in Denmark (Fidjestøl 1987).

6.14—Shotcrete

Shotcrete containing silica fume is being placed using both the wet and dry processes to reduce rebound, to increase application thickness per pass, improve resistance to washout in marine construction or wet areas, and to improve properties of the hardened shotcrete.

The first major placement in the United States was a wet-process trial conducted by the Bureau of Mines at its Lake Lynn test facility in Pennsylvania. There, shotcrete containing steel fibers and silica fume was used to stabilize a mine head wall (Krantz 1984; Opsahl 1983). On the Bad Creek Project in South Carolina, the Duke Power Company has used silica-fume steel-fiber-reinforced concrete during construction of an underground power plant and associated tunnels.

The use of silica fume in dry-process shotcrete has been largely developed in western Canada. Bagged dry shotcrete materials are being used for a variety of applications. For the Pier B-C rehabilitation project in Vancouver, silica-fume shotcrete was used to repair piles, pile caps, and sea walls. Other applications have been the Canadian National Railroad’s use to stabilize a rock cut, Fraser Canyon, British Columbia; Westin Mine's use of silica-fume steel-fiber-reinforced shotcrete to support underground openings in new mine development in British Columbia; and the Canadian Pacific Railroad’s use of silica-fume steel-fiber-reinforced shotcrete for ground support in a 10-mi (16.1-km) long tunnel at Rodgers Pass, British Columbia (Morgan 1988b).

6.15—Underwater concrete

Underwater silica-fume concrete placements were made in 1988 for Corps of Engineers rehabilitation work on the Dashields Lock and Dam on the Ohio River. The project required approximately 3500 yd^3 (2700 m^3) of silica-fume concrete. Then, later in 1988, underwater silica-fume concrete was placed during rehabilitation work on the Point

Marion Lock and Dam No. 8 on the Monongahela River in West Virginia. Silica fume was added to these concretes to increase the cohesiveness to prevent washing out the cement during the underwater placements.

6.16—Waste isolation

Research suggests that silica-fume concrete is a potential sealing material for use in waste isolation (Kumar, Komarnene, and Roy 1987), and experimental precast silica-fume concrete waste isolation chambers have been made in Europe. Silica-fume concrete was used in a chemical storage tank in Columbus, Ohio.

In 1986, forty-seven large concrete dry storage canisters were cast by Ontario Hydro under contract to Atomic Energy of Canada Limited. These self-shielding canisters were used to store all of the irradiated fuel bundles from the shutdown Douglas Point Nuclear Generating Station (Lin 1988). Ten of these canisters were cast at a water-to-cementitious materials ratio of 0.40 using 11.5 percent by mass silica-fume replacement of the low-heat portland cement. These concretes were air-entrained and contained HRWRA. The average 28-day compressive strength was 7500 psi (52 MPa).

CHAPTER 7—PROPORTIONING SILICA-FUME CONCRETE

7.1—General

Most silica-fume concrete is used for enhancement of concrete properties. In such applications, silica fume is usually used to provide concrete with very high strength or very low permeability or both. To achieve the desired properties of the concrete, significant modifications of the proportioning methods outlined in ACI 211.1 are required when silica fume is used.

7.2—Cement and silica-fume content

Mixture proportions for high-strength concrete typically contain 600 to 950 lb/yd^3 (355 to 565 kg/m^3) of cement plus 5 to 15 percent silica fume by mass of cement. These concretes may have a water-to-cementitious materials ratio as low as 0.20. Concretes for increased durability and reduced permeability in parking structures and bridge decks typically have cement contents from 546 to 658 lb/yd^3 (324 to 390 kg/m^3) with water-to-cementitious materials ratio of 0.35 to 0.45. These concretes typically contain 3.5 to 10.0 percent silica fume by mass of cement, as an addition. Fly ash or blast-furnace slag may also be included in these concretes.

7.3—Water content

The use of silica fume will typically increase the water demand of the concrete in proportion to the amount of silica fume added. Therefore, the recommendations for approximate mixing water requirements contained in ACI 211.1 are invalid. Typically the entire mass of the silica fume is added to the mass of all other cementitious materials present to determine the water-to-cementitious materials ratio.

7.4—Aggregate

For proportioning concrete with increased durability or reduced permeability, the recommendations regarding coarse aggregate contained in ACI 211.1 are valid. For high-strength concrete, the recommendations for coarse aggregate content in Table 3.1 of ACI 363R should be followed.

7.5—Chemical admixtures

Information contained in ACI 211.1 regarding chemical admixtures is generally valid for silica-fume concrete for reduced permeability or improved durability applications. Information contained in ACI 363R regarding chemical admixtures is valid for high-strength concrete containing silica fume.

7.6—Proportioning

The committee is not aware of a published step-by-step procedure for proportioning silica-fume concrete. The best approach is to start with mixture proportions that have been used successfully on other projects with similar requirements. Given this starting point, trial mixtures should be made in the laboratory and under field conditions to verify performance with project materials. Examples of silica-fume concrete mixture proportions are shown in Tables 7.1 and 7.2.

CHAPTER 8—SPECIFICATIONS

8.1—General

Specifying concrete that will contain silica fume as a pozzolanic admixture requires attention to detail. The quality of the silica fume and the other admixtures, cements, and aggregates should be closely monitored and controlled, but, due to some of the problems noted with the placement of silica-fume concretes, additional care must be taken when specifying this concrete and the conditions under which it will be placed. Specifying silica-fume concrete for long-term performance of the structure is no more difficult than selecting or specifying any other high-performance concrete.

8.2—Specifying silica fume

8.2.1 *Properties of silica fume*—At this time there are no universally accepted requirements for specifying silica fume for use in concrete. Generally, standards for silica fume in concrete have been developed for project requirements based primarily on recommendations from the suppliers. A RILEM report (RILEM Technical Committee 73-SBC 1988) states that, to assure quality mineral additions* for use in concrete it is necessary to test the following: ignition loss, moisture content, fineness, water requirement for standard consistency, and activity index. At present, the only standards available specify silica fume in a manner similar to that

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* The term “mineral addition” is used for inorganic materials, both natural minerals and industrial by-products, that are used in quantities of five percent or more by mass of the cement. Mineral additions may be blended or interground with portland cement, or added directly to concrete before or during mixing (RILEM Technical Committee 73-SBC 1988). In ACI, these materials are called admixtures.

