

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.

Keywords: curing; durability; high-range water-reducing admixture; high-strength concrete; placing; plastic-shrinkage cracking; silica fume; time of setting; water-reducing admixture; workability.

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CHAPTER 1—INTRODUCTION

1.1—General

Silica fume, a by-product of the ferrosilicon industry, is a highly pozzolanic material that is used to enhance mechanical and durability properties of concrete. It may be added directly to concrete as an individual ingredient or in a blend of portland cement and silica fume. ACI Committee 234 estimates that at least 120,000 metric tons (130,000 tons) of silica fume are used in concrete worldwide annually. Using this figure, more than 6 million cubic meters (nearly 8 million cubic yards) of silica-fume concrete are placed globally each year.

Interest in the use of silica fume resulted from the strict enforcement of air-pollution measures designed to stop release of the material into the atmosphere. Initial use of silica fume in concrete was mostly for cement replacement, along with water-reducing admixtures (WRAs). Eventually, the availability of high-range water-reducing admixtures (HRWRAs, often referred to as superplasticizers) allowed new possibilities for the use of silica fume to produce high levels of performance.

This document provides basic information on using silica fume in concrete. The document is organized as follows:

- Chapter 1 provides general information on silica fume;
- Chapter 2 describes the physical properties and chemical composition of silica fume;
- Chapter 3 describes the mechanisms by which silica fume modifies cement paste, mortar, and concrete;
- Chapter 4 describes the effects of silica fume on fresh concrete;
- Chapter 5 describes the effects of silica fume on hardened concrete;
- Chapter 6 shows how silica fume has been used on actual projects. This chapter covers only a very small number of applications because ACI Committee 234 is currently developing an additional document that will provide detailed case histories of many more projects;
- Chapter 7 discusses specifications for silica fume and silica-fume concrete;
- Chapter 8 presents a step-by-step methodology for proportioning silica-fume concrete for specific applications;
- Chapter 9 presents recommendations for working with silica fume in field concrete;
- Chapter 10 summarizes research needs for using silica fume in concrete; and
- Chapter 11 presents all of the references from the other chapters.

Note that the coverage in Chapters 7–8, and 10 is somewhat brief. More details on working with silica-fume concrete in

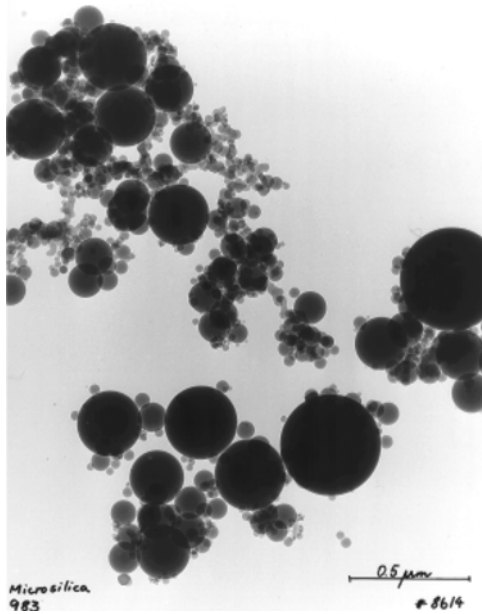


Fig. 1.1—Transmission electron microscope micrograph of silica fume. (Image courtesy of Elkem ASA materials.)

actual applications may be found in a guide published by the Silica Fume Association (Holland 2005).

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 field observations of completed silica-fume concrete and by testing of cores taken from such concrete.

1.2—What is silica fume?

Silica fume, as defined in ACI 116R, is “very fine noncrystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon.” 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 and 1.2) typically averaging 0.1 to 0.2 μm (4 to 8 $\times 10^{-6}$ in.) in diameter. Often, several individual spheres can be fused together to form small agglomerates.

The first mention of silica fume for use in concrete and mortar is found in a U.S. patent from 1946 (Sharp 1946) where the use of silica fume to improve the properties of fresh mortar is the main claim of the patent.

Silica fume was first collected in Kristiansand, Norway, in 1947. Investigations into the properties of the material and its uses began promptly, with the first paper being published by Bernhardt in 1952. Investigations of the performance of silica fume in concrete also followed in other Nordic countries: Iceland, Denmark, and Sweden. Additional early Scandinavian papers included those by Fiskaa et al. (1971), Traetteberg (1977), Jahr (1981), Asgeirsson and Gudmundsson (1979), Løland (1981), and Gjörv and Løland (1982). In 1976, a Norwegian standard permitted the use of silica fume in

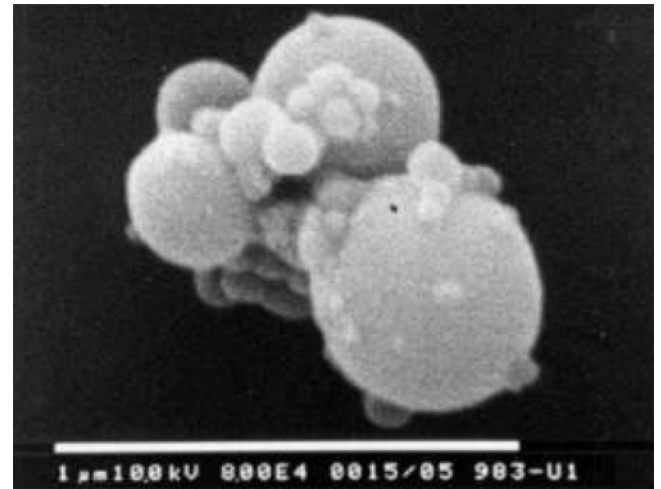


Fig. 1.2—Scanning electron microscope micrograph of silica fume. (Image courtesy of Elkem ASA materials.)

blended cement. Two years later, the direct addition of silica fume into concrete was permitted by a 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 was published in 1981 by Buck and Burkes of the U.S. Army Corps of Engineers Waterways Experiment Station (WES). Other early research was conducted by CANMET (Malhotra and Carette 1983; Carette and Malhotra 1983a), Sherbrooke University (Aïtcin 1983), Norchem (Wolsiefer 1984), and the U.S. Army Corps of Engineers WES (Holland 1983). In 1978, Norchem did the first major placement of ready mixed silica-fume concrete in the United States for resistance to chemical attack.* In late 1983, the U.S. Army Corps of Engineers did the first publicly bid project in the United States using silica-fume concrete (Holland et al. 1986).

The SiO_2 content of the silica fume is roughly related to the manufacture of silicon alloys as follows:

Alloy type	Typical SiO_2 content of silica fume
50% ferrosilicon	74 to 84%
75% ferrosilicon	84 to 91%
Silicon metal (98%)	87 to 98%

Ferrosilicon alloys are usually produced with nominal silicon contents of 50 to 98%. When the silicon content reaches 98%, the product is called silicon metal rather than ferrosilicon. As the silicon content increases in the alloy, the SiO_2 content increases in the silica fume. The majority of published data and field use of silica fume have been from alloys of 75% ferrosilicon or higher. Wolsiefer et al. (1995) and Morgan and Wolsiefer (1992), however, present information on using silica fume from production of alloys with

*Private communication from commercial member.



50% iron in applications such as chemically resistant concrete, shotcrete, blended cement, and oil well cement grouts.

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

Silica fume has also been referred to as condensed silica fume, microsilica, and fumed silica (this last term is particularly incorrect—refer to Section 1.3). The most appropriate term is silica fume. In formal references related to health and safety regulations, the product is characterized as “Thermally Generated Silica Fume.” The Chemical Abstracts Service (CAS) classifies silica fume by the number 69012-64-2. The corresponding European Index of Existing Chemical Substances (EINECS) number is 273-761-1. Other forms of silicon dioxide, including fumed silica, colloidal silica, diatomaceous earth, and quartz have differing chemical and physical properties, and thus have other classification numbers.

Silica fume is covered by several national and international standards. Chapter 7 provides a listing of the various standards in use and a discussion of some of the key provisions.

1.3—Silica fume versus other forms of silica

Other products with a high content of amorphous silica are marketed from time to time to the concrete industry. These can roughly be divided into two groups: synthetic silica and natural silica. None of these products should be confused with silica fume as defined in this document.

1.3.1 Synthetic silica—Synthetic silicas are amorphous products that are occasionally confused with silica fume. Unlike silica fume, they are purposefully made. 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:

- **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;
- **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; and
- **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.

Colloidal silica is a stable suspension of discrete particles of amorphous silicon dioxide. The source of the silica particles may be one of the aforementioned processes. Colloidal silica may also be referred to as silica sol. Silica fume particles are too large to be colloidal.

Additional information on these synthetic types of silica may be found in the work of Iler (1979), Dunnom (1984), Ulrich (1984), Griffiths (1987), and Larbi and Bijen (1992). ASTM E 1156-87 contains additional descriptions of these synthetic amorphous silicas (note that this document has been withdrawn by its committee).

1.3.2 Natural silica—Natural silica is typically material with amorphous silica, and often reactive alumina, that is dug from the ground and then treated through grinding and classification. The origin of the raw materials can, for example, be volcanic ash, diatomaceous earth, or deposits from geothermal wells.