Table 7.1—Representative silica-fume concrete mixture proportions

Mixture proportions (lb/yd^3)											Compressive strength				
Mix ID	Cement	Silica fume	Fly ash	Fine aggregate	Coarse aggregate	Water	HRWRA (fluid oz/yd^3)	w/(c + p) (by mass)	Slump, in.	Air, percent	7 day, psi	28 day, psi	56 day, psi	90 day, psi	35-day rapid chloride permeability, coulombs
Kinzua[1]	650	118	0	1194	1637	219	11[5]	0.29	9.75	3.2	9970	13,720	—	14,970	—
Pac first[2]	900	68	100	1050	1802	220	250	0.21	—	—	—	—	17,980	—	—
Mom column[3]	840	50	0	1180	1850	227	362	0.26	10	—	10,270	12,380	—	13,010[7]	—
LAR-1983[1]	600	90	90	1350	1870	187	9[6]	0.24	—	—	—	10,520	—	—	—
LAR-1984[1]	641	71	0	1275	1840	247	Unknown	0.35	3.25	1.5	—	8000	—	—	—
LAR-1985[1]	600	85	110	1070	1940	228	7-14[8]	0.29	5	2.0	6180	8700	—	—	—
MP1[4]	658	50	0	1155	1625	263	79	0.37	4	6.8	—	8780	—	—	468
MP2[4]	658	66	0	1155	1625	270	86	0.37	5.25	7.0	—	9330	—	—	471
MP3[4]	658	33	0	1155	1625	257	86	0.37	6.5	8.7	—	8500	—	—	592

Notes:
1) Holland and Gutschow 1987.
2) Randall and Foot 1989.
3) Aïtcin and Riad 1989.
4) Unpublished data from a Minneapolis parking structure, from Braun Engineering and Testing, Minneapolis, MN.
5) The silica fume was added via a slurry that contained 11 lb of water reducing admixture solids per yd^3.
6) 9 lb/yd^3 of admixture solids.
7) Compressive strength results at 1 year of 14,150 psi, and at 2 years of 13,660 psi.
8) 7-14 lb/yd^3 of admixture solids.

Table 7.1—Representative silica-fume concrete mixture proportions (SI units)

Mixture proportions (kg/m^3)											Compressive strength				
Mix ID	Cement	Silica fume	Fly ash	Fine aggregate	Coarse aggregate	Water	HRWRA (L/m^3)	w/(c + p) (by mass)	Slump, mm	Air, percent	7 day, MPa	28 day, MPa	56 day, MPa	90 day, MPa	35-day rapid chloride permeability, coulombs
Kinzua[1]	386	70	0	708	971	130	6.5[5]	0.29	250	3.2	68.7	94.6	—	103.2	—
Pac first[2]	534	40	59	623	1069	131	9.7	0.21	—	—	—	—	124.0	—	—
Mom column[3]	498	30	0	700	1098	135	14.0	0.26	255	—	70.8	85.4	—	89.7[7]	—
LAR-1983[1]	356	53	53	801	1109	111	5.3[6]	0.24	—	—	—	72.5	—	—	—
LAR-1984[1]	380	42	0	756	1092	147	Unknown	0.35	85	1.5	—	55.2	—	—	—
LAR-1985[1]	356	50	65	635	1151	135	4-8[8]	0.29	125	2.0	42.6	60.0	—	—	—
MP1[4]	390	30	0	685	964	156	3.1	0.37	100	6.8	—	60.5	—	—	468
MP2[4]	390	39	0	685	964	160	3.3	0.37	135	7.0	—	64.3	—	—	471
MP3[4]	390	20	0	685	964	152	3.3	0.37	165	8.7	—	58.6	—	—	592

Notes:
1) Holland and Gutschow 1987.
2) Randall and Foot 1989.
3) Aïtcin and Riad 1989.
4) Unpublished data from a Minneapolis parking structure, from Braun Engineering and Testing, Minneapolis, MN.
5) The silica fume was added via a slurry that contained 6.5 kg/m^3 of water reducing admixture solids.
6) 5.3 kg/m^3 of admixture solids.
7) Compressive strength results at 1 year of 97.6 MPa and at 2 years of 94.2 MPa.
8) 4-8 kg/m^3 of admixture solids.

used for other pozzolanic materials. The standards available for specifying silica fume include:

8.2.2 *Norwegian standards*—The Norwegian standard for silica-fume concrete requires the silica fume to have a minimum SiO_2 content of 85 percent, the concrete to have a minimum cement content of 405 lb/yd^3 (240 kg/m^3), and a maximum water-cement ratio of 0.7 (Isabelle 1987).

8.2.3 *United States standards*—Until recently there have been no recognized standards in the United States for silica fume for use in concrete. The first standards were those

Table 7.2—Additional silica-fume concrete mixture proportions (Berke, Pfeifer, and Weil 1988)

Mixture proportions (lbyd^3)													
Mix ID	Silica fume by mass of cement, percent	Cement	Silica fume	Fine aggregate	Coarse aggregate	*w/c*, mass	Slump, in.	Air, percent	28-day compressive strength, psi	28-day rapid chloride permeability, coulombs	300 cycles freeze-thaw, RDME^1	Scale factor^2	10-month total chlorides at 0.5 to 1.0-in. depth (lb/yd^3)
1	0	587	0	1194	1819	0.48	6	7.0	5160	3663	105	1	4.9
2	3.75	588	22	1197	1822	0.48	5.5	7.0	5420	3175	—	—	—
3	7.5	585	45	1268	1813	0.48	6.75	9.0	6350	348	100	0	—
4	15	591	89	1204	1834	0.48	5.75	7.0	7360	198	102	1	0.43
5	0	556	0	1205	1723	0.43	9.75	10.5	5260	2585	—	—	—
6	3.75	593	22	1261	1838	0.43	4	7.4	6550	2210	—	—	—
7	7.5	573	43	1167	1779	0.43	8.25	8.0	7210	213	100	0	0.54
8	7.5	575	43	1246	1782	0.43	9	1.0	6750	—	—	—	—
9	15	598	91	1295	1853	0.43	7	6.0	8580	98	—	—	—
10	0	571	0	1312	1770	0.38	8.75	8.0	5780	3485	104	1	1.63^3
11	3.75	585	22	1344	1814	0.38	3.50	8.0	9310	736	—	—	—
12	7.5	591	44	1358	1832	0.38	8.25	7.0	9290	132	104	1	0.41
13	15	599	90	1377	1858	0.38	6	6.0	12,120	75	102	1	0.53^3

Notes:
1) RDME is the relative dynamic modulus of elasticity.
2) Scale factor ratings: 0 = no scaling, 1 = very slight scaling (no coarse aggregate visible), 2 = slight scaling, 3 = moderate scaling (some coarse aggregate visible).
3) Chloride values measured at 18 months.

Table 7.2—Additional silica-fume concrete mixture proportions (SI units) (Berke, Pfeifer, and Weil 1988)

Mixture proportions (kg/m^3)													
Mix ID	Silica fume by mass of cement, percent	Cement	Silica fume	Fine aggregate	Coarse aggregate	*w/c*, mass	Slump, mm	Air, percent	28-day compressive strength, MPa	28-day rapid chloride permeability, coulombs	300 cycles freeze-thaw, RDME^1	Scale factor^2	10-month total chlorides at 13 to 25 mm depth (kg/m^3)
1	0	348	0	708	1079	0.48	150	7.0	35.6	3663	105	1	2.91
2	3.75	349	13	710	1081	0.48	140	7.0	37.4	3175	—	—	—
3	7.5	347	27	752	1076	0.48	170	9.0	43.8	348	100	0	—
4	15	351	53	714	1088	0.48	145	7.0	50.7	198	102	1	0.26
5	0	330	0	715	1022	0.43	250	10.5	36.3	2585	—	—	—
6	3.75	352	13	748	1090	0.43	100	7.4	45.2	2210	—	—	—
7	7.5	340	26	692	1055	0.43	210	8.0	49.7	213	100	0	0.32
8	7.5	341	26	739	1057	0.43	230	1.0	46.5	—	—	—	—
9	15	355	54	768	1099	0.43	180	6.0	59.2	98	—	—	—
10	0	339	0	778	1050	0.38	220	8.0	39.9	3485	104	1	0.97^3
11	3.75	347	13	797	1076	0.38	90	8.0	64.2	736	—	—	—
12	7.5	351	26	806	1087	0.38	210	7.0	64.1	132	104	1	0.24
13	15	355	53	817	1102	0.38	150	6.0	83.6	75	102	1	0.31^3

Notes:
1) RDME is the relative dynamic modulus of elasticity.
2) Scale factor ratings: 0 = no scaling, 1 = very slight scaling (no coarse aggregate visible), 2 = slight scaling, 3 = moderate scaling (some coarse aggregate visible).
3) Chloride values measured at 18 months.

developed for specific projects. Typically, these standards called for the use of silica fume which met a certain minimum number of physical parameters, SiO_2 content, loss on ignition, and surface area. A typical set of project requirements is shown in Table 8.1.

AASHTO has published the first standard in the United States for silica fume. The requirements established by this standard are shown in Table 8.2.

In 1993 ASTM Committee C-9 developed a standard for silica fume, C 1240. The original thought was that silica fume would become a part of ASTM C 618. This idea was rejected by the ASTM subcommittee and silica fume is covered in a separate standard. The requirements established by this standard are shown in Table 8.3.

8.2.4 *Canadian standards*—The Canadian standard issued in 1986 (Canadian Standards Association 1986) is a much more coordinated standard for use of silica fume in concrete. This standard covers natural pozzolans (N), low calcium fly-ash (F), high calcium fly-ash (C), ground granulated blast-furnace slag (G), and silica fume (U) in a common standard (Isabelle 1987; RILEM Technical Committee 73-SBC 1988). Extracts from this standard are included in Table 8.4.

Table 8.1—Silica fume specification established for Los Angeles River Channel Rehabilitation project (Corps of Engineers 1983)

Requirements and test methods
SiO_2, minimum of 85 percent, ASTM C 311, Section 13
Loss on ignition, maximum of 6.0 percent, ASTM C 311
Moisture content, maximum of 3.0 percent, ASTM C 311, Sections 9 and 10
Surface area, minimum of 10,000 m^2/kg, ASTM C 204 (at a bed porosity of 0.50)

Table 8.2—AASHTO standard for silica fume (the following requirements are taken verbatim from AASHTO M 307-90)

Chemical requirements
Silicon dioxide (SiO_2), minimum 85 percent
Sulfur trioxide (SO_3), maximum 3.0 percent
Loss on ignition, maximum 7.0 percent
Optional chemical requirements
Moisture content of dry silica fume, maximum 3.0 percent
Available alkalies, as Na_2O, maximum 1.5 percent
Note: Applicable only when specifically required for mineral admixture to be used in concrete containing reactive aggregate and cement to meet a limitation on content of alkalies.
Physical requirements
Fineness: Amount retained when wet sieved on No. 500 sieve, 0 percent
Note: There is no fineness determination procedure for microsilica with established performance history. Microsilica is expected to meet this requirement; however, negligible amounts of impurities (up to 0.5 percent) are permitted under this requirement.
Pozzolanic activity index: With portland cement, determine at 7 and 28 days, minimum 100 percent of control
Soundness: Autoclave expansion or contraction, maximum of 0.8 percent
Uniformity requirements: The specific gravity and fineness of individual samples from a given source shall not vary from the average established by the ten preceding tests, or by all preceding tests if the number is less than ten, by more than 5 percent
Optional physical requirements
Increase of drying shrinkage of mortar bars at 28 days, maximum of 0.03 percent
Uniformity requirements: In addition, when air-entrained concrete is specified, the quantity of air-entraining admixture required to produce an air content volume of 18 percent of the mortar shall not vary by the average established by the ten preceding tests, or by all preceding tests if less than ten, by more than 20 percent
Reactivity with cement alkalies: Reduction of mortar expansion at 14 days, minimum of 80 percent
Note: The indicated tests for reactivity with cement alkalies should not be requested unless the material is to be used with an aggregate that is regarded as deleteriously reactive with alkalies in cement. The test for reduction of mortar expansion may be made using any high-alkali cement in accordance with ASTM C 311, if the portland cement to be used in the mix is not known or not available at the time of the test.
Sulfate expansion, 14 days, maximum of 0.045 percent

Table 8.3—ASTM standard for silica fume (the following requirements are taken verbatim from ASTM C 1240-93)

Chemical requirements
Silicon dioxide (SiO_2), minimum 85.0 percent
Moisture content, maximum 3.0 percent
Loss on ignition, maximum 6.0 percent
Optional chemical requirement*
Available alkalies, as Na_2O, maximum 1.50 percent†
* Applicable only when specifically required by the purchaser.
† Applicable for silica fume to be used in concrete containing reactive aggregate with cement required to meet a limitation on alkali content.
Phsyical requirements
Oversize:
Amount retained on 45 µm (No 325) sieve, maximum of 10 percent*
Accelerated pozzolanic activity index:†
With portland cement at 7 days, minimum 85 percent of control
Uniformity requirements:
The density and oversize of individual samples shall not vary from the average established by the ten preceding tests or by all preceding tests if the number is less than ten, by more than:
Density, maximum variation from average, 5 percent
Oversize, percent retained on 45 µm (No. 325) sieve, maximum of 5 percentage points from average
* Care should be taken to avoid retaining agglomerations of extremely fine material.
† Accelerated pozzolanic activity index is not to be considered a measure of the compressive strength of concrete containing the silica fume. This is a measure of the reactivity of a given silica fume with a given cement and may vary with the source of both the silica fume and the cement.
Optional physical requirements*
Increase over control of drying shrinkage of mortar bars at 28 days, maximum of 0.10 percent
Specific surface area, 15-30 m^2/g
Uniformity requirements:
When air-entraining concrete is specified, the quantity of air-entraining agent required to produce air content of 18 volume percent of mortar shall not vary from the average established by the ten preceding tests or by all preceding tests if less than ten, by more than 20 percent
Reactivity with cement alkalies:†
Reduction of mortar expansion at 14 days, minimum of 80 percent
Sulfate resistance expansion‡
(moderate resistance) 6 months, maximum of 0.10 percent
(high resistance) 6 months, maximum of 0.05 percent
(very high resistance) 1 year, maximum of 0.05 percent

* Will be made only at request of purchaser.