1.4—Using silica fume in concrete

Silica fume was initially viewed as a cement replacement material, but currently the most important reason for its use is the production of high-performance concrete, where adding silica fume provides enhancements in concrete properties. In this role, silica fume has been used to produce concrete with enhanced compressive strength and with very high levels of durability. Refer to Chapter 5 for a discussion of the effects of silica fume on the properties of hardened concrete.

In the U.S., silica fume is used predominantly to produce concrete with greater resistance to chloride penetration for applications such as parking structures, bridges, and bridge decks. A growing application area for silica fume is as an admixture for shotcrete, where silica fume typically reduces rebound loss, allows increased placement thickness, and generally improves the quality of the material placed (Norwegian Concrete Association 1999; Wolsiefer and Morgan 1993). Additional details of applications of silica-fume concrete are presented in Chapter 6.

Because of the fineness of the material, adding silica fume to concrete mixtures usually increases water demand. To produce high-performance, durable concrete, it is necessary to maintain (or decrease) the water-cementitious material ratio (w/cm). Consequently, HRWRAs, sometimes combined with WRAs, are used to obtain the required performance and workability. Silica-fume concrete will be more cohesive than ordinary concrete; consequently, a somewhat higher slump will normally be required to maintain the same apparent degree of workability.

1.5—Using silica fume in blended cements

The use of silica fume in blended cements has also attracted interest. Aitcin (1983) reported that one Canadian cement manufacturer began making blended cement in 1982. At present, most Canadian cement companies are selling blended cement containing 7 to 12% silica fume, with 7.5% being the nominal amount most frequently used. The use of cement containing 6 to 7% silica fume to combat alkali-silica reaction (ASR) in Iceland was described by Asgeirsson and Gudmundsson (1979) and by Idorn (1988). Since 1979, all Icelandic cement has been blended with silica fume. Lessard et al. (1983) described the use of blended cement containing silica fume to reduce heat of hydration by reducing cement content. Typically, the properties of concrete made from cements containing silica fume as a blending material may be expected to be similar to those of concrete where silica fume was added separately, assuming the silica fume was properly mixed and dispersed in either case (Wolsiefer et al. 1995). As with any blended cement, there will be less flexibility in mixture proportioning with respect to the quantity of silica fume in a given concrete mixture. Unless otherwise

stated, the results and information presented in this document were derived from concrete made with separately added silica fume.

1.6—Worldwide 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 alloy 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). ACI Committee 234 believes that approximately 900,000 metric tons (1,000,000 tons) of silica fume are produced annually worldwide.

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

1.7—Types of silica fume products available

Silica fume is available commercially in several forms. All of the product forms have positive and negative aspects that may affect performance in concrete, material handling, efficiency, and product-addition rate. Material handling methods have been developed to use silica fume in its as-produced form, densified or compacted form, and as water-based slurry. 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 on the willingness of the producer to supply this form.

As-produced silica fume has been handled and transported like portland cement or fly ash. Because of its extreme fineness and low bulk density, however, as-produced silica fume may present serious handling problems. Some as-produced silica fumes will flow only 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 added to concrete by discharging the material directly into truck mixers. This approach, however, 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).

1.7.2 Silica-fume slurry—To overcome the difficulties associated with transporting and handling the as-produced silica fume, some suppliers have concentrated on supplying silica fume as a water-based slurry. Slurried silica fume typically contains 42 to 60% silica fume by mass. Slurry of 50% solids content will contain about 700 kg/m³ (44 lb/ft³) dry material versus 130 to 430 kg/m³ (8 to 27 lb/ft³) for as-produced

material. Transportation of slurry will, despite the water content, often be more economical than transportation of the dry, as-produced silica fume.

The slurries are available with and without chemical admixtures such as WRAs, HRWRAs, and retarders. The actual amount of chemical admixture in the slurry will vary depending on 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. Silica fume slurry offers an advantage of ease of use over the as-produced silica fume once the required dispensing equipment is available at the concrete plant. Slurry products are typically available in bulk, 55 gal. (208 L) drums, and 5 gal. (19 L) pails. If slurried silica fume is used on a project, the manufacturer's recommendations concerning storage and handling must be followed diligently.

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 literature on the air-densification process. Unless otherwise stated, the air-densification process produced the densified silica fume referred to in this report.

Another method for producing densified silica fume is to compress the as-produced material mechanically. Although mechanically densified silica fume was commercially available in the U.S. at one time, ACI Committee 234 is not aware of any mechanically densified material currently available worldwide.

Densified (compacted) dry silica-fume products are available with and without dry chemical admixtures. These products are typically available in bulk, in bulk bags of 1300 to 2700 lb (600 to 1200 kg), and in small bags of 22 to 55 lb (10 to 25 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 and often a little cement, typically on a disk pelletizer. This process forms pellets of various sizes that can be disposed of in landfills. In Norway, pellets have been used as fill behind retaining walls in private and public areas. 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, a Canadian cement producer intergrinds pellets with portland-cement clinker to form a blended cement. Published data are available (Moe-Gundlach 1997) comparing the performance of blended cement containing

interground pelletized silica fume with that of directly added silica fume or blended cement made with as-produced or densified silica fume. They concluded that, regardless of the product form of the silica fume, the mechanical properties and durability characteristics of the silica-fume concretes were comparable.

1.8—Health hazards

ACI Committee 234 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 the Occupational Safety and Health Administration (OSHA) or the American Conference of Governmental Industrial Hygienists (ACGIH).

Although silica fume is not known to cause cancer or silicosis, it is not entirely harmless. Because of the small size of silica fume particles, generally smaller than $1\text{ }\mu\text{m}$ ($4 \times 10^{-5}\text{ in.}$) with an average diameter of $0.1\text{ to }0.2\text{ }\mu\text{m}$ ($4\text{ to }8 \times 10^{-6}\text{ in.}$), all airborne silica fume should be considered respirable. As with other fine, respirable powders, adverse health effects can result from massive inhalation of silica fume (Davies 1974). Such dust levels are highly unlikely to be encountered in modern silicon metal or ferrosilicon alloy plants, let alone in a concrete production plant or at a construction site. No silica fume dust can be produced from in-place concrete, and thus, there is no exposure whatsoever.

Trace amounts (much less than 1%) of crystalline silica (such as quartz) may be present in silica fume; however, the detection limit of the procedures used to quantify crystalline SiO_2 mixed into amorphous SiO_2 is approximately 0.5%. Therefore, conformity to limits of 0.1% crystalline SiO_2 cannot be documented.

Papers from the *Symposium on Health Effects of Synthetic Silica Particulates* (Dunnom 1981) indicate 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 if the threshold limit values (TLVs) of $2 \times 10^{-6}\text{ oz/ft}^3$ (2 mg/m^3) are not exceeded, then the risk of silicosis is very small from exposure to this type of amorphous silica. Jahr concluded that “most of the reported cases of silicosis among workers exposed to amorphous silica in the ferrosilicon industry have either been transient lung changes or connected to exposure to crystalline silica. Workers exposed only to precipitated amorphous silica do not seem to be at any significant risk.”

Members of the ACGIH (1991) reviewed the available literature on exposure to silica fume by inhalation to determine an appropriate threshold limit value. They noted that, based on the available data, it was not possible to identify an airborne concentration below which adverse health effects do not occur. It was also not possible to sort out the confounding effects of other lung irritants, such as crystalline silica, asbestos, and tobacco smoke, to which many of the workers examined were also exposed. Lacking definitive dose-response data, the ACGIH recommended a threshold limit value of $2 \times 10^{-6}\text{ oz/ft}^3$ (2 mg/m^3).

Dalen and Fjelldal (1998) concluded that, when used properly, silica fume does not represent a hazard to health and environment and that, from an environmental point of view, silica fume is comparable to naturally occurring fine powders such as clay and river sediments.

In recognition of the importance of a safe working environment, the Committee wishes to emphasize that users should refer to the manufacturer’s material safety data sheets for the products being used for specific health and safety information.

1.9—Environmental impact

Silica fume is a by-product of the ferrosilicon industry, and its use in concrete means that resources are used in a constructive manner. Because silica-fume concrete can be made to be very durable, the use of the material contributes to more efficient structures with less need for repair and maintenance and, therefore, reduced lifetime impact on the economy and on the environment.

CHAPTER 2—PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF SILICA FUME

This chapter describes the physical properties and chemical composition of silica fume. The limits that exist for these properties in U.S. and international standards are presented in Chapter 7.

2.1—Color

Most silica fumes range from light to dark gray. 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 silica fume. The carbon content of silica fume is affected by many factors relating to the manufacturing process, such as: use of wood chips versus coal, wood chip composition, furnace temperature, furnace exhaust temperature, and the type of product (metal alloy) being produced.

2.2—Specific gravity

The specific gravity of silica fume is approximately 2.2, as compared with about 3.1 for portland cement. Table 2.1 lists the specific gravity of silica fume from several sources. Variations in specific gravity 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/ft³ (130 to 430 kg/m³), 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 approximately 11 to 12 lb/gal. or 83 to 90 lb/ft³ (1.3 to 1.4 Mg/m³). The nominal silica fume content of most slurries is approximately 50% by mass. The actual silica fume content may vary, depending on the particular source and whether chemical admixtures have been added to the slurry.