† The indicated tests for reactivity with cement alkalies shall not be requested unless the material is to be used with an aggregate that is regarded as deleteriously reactive with alkalies in hydraulic cement. The test for reduction of mortar expansion may be made using any high-alkali cement in accordance with ASTM C 311, if the cement to be used in the work is not known or is not available at the time of the test. The test for mortar expansion should be performed by each of the high-alkali cements to be used in the work.

‡ Only one limit shall be specified.

8.3—Specifying silica-fume admixtures

As described in Chapter 1, silica fume is commercially available in three forms: a solid (or powdered), a densified solid, and in a slurry. Each of these forms may or may not be marketed in conjunction with chemical admixtures. Typically, specifications have tended to treat these products as individual components. The silica fume has been required to meet requirements as outlined above and the chemical admixtures, if present, have been required to meet the requirements of ASTM C 494. Until there is activity directed toward preparing a standard specification for silica-fume admixtures, this separate approach seems to be prudent.

To prevent minor variations in fresh or hardened concrete performance that may result from changes in silica-fume admixture source or product form, Holland (1989) has recommended that changing products during a project be avoided unless appropriate testing has been done to verify mixture proportions and concrete performance using the alternate material.

8.4—Specifying silica-fume concrete

Silica-fume concrete has usually been specified as a separate section within Division 3 of a project specification

Table 8.4—Requirements for silica fume from the Canadian Standard for Supplementary Cementing Materials (Canadian Standards Association 1986)

Chemical requirements
Silicon dioxide (SiO_2), minimum 85 percent
Sulfur trioxide (SO_3), maximum 1.0 percent
This limit may be exceeded, provided that the supplementary cementing material when tested in combination with the particular portland cement with which it is to be used, exhibits expansion not in excess of 0.020 percent at 14 days when tested in accordance with Clause 7.5.5 of CAN3-A5. In the test mixture, replace a mass of portland cement by an equal mass of supplementary cementing material in the amount of 20 percent, generally, or for Type U in the amount of 10 percent, or the anticipated maximum field replacement percentage, whichever shall be greater.
Loss on ignition, maximum 6.0 percent
Optional chemical requirements
Moisture content, maximum of 3 percent
Physical requirements
Accelerated pozzolanic activity index, with portland cement, at 7 days, minimum 85 percent of control.
Fineness, maximum of 10 percent retained on 45 µm (No. 325) sieve
Soundness: Autoclave expansion or contraction, maximum 0.2 percent
Uniformity requirements: a) Relative density: maximum 5 percent variation from average b) Fineness, maximum 5 percent variation from average
Optional physical requirements
Increase of drying shrinkage, maximum 0.03 percent of control
Uniformity of addition rate of an air entraining agent, maximum 20 percent variation from average
Reactivity with cement alkalies, minimum 80 percent reduction.

following the format established by the Construction Specifications Institute. The section of the project specification on silica-fume concrete usually contains requirements for the silica fume itself, requirements for the silica-fume concrete, and any procedural requirements that differ from those for concrete not containing silica fume. Sections 8.4.1 through 8.4.5 of this Guide address procedural topics that should be covered in the project specifications for silica-fume concrete.

8.4.1 *Measuring, batching, and mixing*—Concrete containing silica fume has been batched in all of the acceptable methods currently available for production of concretes. In some cases, the dry powder has been added to the mixer after mixing the other materials. In other cases, the dry powder has been premixed with portland cement prior to batching. Generally, the slurried admixtures have been added at the time and manner in which other liquid admixtures have been added. It should be noted that the volume of silica-fume slurry used per unit volume of concrete is generally much greater than other liquid admixtures. For example, a typical water-reducing admixture may require use of 12 fl oz/yd^3 (645 mL/m^3), a typical high-range water-reducing admixture (HRWRA) may require use of 135 fl oz/yd^3 (5.2 L/m^3), whereas a silica-fume slurry may require use of 11 gal/yd^3 (55 L/m^3) (Holland 1988). Automated dispensing equipment is commonly used for efficient handling of large volumes of silica-fume slurry. All dispensing equipment for silica fume should be required to meet the accuracy requirements of ACI 304R and ASTM C 94.

Project specifications must be clear regarding the quantity of silica fume that is being specified. Because of the variety of forms of silica-fume admixtures that are available, there must not be any question whether the quantity refers to silica fume or an admixture containing silica fume.

Project specifications for silica-fume concrete may require extra mixing of the concrete to assure uniform dispersion of the silica fume. If there is a question of whether mixing is adequate, mixer uniformity testing as outlined in ASTM C 94 should be specified.

8.4.2 *Placing and consolidating*—Placing and consolidating silica-fume concrete can be accomplished with any of the currently available techniques as described in ACI 304R. Effective consolidation of silica-fume concrete is critical to performance and requires special attention (see ACI 309R). Even at slump as high as 8 to 10 in. (200 to 250 mm), excessive air has been entrapped in the concrete. This entrapment is a result of the cohesive nature of the silica-fume concrete and can be removed only by effective vibration (Holland 1988).

8.4.3 *Finishing*—Procedures for finishing silica-fume concrete are similar to those used for finishing other concrete. However, because silica fume concrete does not bleed, the timing of finishing operations will usually have to be adjusted. Silica-fume concrete is also highly susceptible to plastic shrinkage cracking. All of these factors need to be taken into account in the finishing portion of the project specifications. Additional information on finishing and preventing plastic shrinkage cracking may be found in Chapter 9.

8.4.4 *Curing and protecting*—Procedures for curing and protecting silica-fume concrete are similar to those used for other concretes. However, because of the potential for plastic shrinkage cracking, it is more critical that protective measures be taken during placement and that curing procedures begin immediately after the finishing process is completed (see ACI 308). Project specifications must emphasize this point. Additional information on curing silica-fume concrete may be found in Chapter 9. Winter protection procedures for silica-fume concrete do not differ from those used for any other concrete (see ACI 306R).

8.4.5 *Preconstruction testing*—Preconstruction testing of silica fume, cements, aggregates, and admixtures is essential to assure that the desired properties can be obtained with the most economical concrete mixtures. Mixture proportions should be developed to obtain optimum cement and silica fume contents. Testing should include slump, air content, compressive strength, resistance to abrasion, chloride permeability, resistance to freezing and thawing, and scaling, as appropriate to meet project requirements.

On many projects preconstruction testing may include a demonstration of placing, finishing, and curing techniques during a trial placement. Such testing should be included in the project specifications and the contractor should be warned that placing silica-fume concrete in the actual structure will not be allowed until successful completion of these trial placements.

CHAPTER 9—WORKING WITH SILICA FUME IN FIELD CONCRETE

9.1—Transporting and handling silica fume and silica-fume admixture products

Handling procedures for silica-fume materials depend upon the form of the product being used, dry or slurry. Within these two general product forms, silica fume can be provided as "plain" silica fume (without chemical admixtures) and as a silica-fume product containing high-range water-reducing admixtures (HRWRA) and, possibly, other chemical admixtures. Since silica-fume products are available in dry bulk, dry "super sack," dry paper sack, liquid bulk, and liquid drums, the material handling systems and the equipment used in transportation, discharge, storage, batching, and mixing of the silica fume depend upon the specific product form.

Transportation of silica fume depends on the product form and consequently the economics of transportation and material handling are determined by the product's weight (mass), density, available handling equipment, and applicable regulations.

9.1.1 *Dry silica fume*—Dry silica-fume products may be further categorized into two forms, as-produced silica fume with a typical bulk loose density of 8 to 27 lb/ft^3 (130 to 430 kg/m^3) and compacted silica fume with a typical bulk loose density of 30 to 45 lb/ft^3 (480 to 720 kg/m^3).

Silica fume in the as-produced form tends to be dusty, prone to lumping, and difficult to move in cement handling equipment. Bulk silica fume in the as-produced form is being used in some parts of the United States and Canada.

Silica fume in the compacted form is virtually dustless, free of lumps, and flows readily. In bulk form it can be transported in bulk cement tankers (both truck or rail), and stored in ordinary cement silos. The bulk product is moved into storage silos by pneumatic lines or bucket elevators.

In cement tankers, bulk compacted silica fume load size is 12 to 17 tons (10.9 to 15.4 Mg) for a 1000-ft^3 (28.3-m^3) tank truck and 18 to 25 tons (16.3 to 22.7 Mg) for a 1400-ft^3 (39.4-m^3) tank truck. A 100-ton (90.7-Mg) cement rail car can typically hold 60 to 80 (54.4 to 72.6 Mg) tons of compacted material. The bulk load size for as-produced fume is significantly less, at 7 to 10 tons (6.4 to 9.1 Mg) for a 1400-ft^3 (39.4-m^3) tanker because of decreased density and fluffing. Skrastins and Zoldners (1983) reported that a ready-mixed concrete company in Canada had built a special van truck for transporting as-produced silica fume in load sizes of 20 tons (18 Mg).

Loading of compacted silica fume is accomplished with an air slide or gravity feed and normally requires 15 to 20 min to transfer 25 tons (22.7 Mg) to a bulk tank truck. As-produced silica fume is blown pneumatically into bulk tank trucks, and typically takes 3 to 5 hours of loading time.

When the bulk tank truck arrives at the concrete plant, the silica fume is pneumatically discharged into the input pipe of the storage silo. Discharge time varies typically from 90 min to 4 hr for compacted silica fume and 3 to 6 hr for as-produced fume. Sonic horns have been used to help move as-produced silica fume during unloading and handling within a concrete plant. Use of rubber hoses rather than steel pipe has been shown to reduce unloading times for as-produced and compacted bulk silica fume.

As silica-fume concrete mixtures are usually proportioned by mass of cement (typically 5 to 20 percent), the compacted silica-fume silo can be smaller than the concrete producer's normal cement silo. However, the silo should be at least 3000 ft^3 (85 m^3) in capacity so it holds at least two full truck-loads [50 tons (45.4 Mg) of compacted fume] so that the schedule of silica-fume deliveries is not critical to the concrete volume requirements for large placements. Storage silos for undensified silica fume are much larger, as the bulk densities are one third to one half that of compacted silica fume.

The dry compacted form can also be packaged in large 70-ft^3 (2-m^3) polypropylene bags or "super sacks" holding approximately 1 ton (900 kg) of compacted silica fume. A 40-ft (12-m) truck trailer can haul approximately 22 tons (20 Mg) when using these super sacks. Super sacks are usually packaged on skids for easy removal from closed trailers. These bags are manufactured with slings or sleeves for lifting purposes. The bags are either "one use," where the material is discharged by piercing the bottom with a bag breaker mounted in the receiving hopper, or reusable incorporating a pouring spout in the bottom of the sack. Super sacks can be emptied into a receiving hopper and transferred pneumatically or by bucket elevator into bulk storage silos. These polypropylene sacks can also be custom sized and filled, with any mass [typically 1/2 to 1 ton (500 to 900 kg)], to be consistent with a convenient multiple of the silica fume content in a concrete mixture and thus be field batched directly into a truck mixer.

Dry silica fume (both as-produced and compacted) is also available in small paper bags [50 or 55 lb (22.7 or 24.9 kg)], plain or with dry chemical admixtures. They are normally shipped on shrink wrapped pallets, and depending on the density of the product, 18 to 22 tons (16.3 to 20.0 Mg) of material can be shipped on a standard truck trailer. The advantage of this product form is that it lends itself to relatively small projects or remote locations. The product form that contains HRWRA may eliminate the need to handle the HRWRA separately, thus simplifying batching and mixing of silica-fume concrete for applicable field projects.

9.1.2 *Slurried silica fume*—Several manufacturers supply silica-fume-water slurries. This is done to enable the silica fume to be stored and dispensed in liquid form. Transportation costs are reduced relative to those of as-produced silica fume because over twice as much silica fume can be shipped in a given container volume. However, slurry transportation cost is typically higher than that of compacted silica fume due to the requirements of shipping the water portion of the slurry. Transportation costs for slurry may be reduced if a portion of the journey is via barge or tanker.