Table 2.1—Silica fume specific gravity versus alloy type

Silicon alloy type	Silica fume specific gravity	Reference
Si	2.23	Aïtcin et al. (1984)
Si and FeSi-75% blend	2.27; 2.26	Pistilli et al. (1984a,b)
FeSi-75%	2.21 to 2.33	Aïtcin et al. (1984)
FeSi-50%	2.30	Aïtcin et al. (1984)

2.3.3 Densified (compacted) silica fume—Densification from an initial bulk density of 13 lb/ft³ (200 kg/m³) to a densified value of 31 lb/ft³ (500 kg/m³) has been reported (Elkem 1980; Popovic et al. 1984). The bulk density of commercially available densified silica fume ranges from approximately 25 to 45 lb/ft³ (400 to 720 kg/m³).^{*} At higher bulk densities, it may become increasingly difficult to disperse densified silica fume particles within concrete. Concrete made with a silica fume with a bulk density of 50 lb/ft³ (810 kg/m³) showed decreased performance in both strength and frost resistance (Fidjestøl 1992).

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 98,000 ft²/lb (20,000 m²/kg) when measured by the nitrogen-adsorption method. The extreme fineness of silica fume is 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: 63,000 to 150,000 ft²/lb (13,000 to 30,000 m²/kg), nitrogen adsorption
- Fly ash: 1400 to 3400 ft²/lb (280 to 700 m²/kg), Blaine air permeability
- Ground-granulated blast-furnace slag: 1700 to 2900 ft²/lb (350 to 600 m²/kg), Blaine air permeability
- Portland cement: 1500 to 2000 ft²/lb (300 to 400 m²/kg), Blaine air permeability

The nitrogen-adsorption method is currently the most frequently used test to determine the surface area of silica fume. The Blaine air permeability apparatus is not appropriate for measuring the surface area of silica fume because of difficulties in obtaining the necessary 0.50 porosity to conduct the test. Nitrogen-adsorption surface area results for various silica fumes range from 63,000 to 150,000 ft²/lb (13,000 to 30,000 m²/kg) (Malhotra et al. 1987b). One study of Si and FeSi-75% silica fumes reported results between 88,000 and 110,000 ft²/lb (18,000 and 22,000 m²/kg) (Elkem 1980). Another study (Nebesar and Carette 1986) reported average surface area values of 98,000 and 84,000 ft²/lb (20,000 and 17,200 m²/kg) for Si and FeSi-75% silica fumes, respectively.

Individual silica fume particles have a diameter of less than 1 μm (4 × 10⁻⁵ in.), which is approximately 1/100 of the size of an average cement particle. The individual particles, however, are usually found in agglomerations that may range in

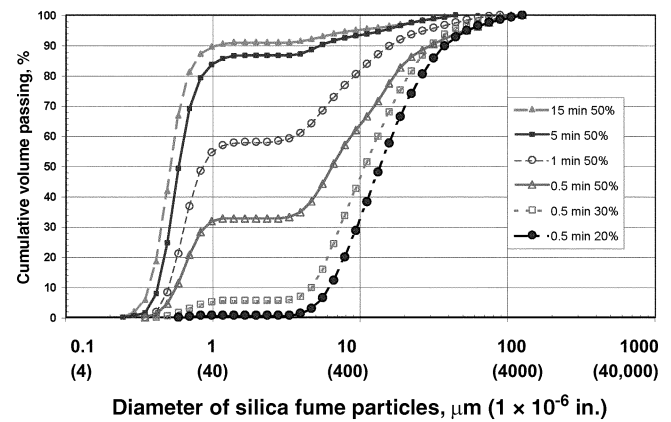


Fig. 2.1—Particle-size distribution of silica fume subjected to varying amounts of dispersion. The set of curves shows the importance of the amount of dispersion on the measured distribution. Varying the intensity and duration of ultrasonic dispersion gives very different results for the same silica fume. The values shown are percentages of full stroke in a Microtrac apparatus; higher percentages indicate increased dispersion effort. (Figure courtesy of Elkem ASA Materials.)

size from 1 to 100 μm (4 to 400 × 10⁻⁵ in.) (Dingsoyr et al. 1992). The degree and extent of agglomeration will vary depending on the fume type and the furnace gas exhaust temperature.

Any attempt to show particle-size distribution of silica fume must take the agglomeration tendency into account. Figure 2.1 shows several particle-size distributions from the same as-produced silica fume subjected to differing degrees of dispersion. ACI Committee 234 is not aware of data showing that different degrees of agglomeration of as-produced silica fume affect its performance in concrete.

One of the most common tests conducted on silica fume is the residue (oversize) on the 45 μm (No. 325) sieve. In this test, a sample of silica fume is washed through the 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. Various values have been reported for the amount of oversize: 0.3 to 3.5% (Elkem 1980), 3.7 to 5.6% (Pistilli et al. 1984a), and 1.8 and 5.4% for Si and FeSi-75%, respectively (Nebesar and Carette 1986).

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 sieves, 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.

^{*}Private communications from producer members to ACI Committee 234.

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

Silicon alloy type	Si [*]		FeSi-75% [*]		Si and FeSi-75% blend [†]		FeSi-75% [‡]		Si [§]	
No. of samples <i>n</i>	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 ₂ O ₃	0.28	0.13	0.31	0.20	0.25	0.12	0.57	0.03	0.36	0.04
Fe ₂ O 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 ₂ O	0.02	0.02	0.10	0.06	0.17	0.04	0.20	0.02	—	—
K ₂ O	0.49	0.24	1.37	0.45	0.96	0.22	1.06	0.05	—	—
S	0.20	0.16	0.22	0.06	—	—	—	—	—	—
SO ₃	—	—	—	—	0.36	0.10	0.36 [#]	0.16 [#]	—	—
C	3.62	0.96	1.92	1.15	—	—	—	—	3.05	0.25
Loss on ignition	4.36	1.48	3.10	0.90	3.20	0.45	2.62 [#]	0.42 [#]	3.60	0.33

^{*}Nebesar and Carette (1986).

[†]Pistilli et al. (1984a).

[‡]Pistilli et al. (1984b).

[§]Luther (1989).

^{||}*n* = 24.

[#]*n* = 30.

The silica fumes generally contain more than 90% silicon dioxide (SiO₂). The chemical composition of the silica fumes varies with the type of alloy that is being produced (Section 1.2).

The acid-soluble chloride content of as-produced and densified silica fumes is typically below 0.1%, but individual plants have reported 0.4% as an upper limit.^{*} In cases where chloride limits in concrete are critical, chlorides contributed by the silica fume should be included in the calculation of total chloride content.

The pH of silica fume and water slurries may be determined. This test may be performed on a sample prepared by adding 0.7 oz (20 g) of silica fume to 2.8 oz (80 g) of deionized water. Typical pH values at one silicon metal source were between 6.0 and 7.0.

Trace amounts of silicon metal may be found in some silica fumes. The evolution of hydrogen gas from this metal is discussed in Chapter 4. ACI Committee 234 is not aware of data describing effects of variations in any other 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; Aitcin et al. 1984). Silicon carbide (SiC), an intermediate compound occurring during the production of silicon and ferrosilicon alloys, has been observed (Popovic et al. 1984).

Reported x-ray diffraction patterns exhibit a broad hump centered around the area where 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. Available results of within-source silica-fume variability studies for chemical composition and physical properties are presented in Tables 2.2 and 2.3. These results indicate that uniformity of silica fume from a single source is reasonably similar to that associated with ground-granulated blast-furnace slags (GGBFS), and the variations are smaller than those associated with fly ashes (Malhotra et al. 1987b). This observation is not surprising considering that the metallurgical processes used in the production of silicon and alloys containing silicon are well controlled.

Within-source variations occur in silica fume from a single furnace due to the age or condition of the furnace. Typical furnace linings are rebuilt biennially or as refractory deterioration occurs. Changes in the materials used to produce silicon or silicon alloys will cause variations in the silica fume collected from the furnace. If the silicon-alloy type is changed in a furnace, then the silica fume recovered from this furnace will also 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 produces densified and slurried silica fume products by blending silica fume from four furnaces producing the same alloy.

2.8—Relating physical and chemical properties to performance in concrete

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

^{*}Private communications from producer members to ACI Committee 234.

Table 2.3—Physical properties of several silica fumes

Silicon alloy type		Si [*]	FeSi-75% [*]	Si and FeSi-75% blend [†]	FeSi-75% [‡]
Number of samples		24	24	32	30
Percent retained on No. 325 (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 absorption method, ft ² /lb (m ² /kg)	Mean	98,000 (20,000)	84,000 (17,200)	—	—
	Standard deviation	10,000 (2100)	—	—	—
Specific gravity	Mean	—	—	2.27	2.26
	Standard deviation	—	—	0.02	0.08
Pozzolanic activity index with portland cement, %	Mean	102.8	96.5	91.9 [§]	95.3 [§]
	Standard deviation	5.1	13.7	10.0	4.0
Pozzolanic activity index lime, psi (MPa)	Mean	1290 (8.9)	—	1020 (7.0) [§]	1320 (9.1) [§]
	Standard deviation	120 (0.8)	—	120 (0.8)	130 (0.9)
Water requirement, %	Mean	138.8	139.2	140.1 [§]	144.4 [§]
	Standard deviation	4.2	7.2	2.6	2.0

^{*}Nebesar and Carette (1986).