There are many different kinds of slurried silica-fume products, and each may have specific handling characteristics. The so-called plain slurry products are about 50 percent silica fume by mass and are stored for regional distribution in steel tanks that are frost protected in regions where cold temperatures occur. Some tanks are equipped with recirculation pumps or mechanical paddle agitators to keep the material homogenized and liquefied. Often only intermittent agitation or recirculation is needed, and sometimes compressed air is used briefly to disperse the material.

The plain slurry material and formulated (containing chemical admixtures) slurry products are pumped, or moved by gravity, into 4000-gal (15,100-L) tanker trucks or 20,000-gal (75,700 L) rail tanker cars for transportation to permanent or mobile dispensers located at concrete production plants. If the weather conditions warrant, the tankers should be insulated.

Formulated slurry products, with water-reducing admixtures, are stored and dispensed in essentially the same manner as the plain slurry products, although the pump and dispensing line sizes may be somewhat larger, and the recirculation and agitation periods may vary from those used for plain slurry.

Slurry products are also shipped in 50 or 55-gal (190 or 208-L) steel drums or 5-gal (19-L) pails. Sometimes, particularly for small jobs or trial batch work, drums are filled to a specified mass, and the entire contents of the drum are added to a specified concrete volume. The product is usually liquefied via mechanical agitation prior to being used in this manner, and it can be transported to the mixer through a small pump.

Slurried silica fume should be protected against freezing during transportation or storage. Should a particular slurry freeze, the supplier should be consulted to determine what steps should be taken.

9.2—Producing concrete

9.2.1 *Dry silica fume*—Producing silica-fume concrete with bulk dry compacted material is very similar to producing ordinary concrete with other bulk mineral admixtures such as fly ash or slag. The bulk compacted material is handled by normal cement storage and internal conveying and weighing equipment along with ordinary admixture dispensing, concrete batching, and mixing equipment. Dry silica-fume weigh batching is usually accomplished by discharging into the cement weigh hopper, on top of the cement after the cement weighing is completed. If cumulative weighing is used, care should be taken to assure that the cement is not overweighed as this will reduce the amount of silica fume that will be added. Silica-fume concrete almost always requires a HRWRA, thus standard liquid HRWRA dispensing systems are used, along with existing normal admixture dispensing systems for ordinary water reducers and air-entraining admixtures. Silica-fume concrete using dry compacted silica fume has been successfully prepared in both dry batch and central-mixing concrete plants. Bags and super sacks are typically introduced to the batch at the most appropriate time as determined by trial batches.

Producing concrete using as-produced dry silica fume has been done. The exact techniques and materials handling procedures will depend upon whether the silica fume is provided in bulk or in bags.

9.2.2 *Slurried silica fume*—At the concrete production plant, the slurry products are typically stored in steel or fiberglass 2000 to 6000-gal (7500 to 22,700-L) tanks. These tanks usually have recirculation or mechanical agitation capability or both that are used intermittently as required to liquefy the material for dispensing. Typically, the slurry is pumped from the storage tank through a flow meter and a hose into the mixer or into the water weigh hopper. Some systems dispense the slurry by mass, but volumetric dispensers are more commonly used.

Slurry silica-fume products have been mixed successfully in various kinds of mixers, including truck mixers, central mixers (both drum and pan mixers), mortar mixers, and auger mixers. In most cases the slurry products are added to the mixer either before or during charging of the other concrete ingredients, although more rarely it may be the last ingredient added to the concrete.

9.2.3 *Mixing silica-fume concrete*—To produce consistent silica-fume concrete, it is important that the mixing equipment is in good condition. Mixing time may need to be increased and the volume of concrete mixed in truck mixers in particular may need to be decreased somewhat to achieve good concrete uniformity when using high dosages of silica fume with low water content concrete. The amount of increased mixing is generally higher for densified silica fume to achieve proper dispersion.

9.3—Transporting

Silica-fume concrete has been successfully transported and placed using most commonly available concrete equipment and methods as described in ACI 304R. There has typically been no requirement to modify transportation and placing equipment or procedures.

9.4—Placing

Although silica-fume concrete offers significant advantages for steel reinforcement corrosion protection, high strength, abrasion resistance, and chemical resistance, it is absolutely essential to adhere to good concrete placement practices as outlined in ACI 304R to achieve this high level of concrete performance. Before placing silica-fume concrete, the contractor must be prepared. Adequate manpower, back-up equipment (vibrators, vibratory screeds, power sprayers) and the proper curing materials should all be on hand. With silica-fume concrete, generally the placing, finishing, and curing procedures must all be performed in a continuous operation.

Silica-fume concrete should be placed at the highest practical slump [6 to 9 in. (150 to 225 mm)]. It may also be advisable to redose with additional HRWRA on site to maintain the high placement slump. Silica-fume concrete is very cohesive and resists segregation at high slumps. Even though silica-fume concrete flows well, vibration is needed for good consolidation even at high slumps. Use of a vibratory screed is recommended when placing slabs and concrete overlays.

9.5—Finishing

Addition of silica fume to concrete will increase cohesiveness and reduce bleeding thereby altering the finishability and the finishing operations required. As the amount of silica fume in the concrete increases, so will the effect of the silica fume on finishing. The absence of bleed water and the stickiness of concrete with high silica fume dosages (10 to 20 percent) makes screeding and troweling slab surfaces more difficult than ordinary concrete.

The best way to establish exact finishing methods for any particular project (especially for large scale flatwork) is to stage small trial placements prior to the start of the actual work. These trials can be repeated until the best methods for a given project and its specified mixture proportions are identified. Trial placements also “prove” placement equipment and provide valuable experience for the placing and finishing crews, as the timing and readiness of the finishing crew is important.

A general approach to finishing silica-fume concrete is to “under finish” as opposed to “over finishing” the concrete surface (Holland 1987b). Although it may not always be esthetically pleasing, the minimum required finish is the best approach since it provides the most resistance to aggressive freezing and thawing and aggressive chemical environments.

Proper vibration will also help finishing by bringing fines to the surface of the slab. The use of a vibratory screed on slabs and concrete overlays is recommended.

9.5.1 *Plastic shrinkage cracking*—Because of the absence of bleed water, plastic shrinkage cracking is a concern associated with silica-fume concrete, although it can occur in any type of concrete (see also Section 4.6). If proper procedures are followed, plastic shrinkage cracking can be completely eliminated from silica-fume concrete. Plastic shrinkage cracking can occur at any time between initial finishing operations (leveling and screeding) and the time of final setting and hardening of the concrete.