[†]Pistilli et al. (1984a).

[‡]Pistilli et al. (1984b).

[§]Eight samples.

It is sometimes assumed that the higher the SiO₂ content of a silica fume, the more reactive the silica fume will be in concrete. Most international standards (Chapter 7) have a minimum requirement for SiO₂ of 85%. Published data were not found to show differences in performance in concrete for SiO₂ contents above this minimum. A higher SiO₂ content implies that there are fewer non-SiO₂ components. Both the current ASTM and Canadian standards (ASTM C 1240 and CSA A23.5) limit the use of silica fume to materials recovered from the production of silicon or ferrosilicon alloys containing at least 75% silicon (Si). Silicon and ferrosilicon (75% Si) silica fumes contain higher amorphous SiO₂ contents than the other silica fumes from alloys with lower amounts of silicon. The Canadian standard, however, does allow the use of silica fume recovered from the production of ferrosilicon alloys containing less than 75% Si if acceptable performance of the silica fume in concrete has been demonstrated.

Among the silica fumes that have been used in concrete in North America to date, it has been possible to achieve desired air contents, although silica fumes having relatively high carbon contents may require increased air-entraining admixture dosages.

Although some project specifications have required a surface-area (fineness) range for the silica fume that will be used in the concrete, no data were found that 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 WRA or HRWRA is used.

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

Published data relating the delivery form of silica fume (as-produced, slurried, or densified) to performance in concrete are available (Cohen et al. 1990; Luther and Smith 1991; Hooton 1993; Boddy et al. 2000; Wolsiefer et al.

1995). Minor differences in the fresh and hardened concrete properties are reported for concrete made with the different available delivery forms. Concern has been raised over the potential for inadequately dispersed densified silica fume to initiate ASR (Marusin and Shotwell 2000; Boddy et al. 2000). This topic is discussed in Chapter 5.

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

Because 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 ensuring uniformity of properties of a particular silica fume 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—MECHANISMS BY WHICH SILICA FUME MODIFIES CEMENT PASTE, MORTAR, AND CONCRETE

3.1—General

This chapter examines how silica fume changes the properties of paste, mortar, and concrete. The effects of silica fume are attributed to physical and chemical mechanisms, both of which are described. Because the results of both the physical and chemical mechanisms are seen in modifications to the paste microstructure, the changes that take place there are discussed in this chapter rather than in Chapter 5. Additionally, topics that are related to the mechanism of silica fume reactions, such as autogenous shrinkage, pore water chemistry, reactions of silica fume with fly ash and GGBFS, reactions with different types of port-

land cement, heat of hydration, and reactions with chemical admixtures, are discussed in this chapter.

Cohen et al. (1990) have calculated that for a 15% silica-fume replacement of cement, there are approximately 2 million particles of silica fume for each grain of portland cement in a concrete mixture. Therefore, it is no surprise that silica fume has a pronounced effect on concrete properties.

All of the physical and chemical mechanisms described in Sections 3.2 and 3.3 depend on thorough dispersion of the silica-fume particles to be effective. This requires the addition of sufficient quantities of WRAs to overcome the effects of surface forces, ensure good dispersion, and thereby promote good packing of the solid particles. The addition of materials to the mixer in the proper sequence as well as thorough mixing are also essential (Chapter 9).

3.2—Physical effects

Silica fume enhances the properties of concrete by both physical and chemical mechanisms. The physical mechanisms include reduced bleeding, provision of nucleation sites, and more efficient packing of the solid particles.

3.2.1 Reduced bleeding—The presence of silica fume in fresh concrete results in significantly 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. The higher the silica fume content, the more pronounced the effect. 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.” This reduced bleeding must be taken into account when finishing silica-fume concrete, as discussed in Chapter 9.

3.2.2 Provision of nucleation sites—Silica fume accelerates the hydration of cement during the early stages by providing nucleation sites where the products of cement hydration can more readily precipitate from solution. Sellevold et al. (1982) found that equal volumes of a relatively inert filler (calcium carbonate) produced the same effect. They concluded that the mere presence of numerous fine particles—whether pozzolanic or not—has an accelerating effect on cement hydration.

3.2.3 Particle packing—In hardened concrete, silica-fume particles improve the packing of the solid materials by occupying some of the spaces between the cement grains in the same way as cement occupies some of the spaces between the fine-aggregate particles, and fine aggregate occupies some of the spaces between coarse-aggregate particles in concrete. This analogy applies only when the surface forces between the cement particles are negligible, that is, when there is enough WRA present to overcome the effects of surface forces. Bache (1981) showed that the addition of silica fume, at low levels of replacement, could reduce water demand because the silica-fume particles were occupying space otherwise occupied by water between the cement particles. Sellevold and Radji (1983) also reported on a decrease in water demand for silica-fume mixtures and stated that WRA had a greater effect on silica-fume concrete.

These decreases can be observed when silica fume comprises less than approximately 5% by mass of cement. In most concrete used for general construction purposes, however, higher doses of silica fume are used, resulting in an increase in water demand. Such concrete will require the use of a WRA or HRWRA for good dispersion of the silica fume as well as the desired workability.

Detwiler and Mehta (1989) found that at an age of 7 days, the strengths of concretes containing a 10% replacement of cement by an inert filler (carbon black) were comparable to those of both the 10% silica-fume concrete and the control portland-cement concrete having the same w/cm . By the age of 28 days, the strengths of the silica-fume concrete were higher. Bentz and Garboczi (1991) noted that at values of w/cm below about 0.40, the closer packing of the particles allows the inert particles to bridge gaps between hydration products, provide additional sites for the nucleation of calcium hydroxide (CH), or both. At a higher w/cm , the particles are spaced farther apart, so that the particle packing effects become negligible.

3.3—Chemical effects

Silica fume is a highly reactive pozzolan. In hydrating cement paste, silica fume will react with CH to form calcium-silicate hydrate (CSH).

Buck and Burkes (1981) studied the reactivity of silica fume with CH in water at 100 °F (38 °C). They found that a well-crystallized form of CSH had formed after 7 days of curing. Kurbus et al. (1985) found that reaction rates were greatly increased at higher temperatures. At 190 °F (90 °C), 95% of added CH was reacted after only 2.5 hours in a 4:1 mixture of SF:CH.

In cement pastes, the reactions are more complex. Grutzeck et al. (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. This gel then agglomerates between the grains of unhydrated cement, coating the grains in the process. CH reacts with the outer surface of this gel to form CSH. This silica-fume gel CSH forms in the voids of the CSH produced by cement hydration, thus producing a very dense structure.

Ono et al. (1985) studied the cement-silica fume system in low w/cm (0.23) pastes at 68 °F (20 °C). The amounts of CH present after various periods of hydration with different dosages of silica fume are shown in Fig. 3.1. At very high dosages, almost all CH is consumed by 28 days. At 10% silica fume, CH is reduced by almost 50% 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% silica fume, no CH was detected after 14 days. Hooton (1986) found that with 20% by volume silica fume replacement, no CH was detectable after 91 days of moist curing at 73 °F (23 °C), while 10% silica fume reduced CH by 50% at the same age. The extent of consumption of portland cement, silica fume, or both that determine the

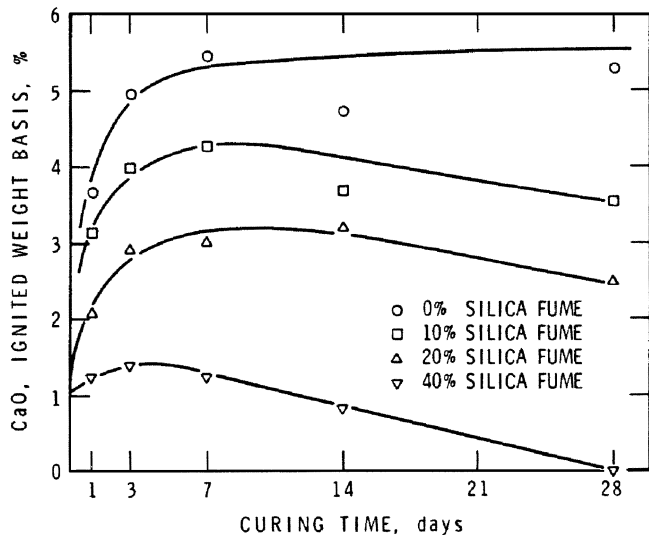


Fig. 3.1—Amount of calcium hydroxide (as CaO) in cement pastes containing different amounts of silica fume (Ono et al. [1985]; as shown in Malhotra et al. [1987b]).

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 SiO₂ contents increase the extent of the pozzolanic reaction.

3.4—Microstructure modifications

The primary effect of silica fume is to reduce the porosity of the transition zone between the cement paste and aggregate, which is the weak link in most concrete. It also refines the pores in the bulk cement paste by various mechanisms described in this section. The net results are an increase in the strength of the concrete and reductions in its permeability and diffusivity.

3.4.1 Cement paste-aggregate transition zone—The transition zone is usually defined as a layer about 50 μm thick surrounding aggregate particles. In general, the strength of the transition zone 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 CH forms in this region than elsewhere. A large number of researchers have looked at the effects of silica fume on this transition zone. Some findings are:

- Carles-Gibergues et al. (1982) concluded that fly ash, GGBFS, and silica fume all affect the morphology of the transition zone, decreasing the thickness and degree of orientation of calcium hydroxide crystals that form adjacent to aggregate particles;
- Monteiro et al. (1985) found that, without silica fume, the CH crystals grow large and tend to be strongly oriented parallel to the aggregate particle surface. CH does not contribute appreciably to the strength of concrete. When the crystals are large and strongly oriented parallel to the aggregate surface, they are easily cleaved. A weak transition zone results from the

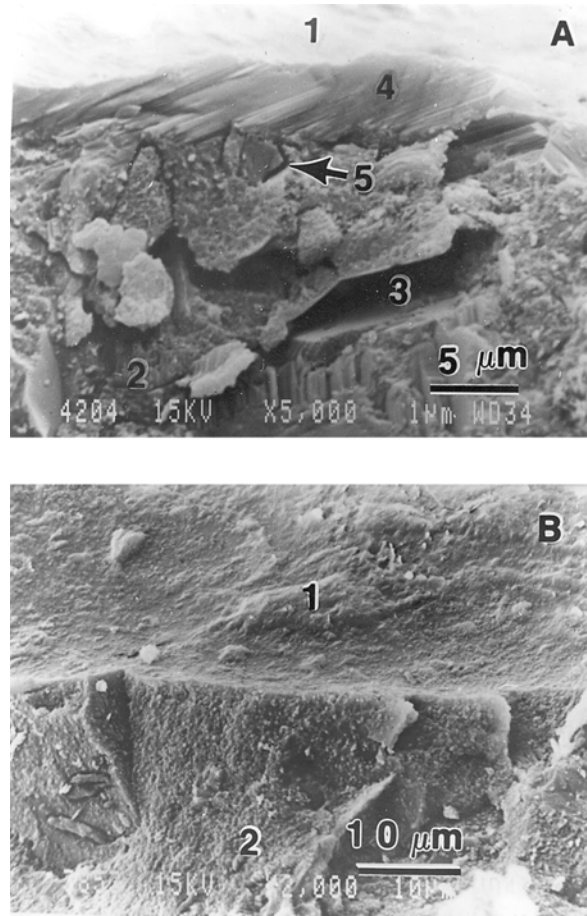


Fig. 3.2—Typical structure of transition zone between the cement paste matrix and aggregate, characterized by scanning electron microscopy (Bentur and Cohen 1987): (a) 28-day system without silica fume; and (b) 28-day system with silica fume. (Note: 1 = aggregate surface; 2 = cement paste; 3 = voids; 4 = calcium hydroxide; and 5 = microcracks.)

combination of high void content and large, strongly oriented CH crystals;

- Wang et al. (1986) found that even small additions (2 to 5%) of silica fume produced a denser structure in the transition zone with a consequent increase in microhardness and fracture toughness. They also found that the mean size was reduced, and the orientation was less random for the CH crystals within the transition zone when silica fume was added;
- Monteiro and Mehta (1986) proposed that silica-fume particles provide nucleation sites for CH crystals so that the CH crystals are smaller and more randomly oriented;
- Bentur and Cohen (1987) found that the microstructure of the transition zone is characterized by a massive calcium hydroxide layer engulfing the sand grains and by some channel-like gaps, as shown in Fig. 3.2. When silica fume was added, the transition zone had a homogeneous and dense microstructure resembling that of the bulk paste; the massive calcium hydroxide layer was absent and there were no gaps at the interface itself.
- Detwiler et al. (1988) wrote that at the interface itself,

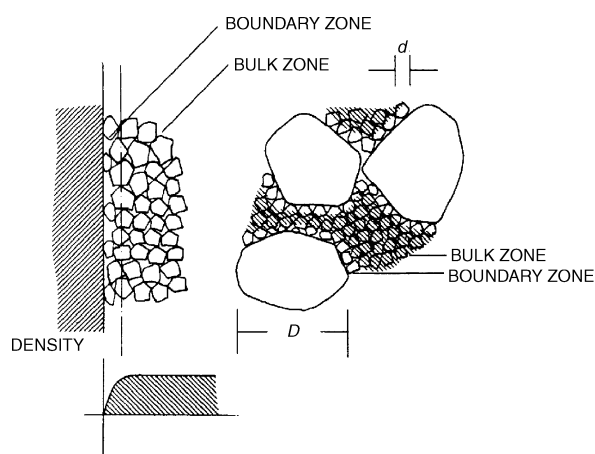


Fig. 3.3—Wall effect and barrier effect are expressions of the fact that particles are packed more loosely in the immediate vicinity of a surface than in the bulk, and of the fact that there is not room for small particles in the narrow zones between large particles.

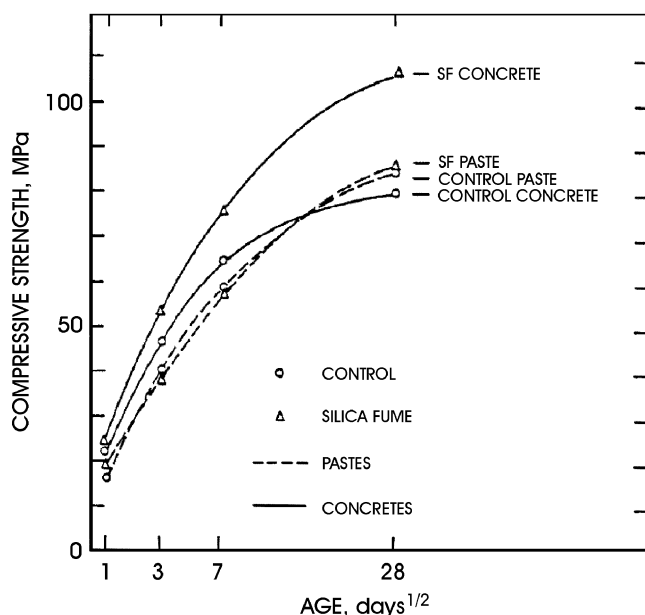


Fig. 3.4—Compressive strength of pastes and concretes with and without silica fume at the same water-cementitious material ratio (Bentur et al. 1988).

the CH crystals are oriented parallel to the aggregate surface whether silica fume is present or not. In the transition zone, however, both the crystal size and amount of CH are reduced by silica fume, thus leading to a strengthening of this region;

- Bentz et al. (1992) observed that by making the transition zone similar in porosity to the surrounding paste, silica fume would be expected to improve the durability of concrete because of decreases in ionic diffusivity and fluid permeability;
- Kjellsen et al. (1998) found practically no observable or measurable differences between the bulk paste phase and the paste phase close to aggregate particles in concrete specimens of 0.25 w/cm and with 10% silica fume; and

- Many other researchers have also written that the performance of high-quality concrete achieved with the use of silica fume is, at least in part, the result of interfacial effects (Regourd 1985; Bentur et al. 1988; Sellevold and Nilsen 1987; Sarkar et al. 1988).

Because of their small size, the silica-fume particles, when dispersed with enough HRWRA to overcome the effects of surface forces, are better able to pack around the aggregate particles during mixing and placing (Bentur and Cohen 1987). Figure 3.3 illustrates how silica-fume particles improve packing in the transition zone. Near the surface of an aggregate particle, hydration products can form only from the cement paste side. Garboczi and Bentz (1991) called this phenomenon the one-sided growth effect, which has a significant influence on the transition zone within approximately 2×10^{-4} in. (5 μ m) of the aggregate surface.

According to Mindess (1988), silica fume increases the strength of concrete because it increases the strength of the bond between the cement paste and the aggregate particles. Bentur et al. (1988) showed that silica fume does not show the same strengthening effects in paste that it exhibits in concrete (Fig. 3.4). Goldman and Bentur (1989) also concluded that only in concrete does the addition of silica fume lead to a significant increase in strength. Detwiler (1990) found that silica fume increased the fracture toughness of the transition zone between cement paste and steel. Goldman and Bentur (1989) concluded that the enhancement of the bond strength at the paste-aggregate interface could lead to the rigid aggregate particles acting as a reinforcing filler rather than an inert one.

Much of the improvement in concrete properties is attributed to transition zone modification caused by the addition of silica fume. 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. More recent information, however, calls into question the hypothesis that the effect of silica fume on concrete compressive strength is due to its ability to improve the bond strength between the cement paste and aggregate particles. Cong et al. (1992) and Kjellsen et al. (1999) found that silica fume increased the strength of paste to the same extent as it increased the strength of concrete, provided that segregation was prevented. It appears that the enhancing effect of silica fume on concrete compressive strength may be partly due to improved strength of the paste phase as a whole. The strength of both the bulk paste phase and the paste phase close to aggregate interfaces is improved in the presence of silica fume.