Contractors have frequently been urged by suppliers of silica fume or required by project specifications to use the chart presented as Fig. 2.1.5 in ACI 305R or as Fig. 1 in ACI 308 that allows estimates to be made regarding the rate of evaporation from fresh concrete. For instances in which the chart predicts that plastic shrinkage cracking is likely, contractors have been referred to the preventative steps included in ACI 305R and 308. Cohen, Olek, and Dolch (1990) have suggested that the potential for plastic shrinkage cracking of silica-fume concrete is greater than that predicted by the ACI chart. The potential for such cracking increases with increasing dosages of silica fume because of the further reductions in the rate of bleeding. The Virginia Department of Transportation (1991) requires that measures to reduce moisture loss be taken when the predicted rate of evaporation of surface moisture from silica-fume concrete exceeds 0.05 lb/ft^2/hr (0.5 kg/m^2/hr) during the placement.

The use of a compressed-air/water misting device can help prevent moisture from evaporating from the concrete surface and help prevent plastic shrinkage cracking. A misting device will also aid bull floating and finishing; however, it should not be used to apply excess water to the concrete's surface for finishing purposes. Only a fine coating or sheen should be applied with the misting device. Evaporation retarders will also aid finishing, retain moisture in the concrete, and prevent plastic shrinkage cracking. Another method of preventing plastic shrinkage cracking is the immediate covering of the concrete surface after screeding and between finishing operations.

Slab placements in hot climates often include the use of retarders to increase working time. Excessive use of retarders will lead to the formation of a sponge-like dry crust on the concrete surface, making finishing difficult. This crust may also be highly susceptible to plastic shrinkage cracking. This problem can be prevented by the reduction or elimination of retarders or by using the same protective measures used against plastic shrinkage cracking.

For slabs requiring a steel-trowel finish, after screeding and bull floating, apply an evaporation retarder, continuously water mist the surface, or cover with plastic sheeting until the slab is firm enough to support finishers and finishing equipment.

9.6—Curing

To obtain the full benefits of silica-fume concrete, proper curing procedures must be followed. Because of the typically low water content and low water-to-cementitious material ratio, silica-fume concrete requires additional attention to curing as compared to ordinary concrete. This extra emphasis on curing helps to retain the water needed for development of the desired properties of the concrete.

Chlorinated-rubber based curing compounds meeting the requirements of ASTM C 309 have proved to be very effective for silica-fume concrete. When applying this curing compound to slabs or other large areas, a power sprayer is recommended for thorough coverage and faster application. Curing agents should be applied immediately after finishing to protect against plastic shrinkage cracking.

An alternate curing method for silica-fume concrete slabs is to cover them with wet burlap and plastic sheeting. However, if wet curing is used, the concrete must be protected against plastic shrinkage since there is usually a time delay associated with placing burlap that could allow cracking. Protect against plastic shrinkage using one of the techniques mentioned earlier such as fog misting or using an evaporation retarder until the concrete has enough strength to support the placement of the wet burlap and plastic. Leave the burlap and plastic in place and keep the concrete wet for at least three days and preferably for five to seven days. Exposed surfaces should be coated with a curing compound or, if feasible, covered with wet burlap and plastic after form removal.

Carefully following these curing procedures will help to assure the realization of all of the intended and specified benefits of silica-fume concrete.

9.7—Accelerated curing

There is synergy between silica-fume concrete and steam or heat accelerated curing. Although there are no published data, manufacturers of precast silica-fume concrete products have achieved impressive gains in early age compressive strength. In many cases, the economics of fuel cost savings compared to the cost of the silica-fume admixture were favorable.

In the case of heat-cured concrete, ACI 517.2R discusses the variables which must be considered when planning the heat curing cycle. In general, a presteaming period approximately equivalent to the period of initial setting of the concrete will produce satisfactory results.

Calcium chloride and non-chloride accelerators have been used with silica-fume concrete in the field. Feedback from those projects suggests that accelerating admixtures have the same effects upon silica-fume concrete as they have upon concrete without silica fume.

CHAPTER 10—RESEARCH NEEDS

The following topics have been identified as needing further research, either to allow for more advanced applications or to increase the effectiveness of and confidence in current applications.

10.1—Frost resistance

As discussed in Chapter 5, studies of the resistance of silica-fume concrete to freezing and thawing have produced conflicting results. Some researchers have found the concrete to be frost resistant without entrained air; others have found that even with entrained air the concrete is not durable. No doubt much of the controversy stems from differences in test conditions: mixture proportions, curing, degree of saturation of the specimens, choice of test method. There is also concern that the general standard test methods (ASTM C 666) applied to normal concrete may not be applicable to silica-fume concrete and may need to be modified (Sellevold and Nilsen 1987; Feldman 1986; Gudmundsson and Asgeirsson 1983; Huang and Feldman 1985c). Use of ASTM C 671 for assessing resistance to freezing and thawing of high-strength silica-fume concrete should be investigated as a possible replacement or extension of ASTM C 666. The influence of air-entraining admixtures on frost resistance and the plausibility of obtaining a non-air-entrained frost-resistant high-strength silica-fume concrete is currently being studied. If the concrete will never become critically saturated in service, it doesn't need entrained air to be frost resistant.

10.2—Sulfate attack

A detailed research needs statement regarding sulfate attack was provided by Cohen and Mather (1991). Most of the literature deals with one type of sulfate attack — sodium sulfate. Information on magnesium sulfate attack on silica-fume concrete is incomplete (Goldman 1987; Cohen and Bentur 1988). In sodium sulfate solutions, silica fume has been shown to have good resistance. It is possible to use a blend of ASTM Type I portland cement with silica fume to replace ASTM Type V sulfate-resistant portland cement (Cohen and Bentur 1988). Work dealing with magnesium sulfate action on pastes of portland cement plus silica fume showed that the presence of silica fume can be deleterious (Cohen and Bentur 1988). The pastes experienced reductions in strength, loss of mass, and expansion. These results were confirmed on tests with silica-fume concrete (Goldman 1987).

10.3—Drying shrinkage and creep

The literature dealing with the subjects of shrinkage and creep is limited and inconclusive. Their relationship needs to be established. The influence of high-range water-reducing admixtures (HRWRA) seems to generate some confusion in the analysis of shrinkage data. Use of HRWRA is important since it allows a reduction in the volume of the binder phase fraction. However, the use of HRWRA can lead to increased shrinkage, thus offsetting some or all of the advantages gained by the reduced water content (Sellevold and Nilsen 1987). In addition to shrinkage, creep and stress-relaxation seem to play major roles in the crack sensitivity of silica-fume concrete. Thus data on shrinkage alone are of limited value in connection with crack sensitivity (Sellevold and Nilsen 1987).