3.4.2 Porosity—Silica fume makes the pore structure of paste (Mehta and Gjrv 1982) and mortar (Huang and Feldman 1985b; Yamato et al. 1986) more homogeneous by decreasing the number of large pores (Fig. 3.5). Total porosity, however, appears to remain largely unaffected.

The findings of Kjellsen et al. (1997) imply that hydration products of silica fume are deposited primarily outside the boundaries of the original cement particles, resulting in a refinement of the capillary pore system.

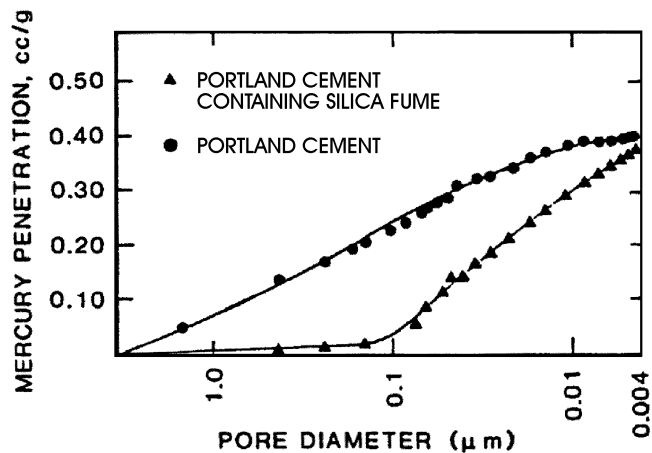


Fig. 3.5—Pore size distribution in pastes of neat portland cement with silica fume (Mehta and Gjrv 1982). (Note: 1 mm = 3.9×10^{-5} in.; 1 cc/g = 15.3 fl. oz./lb.)

Bentur et al. (1988) demonstrated this effect by the reduced rate of water loss during drying of paste and concrete (Fig. 3.6). The total porosity remained nearly the same 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 small pore entrances than do conventional paste and concrete.

Li et al. (1996) found that silica fume did not reduce the porosity of cement pastes, but that it reduced the maximum continuous pore radius. Thus, it has a significant effect on the transport properties of cement paste. Zhang and Gjrv (1991b) found that while replacement of 10% of the cement with an equal mass of silica fume only slightly reduced the total porosity of cement paste, it refined the pore structure. Because the number of larger pores was reduced, the diffusivity of the pastes to chloride ions was also substantially reduced.

3.5—Self-desiccation and water of hydration

Silica-fume concrete with a low w/cm has a tendency to self-desiccate, as does any concrete with a low w/cm . Unlike concrete without silica fume, however, silica-fume concrete can continue to gain strength without binding additional water.

McGrath and Hooton (1991) found that in silica-fume mortars, the internal relative humidity decreased monotonically over time and had not reached steady-state conditions at an age of 90 days. The effect of the w/cm on self-desiccation was greater than that of silica fume content. The significance of the self-desiccation of the mortar was demonstrated in tests of resistance to freezing and thawing. Specimens having an internal relative humidity less than 95% survived the 300 cycles of freezing and thawing despite a lack of entrained air.

Justnes et al. (1992) found that even at a low w/cm , silica fume acts as a highly reactive pozzolan. The high reactivity of silica fume may even lead to a reduction in the degree of hydration of the cement at later ages as compared with cement paste without silica fume. The presence of silica

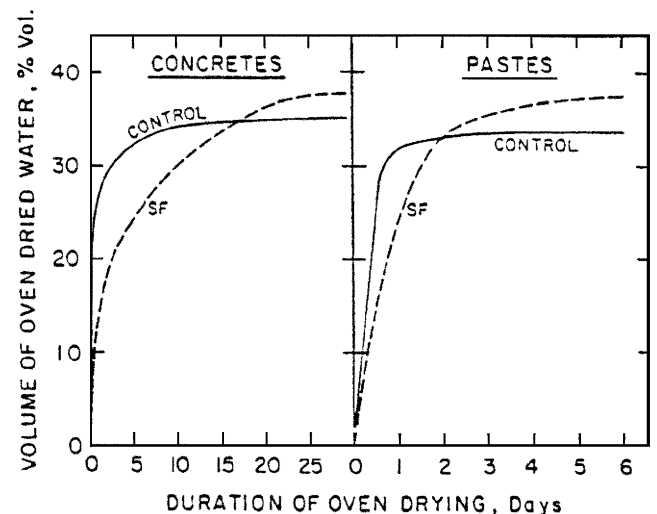


Fig. 3.6—Water loss curves during drying of pastes and concretes with and without silica fume at a water-cementitious material ratio of 0.33. Water loss is presented as volume of water lost relative to paste volume (Bentur et al. 1988).

fume and reductions in the w/cm correlated with the tendency of the cement paste to self-desiccate over time.

Sellevold and Justnes (1992) further examined the hydration of cement at low a w/cm with and without silica fume. Silica fume increases the CSH content per gram of hydrated cement. The CSH binds water by adsorption, as interlayer water, or both, contributing to the self-desiccation effect. Consistent with McGrath and Hooton (1991), Sellevold and Justnes (1992) found the decrease in internal relative humidity to be controlled more by w/cm than by silica fume content.

Pinto et al. (1999) studied the relationship between compressive strength and nonevaporable water content for mortars with and without silica fume. They found that increases in strength above about 8000 psi (55 MPa) were accompanied by increases in the nonevaporable water content for the mortars without silica fume, while there was no increase in nonevaporable water content for the silica fume mortar. The ability of the silica-fume mortar to increase in strength without binding additional water is consistent with the findings of Sellevold and Justnes (1992) and Zhang and Gjrv (1991a).

3.6—Autogenous shrinkage (volume change)

All concrete with a low w/cm is subject to autogenous shrinkage. Silica fume appears to increase autogenous shrinkage.

ACI 116R defines autogenous volume change as “change in volume produced by the continued hydration of cement, exclusive of the effects of applied load and change in either thermal condition or moisture content.” It is the consequence of the withdrawal of water from the capillary pores by the hydration of the unhydrated cement, a process also known as self-desiccation, resulting in a reduction in internal relative humidity in the remaining pores.

When autogenous shrinkage strain exceeds the strain capacity of concrete, cracks form. Cracking is a major concern in high-strength silica-fume concrete under a sealed condition

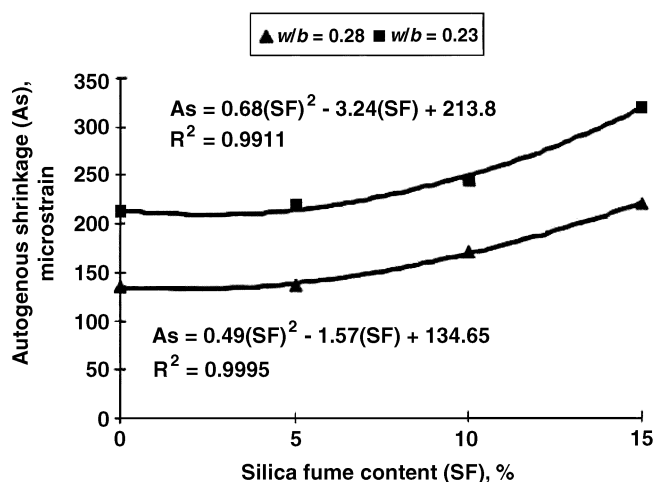


Fig. 3.7—Autogenous shrinkage versus silica fume content and w/cm (Brooks et al. 1998).

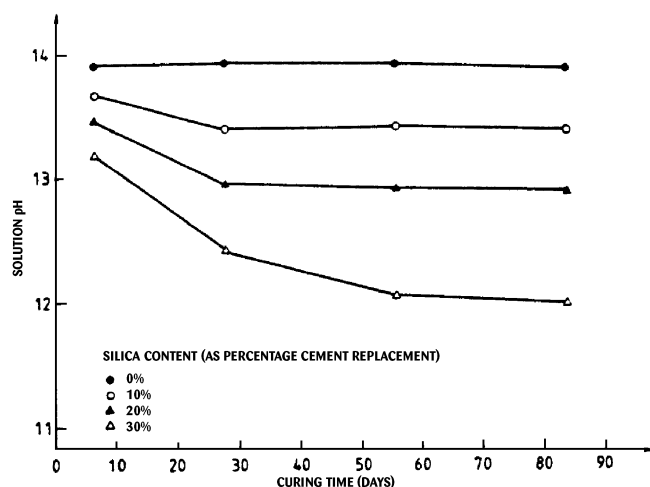


Fig. 3.8—Influence of silica fume on pH values of porewater squeezed from cement pastes. Normal portland cement, water-to-cement-plus-silica-fume ratio of 0.50 (Page and Vennesland 1983).

was attributed to intense autogenous shrinkage (Paillere et al. 1989). Autogenous shrinkage was considered to be one of the causes of cracking observed in the high-strength silica fume concrete used for repairing the stilling basin of the Kinzua Dam (Holland et al. 1986).

Typical values of autogenous shrinkage strain of conventional concrete are approximately 40×10^{-6} at the age of 1 month, and 100×10^{-6} after 5 years (Davis 1940), which are relatively low compared with those of drying shrinkage. Because of this, autogenous shrinkage has been ignored for practical purposes for conventional concrete.

Cement paste incorporating silica fume generally has greater autogenous shrinkage than portland-cement paste without silica fume (Jensen and Hansen 1996). Tazawa and Miyazawa (1995) reported an autogenous shrinkage of 4000×10^{-6} at 14 days for paste at a very low w/cm of 0.17 with 10% silica fume replacement.

For concrete with a low w/cm , particularly when it contains silica fume, autogenous shrinkage is generally greater than for concrete without silica fume with a comparable w/cm and curing history (Persson 1997; Mak et al. 1998; Brooks et al. 1998). According to Aitcin et al. (1997), autogenous shrinkage will not be high if the w/cm is greater than about 0.42, but will increase rapidly if the w/cm is lower than 0.42. Autogenous shrinkage increases with increasing silica-fume content and with a decreasing w/cm (Fig. 3.7) (Brooks et al. 1998).

Because only the cement paste has a tendency to shrink, Persson (1996) suggested that the autogenous shrinkage causes tensile stresses in the cement paste and compressive stresses in the aggregate of concrete. When the autogenous shrinkage exceeds the tensile strain capacity of the cement paste, which often occurs in concrete with a low w/cm and silica fume, microcracks will occur. Persson (1998) wrote that microcracking caused by autogenous shrinkage may be an explanation for the long-term reduction in compressive strength sometimes seen in silica-fume concrete. He noted, however, that the strength reduction he found was insignificant compared with the precision of the test.

3.7—Chemical composition of pore fluid

Silica fume changes the chemistry of hydrated portland-cement paste so as to increase its capacity to bind alkalis, and may decrease its capacity to bind chlorides. It also reduces the pH of the pore solution. The net effect of these last two does not increase the tendency of embedded steel to corrode, however, because the reduction in pH is not large and the reduction in diffusivity offsets the reduced capacity to bind chlorides.

The $CaO-SiO_2$ ratio of hydration products has been found to decrease with increased silica fume dosages (Justnes et al. 1992). Because of the low $CaO-SiO_2$ ratio, the CSH is able to incorporate more substituents such as aluminum and alkalis. Diamond (1983) noted that the alkalis in silica-fume cement paste 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. 3.8). The reduction in pH could be due to increased reaction of alkalis and calcium hydroxide with silica fume.

Diamond (1983) found that silica fume caused a reduction in hydroxyl-ion concentration. According to Byfors et al. (1986), silica fume causes a much greater reduction in the hydroxyl ion content of pore solutions than either slag or fly ash. Zhang and Gjorv (1991a) found that the lowest pH they measured for the pore solution of silica-fume cement pastes was 12.7 for a 16% silica-fume cement paste having a w/cm of 0.20. They noted that this is slightly higher than that of a saturated solution of CH.

There are conflicting data on the chloride binding capacity of cement paste and concrete containing silica fume, with Byfors et al. (1986) finding an increase, and Page and Vennesland (1983) finding a decrease. Arya and Neville (1990) also found that silica fume reduced the chloride

binding capacity of cement paste. Mangat and Molloy (1995) found that replacement of cement with silica fume resulted in a greatly reduced chloride binding capacity of concrete exposed to seawater for extended periods. They also noted that the diffusivity of the concrete to chlorides is considerably more significant than chloride binding capacity in determining the chloride concentration in the pore fluid.

Concern has been raised regarding a reduction in pH of pore fluid by the consumption of CH and the effect of any such reduction on the passivation of reinforcing steel. At the levels of silica fume dosage typically found in concrete, the reduction of pH is not large enough to be of concern (Fig. 3.8). For corrosion protection purposes, the increased electrical resistivity and the reduced diffusivity to chloride ions are believed to be more significant than any reduction in pore solution pH. (Refer also to Chapter 5.)

3.8—Reactions in combination with fly ash or ground-granulated blast-furnace slag

Ternary concretes—incorporating portland cement, silica fume, and either fly ash or GGBFS—may provide the best of both worlds; that is, the durability and high early strength of silica-fume concrete can be obtained at lower cost and with greater workability using ternary mixtures.

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 concrete and to evaluate the durability of concrete with combinations of pozzolans. The committee is not aware of definitive information regarding reaction mechanisms when fly ash and silica fume are both present. (Refer also to Chapter 5.)

Mehta and Gjrv (1982), in an investigation of compressive strengths of concrete 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 a 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 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 et al. (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 30% GGBFS or a combination of 25% GGBFS and 5% silica fume. They did note that the cement paste-aggregate bond seemed better in the presence of silica fume. Sarkar et al.

(1990) reported on the microstructural development of a high-strength concrete containing 10% silica fume and a 30% GGBFS replacement of portland cement. They found that the silica fume began to react within 1 day. The reaction of GGBFS was much slower, probably because of the higher CH consumption of the silica fume.

3.9—Reactions with different types of portland cements

The committee is not aware of data concerning the reaction of silica fume with different types of portland cement. As far as is known, there have not been any reports of incompatibilities of silica fume and specific types of portland cement.

3.10—Heat of hydration

The presence of silica fume increases the rate of heat evolution due to its accelerating effect on cement hydration. The data on the total amount of heat evolved are contradictory, with some indicating increases, and some indicating decreases. The user is advised to test the job materials in the proposed combinations for applications in which heat evolution is of concern.

Silica fume, because of its high surface area, accelerates the hydration of alite (Malhotra et al. 1987b). 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 cement with a high alite content would benefit from silica fume; more CH is created, which, in turn, is available to react pozzolanically with silica fume. Hooton (1986), however, used silica fume with ASTM C 150 Type V portland cement and found a reduced rate of hydration of alite.

Data on heat development in portland-cement-silica fume systems relate to early-age tests. Huang and Feldman (1985a) studied cement paste containing 0, 10, 20, and 30% silica fume using conduction calorimetry. Two peaks were discernible (Fig. 3.9)—one occurring at 5 hours, and one at about 6 to 10 hours. 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%, depending on 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% silica fume. Except for the combination of 10% silica fume and a lignosulfonate WRA, all of the pastes showed a decrease in the total heat of hydration when compared with a portland-cement paste without silica fume. Meland (1983) attributed the one case of increased total heat to a possible interaction between the silica fume and the lignosulfonate material.

Ma et al. (1994) studied the first 24 hours of the hydration of cement paste containing supplementary cementing materials over a temperature range of 50 to 130 °F (10 to 55 °C) using isothermal calorimetry. Comparison of the heat of heat evolution of a 7.5% silica-fume cement paste with that of the

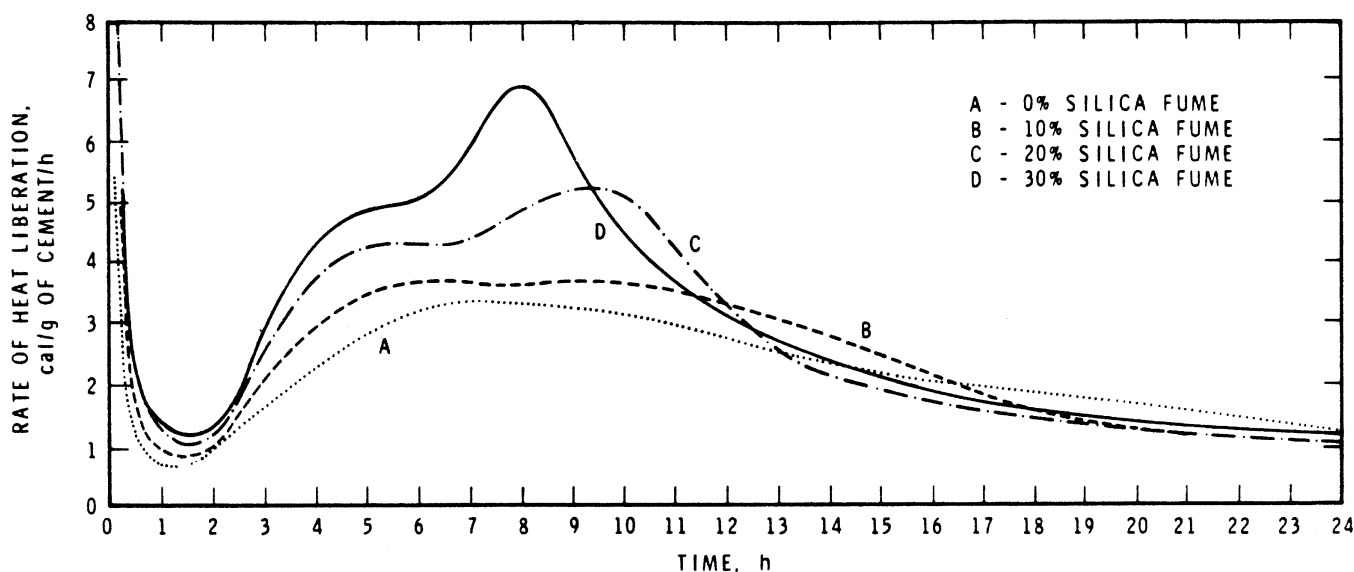


Fig. 3.9—Rate of heat evolution in cement-silica fume pastes (Huang and Feldman 1985a).

portland-cement control showed that the silica-fume cement mixture reacted faster. The total heat evolved was greater for the silica-fume cement paste for the lower hydration temperatures (50 to 77 °F [10 to 25 °C]), while the heat evolved at a hydration temperature of 130 °F (55 °C) was less than for the portland-cement control.