10.4—Steel corrosion

Corrosion of steel reinforcement is one of the most critical durability problems for concrete exposed to chloride ions. Laboratory tests of silica-fume concretes show that they have low chloride permeability and high electrical resistivity (Chapter 5). Both of these are important in protecting the embedded reinforcement from depassivation and the resulting acceleration in the rate of corrosion. However, they are only indications of how the concrete will perform in service. Chloride permeability analysis by both the rapid chloride ion permeability and ponding tests needs to be conducted and compared. The applicability and usefulness of the ASTM and AASHTO methods need to be evaluated. Laboratory tests generally measure a single factor affecting the complex process of corrosion. Research is needed to develop better test methods, to investigate the performance of concrete under field conditions, and to determine construction practices that produce the best results in terms of resistance to corrosion. A related issue of particular interest in North America is the repair of deteriorated structures. Research is needed to develop repair methods that will not simply create new corrosion cells in different locations. Silica-fume concrete may well have a role to play in these repairs.

10.5—Performance under high-temperature conditions

Despite positive results for tests of the fire endurance of silica-fume concrete (Chapter 5), further investigation is needed, particularly for high-strength concrete. As Jahren (1989) points out, some applications of high-strength concrete (with or without silica fume) may entail greater risks of explosive spalling. These include slender members under high stresses, prestressed concrete, and offshore structures.

10.6—Long-term durability

Most of the data on the durability of silica-fume concrete have come from laboratory tests. These need to be supplemented and correlated whenever possible with data from concrete exposed to field conditions. Accelerated tests are necessary for practical reasons, but they may be misleading. Some structures and pavements made from silica-fume concrete are now old enough to provide useful information about actual performance. A comprehensive study of these applications would provide invaluable information in terms of relating laboratory test results with field performance as well as indicating good construction practices for future projects.

10.7—Pore structure and permeability

As discussed in Chapter 5, silica fume does not substantially reduce the porosity as measured by mercury intrusion porosimetry. The main effect on the pore structure is the reduction of large pores by blocking them with hydration products. The transformation of continuous pores into discon-tinuous pores has a profound effect on the permeability of silica-fume concretes (Chapter 5). From their study of pastes containing fly ash and portland cement, Marsh, Day, and Bonner (1985) concluded that when there is a significant amount of pozzolanic activity, helium porosity correlates better with permeability than does mercury porosity. This is most likely true of silica fume and portland cement pastes as well. Testing the water permeability of low-permeability concretes is difficult because of problems with leakage around the specimen and with measuring low flows. The commonly used methods for assessing chloride permeability are also unsatisfactory in some respects. Development of better test methods is thus of major importance. Another concern is the optimization of mixture proportions and curing conditions to minimize the permeability of the concrete.

10.8—Rheology and setting properties

As mentioned in Chapter 4, silica-fume concrete frequently requires a higher slump to provide the same workability as concrete without silica fume. This difference illustrates one limitation of the slump test as a measure of workability. Test methods are currently being developed that measure both yield value and plastic flow parameters of fresh concrete (Wallevik 1990). These promise more meaningful data on workability, but will require more research before they can be used with confidence in the field. A related issue is the role of HRWRA, particularly with regard to slump loss. A detailed study addressing the problem of plastic shrinkage cracking would be particularly helpful.

10.9—Mechanism of strength development

The presence of silica fume in concrete increases its strength. This is due to physical and pozzolanic effects in the bulk matrix and at the interfaces between the matrix and inclusions (Detwiler 1988; Cong et al. 1990). The significance of each effect is still uncertain. Also, their significance during each stage of hydration (fresh and hardening) is not known, although during the fresh stage the physical effects clearly dominate, setting the stage for the hardening period. The mechanism of strength development in silica-fume concrete still needs to be established. The important parameters controlling the development need to be identified and quantified to optimize the effect of silica fume and mixture proportioning.

10.10—Role of silica fume in special concretes

Research is needed to study the influence of silica fume in nonconventional concretes. A recent article (Cohen, Olek, and Mather 1991) indicates that positive use of silica fume should not be limited to ordinary portland cement concrete, but also has a role in expansive-cement concrete.

10.11—Effect of silica fume on hydration

Chapter 3 describes the physical and chemical effects of silica fume on the hydration of portland cement. However, most of the research in this area has focused separately on the chemistry or the microstructure or the behavior of the concrete, with some discussion of the likely implications for the other areas, but with little or no experimental work to verify the discussion. Very little experimental work has been done to integrate these aspects. Studies of two or more of these areas using consistent ingredients and test conditions throughout can provide a meaningful basis for further advancement.

10.12—Curing

Most laboratory tests of concrete involve curing at room temperature, even though in practice most concrete cures at other temperatures. Very few data are available in the literature on the effects of typical curing regimes on the properties of silica-fume concrete. Research on the development of the microstructure of silica fume cement-based materials, supplemented by tests of the mechanical and durability characteristics of silica-fume concrete, is needed to provide a sound basis for field practice. A good model for a study of this type would be the work of Kjellsen (1990).

10.13—Recommended field practice

Experience with silica-fume concrete to date has demonstrated that it can perform well when properly proportioned, mixed, placed, and cured. However, some questions remain only partially answered: How is adequate resistance to freezing and thawing assured? What limits should be placed on minimum and maximum curing temperatures? What practices will result in the best protection against corrosion of reinforcement?

CHAPTER 11—REFERENCES

11.1—Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

American Association of State Highway and Transportation Officials

M 307-90	Standard Specification for Microsilica for Use in Concrete and Mortar
T 277	Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete (See also ASTM C 1202)

American Concrete Institute

116R	Cement and Concrete Terminology
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
305R	Hot Weather Concreting
306R-88	Cold Weather Concreting
308	Standard Practice for Curing Concrete
309R-87	Guide for Consolidation of Concrete
363R	State-of-the-Art Report on High-Strength Concrete
517.2R	Accelerated Curing of Concrete at Atmospheric Pressure — State of the Art

American Society for Testing and Materials

C 94	Standard Specification for Ready-Mixed Concrete
C 204	Test Method for Fineness of Portland Cement by Air Permeability Apparatus
C 227	Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C 309	Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 311	Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete
C 441	Standard 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 494	Standard Specification for Chemical Admixtures for Concrete
C 618	Standard Specifications for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 642	Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete
C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 671	Standard Test Method for Critical Dialtion of Concrete Specimens Subjected to Freezing
C 672	Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
C 1012	Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C 1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
C 1240-93	Standard Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar
E 1156	Standard Practice for Health Requirements for Occupational Exposure to Synthetic Amorphous Silica

U. S. Army Corps of Engineers

CRD-C 63	Test Method for Abrasion-Erosion Resistance of Concrete (Underwater Method)

The above publications may be obtained from the following organizations:

American Association of State Highway and Transportation Officials
444 North Capitol Street NW, Suite 225
Washington, DC 20001

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

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

U. S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180

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