3.11—Reactions with chemical admixtures

Silica fume interacts with chemical admixtures in various ways. The user is advised to consult with the admixture manufacturer for specific information on the likely interactions and to make trial batches to determine the appropriate dosages and verify performance.

3.11.1 High-range water-reducing admixtures—Because silica fume has a very high surface area, it will usually increase the water demand when used in concrete. HRWRAs are usually recommended for good workability and for adequate dispersion and proper packing of the silica-fume particles.

Silica fume has been used successfully with all of the commonly available HRWRAs: sulfonated melamine formaldehyde condensate, sulfonated naphthalene formaldehyde condensate, and polycarboxylate-based admixtures. Because of the small size of silica-fume particles, the interactions between the HRWRAs and the silica-fume particles are similar to the interactions between these chemical admixtures and cement grains. The committee is not aware of instances where there have been adverse reactions between silica fume and any of these admixtures.

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 CSH gel. This is probably due to the 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 that does not appear to be related

to reduced porosity. Porosity is controlled primarily by the w/cm , which can be lowered by the use of a HRWRA.

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 retardation of setting time and excessive air-entraining effects. Investigations by Meland (1983), Helland and Maage (1988), and Berg (1989) show that retardation is much less in concrete where silica fume has replaced cement (mass for mass).

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

3.11.3 Nonchloride accelerators—The addition of silica fume to concrete containing nonchloride accelerator does not appear to modify 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.

3.11.4 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 et al. 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. When used together, silica fume reduces the rate of chloride ion ingress, while calcium nitrite will raise the corrosion threshold to delay corrosion once the chloride ions reach the reinforcing steel.

An organic corrosion-inhibiting admixture is also used to protect reinforcing steel. This admixture has been successfully used in conjunction with silica fume in many commercial applications. Johnson et al. (1996) showed that the combination of organic corrosion inhibitor and silica fume was more effective in reducing the diffusion coefficient than either silica fume or corrosion inhibitor alone.

3.11.5 Air-entraining admixtures—Experience indicates that the use of silica fume generally requires that the amount of air-entraining admixture be increased to produce a specified air content in the concrete. The amount of silica fume and the type of mixing were found to have no significant influence on the development and stability of the air-void system (Pigeon et al. 1989).

The production of air-entrained, high-strength, flowing concrete using a HRWRA based on a combination of sulfonated melamine and sulfonated naphthalene showed that the addition of 2% silica fume did not affect the size distribution of the air voids. The air-entraining admixture was based on a sulfonated alkyl polyglycol ether (Rønneberg 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. (Refer also to Chapter 4.)

3.11.6 Compatibility with admixture combinations—No published data were found describing incompatibility of silica fume with admixture combinations normally used in concrete. It is advisable to conduct laboratory testing of concrete using the proposed admixtures to ensure 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 (Carette and Malhotra 1983a; Scali et al. 1987). This increase is caused primarily by the high surface area of the silica fume. To achieve a maximum improvement in strength and durability, silica-fume concrete should contain a WRA, HRWRA, or both. The dosage of the HRWRA will depend on the amount of silica fume and the type of HRWRA 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 becomes sticky. Experience has shown that it is necessary to increase the initial slump of concrete with silica fume by approximately 2 in. (50 mm) above that required for conventional portland-cement concrete to maintain the same apparent workability (Jahren 1983).

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. The slump loss of silica-fume concrete will be determined by the presence and characteristics of a WRA or HRWRA, or by any of the other factors that affect slump loss of any concrete, such as high cement temperature, high concrete temperature, or failure to account for aggregate moisture correctly. Trial batches conducted at conditions simulating the concrete placing environment using project materials are recommended to establish slump-loss characteristics for a particular situation.

4.4—Time of setting

Experience indicates that the time of setting is not significantly affected by the use of silica fume by itself. The chemical admixtures typically used in silica-fume concrete may affect the time of setting of the concrete. 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. 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 compensate for poor handling or consolidation practices.

4.6—Bleeding and plastic shrinkage

Concrete containing silica fume shows significantly reduced bleeding. As silica fume dosage is increased, bleeding will be reduced. 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 et al. 1982).

Plastic-shrinkage cracks occur when the rate of water evaporation 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. Because 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 (Aitcin et al. 1981). Therefore, care should be used to prevent early moisture loss from freshly placed silica-fume concrete, particularly under conditions that promote rapid surface drying from one or more factors, such as high ambient or concrete temperature, low relative humidity, low ambient temperatures combined with higher concrete temperatures, and high wind velocity. Thus it is necessary to protect the surfaces of freshly placed silica-fume concrete to prevent rapid water evaporation (Jahren 1983). Fog misting, evaporation retardants, windbreaks, and immediate curing have been used successfully to reduce plastic-shrinkage cracking during placing of silica-fume concrete flatwork. The reports prepared by ACI Committees 305 and 308 as well as Section 9.5.1 of this report provide additional information regarding prevention of plastic-shrinkage cracking.

4.7—Color of concrete

Fresh and hardened concrete containing silica fume are generally darker than conventional concrete. This is particularly apparent for concrete containing higher percentages of silica fume as well as some silica fumes that have a high percentage of carbon. The color difference may lessen and virtually disappear after some time (Gjorv and Løland 1982). Light-colored silica fumes are also available from some smelting plants equipped with a heat recovery system.

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. Typically, the increase in air-entraining admixture will be about 125 to 150% of that used in similar concrete without silica fume. This increase is attributed to the very high surface area of silica fume and possibly to the effect of carbon when the latter is present (Carette and Malhotra 1983a).

4.9—Bulk density (unit weight) of fresh concrete

The use of silica fume will not significantly change the bulk density of concrete. Any changes in bulk density 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; this is misuse of the term “density.” Silica fume will produce a much less permeable concrete, but it will not produce a concrete with a higher mass per unit volume.

4.10—Evolution of hydrogen gas

Buil et al. (1988) reported on the evolution of hydrogen gas from a mixture of silica fume and lime. The reaction involves silicon metal that may be present in very small quantities in some silica fumes, and is similar to that which takes place when aluminum powder is placed in concrete. From the hydrogen gas measurements, they estimated that their silica fume samples contained approximately 0.06 to 0.6% silicon metal.

Fidjestøl and Jørgensen (1997) studied the evolution of hydrogen gas from silica fume containing silicon metal. They measured the silicon metal content of silica fume from various sources and found values from 0.01 to 0.23% on a mass basis. Mortars were also tested by admixing silicon metal powders. At room temperature, gas formation took place approximately 24 hours after mixing. Only 10 to 15% of the silicon metal added to mortars generated hydrogen gas at room temperature. The rate of gas evolution increased with increased temperature. They also studied mortars with aluminum powder and determined that the aluminum reaction was faster than that with admixed silicon metal.

The evolution of hydrogen gas has raised concerns over possible explosion hazards. ACI Committee 234 members are aware of one incident in Sweden in which bagged silica fume apparently had become contaminated with silicon metal fines during packaging. The hydrogen gas generated was trapped in the circular voids of extruded hollow core elements cured under accelerated (120 to 140 °F [50 to 60 °C]) conditions. Fidjestøl and Jørgensen (1997) conducted hollow-core scale model tests simulating confined high temperature curing (120 °F [50 °C]). The concrete tested had added silicon metal fines. They reported that a maximum limit of 1% silicon metal would eliminate the risk of explosion, even in the most disadvantageous situations.

Edwards-Lajnef et al. (1997) proposed an accelerated test method for determining the elemental silicon content in silica fume by measuring the amount of hydrogen gas released.

Zhang et al. (2000) determined the silicon content of 24 silica fume samples using the German Standard DIN 51075 (Deutsches Institut für Normung 1982). These samples were obtained from six separate furnaces over a period of 4 months. The silicon content ranged from 0.23 to 0.60% by mass of silica fume. They also conducted tests using silicon metal powder added to mortars. For most mortar mixtures, no gas release was detected for 6 hours after casting; gas evolution ceased after about 4 to 5 days. The volume of gas released increased with the w/cm and silicon metal content. The hydrogen gas released in the mortars kept at 72 °F (22 °C) for about a month was no more than 3.1% of the maximum amount that could be generated if the silicon was fully reacted.

ACI Committee 234 believes that silica fume normally does not contain sufficient silicon metal for hydrogen generation to be a concern. The generation of hydrogen gas in mortar and concrete is a concern only if all of the following conditions are met:

- The silica fume comes from an extraordinary furnace operation, with silicon metal contents at least 3 to 10 times that of material from regular production;
- The concrete member contains confined areas with extremely poor ventilation; and
- Curing is done at an elevated temperature (>120 °F [50 °C]).

For typical construction applications, it is not possible to develop a situation with enough hydrogen gas present in the atmosphere to give an explosive atmosphere.

Because hydrogen gas, rather than atomic hydrogen, is produced, this reaction does not indicate a risk of hydrogen embrittlement for prestressing steel (Warren 1987).

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

5.1—General

The effects of silica fume on the properties of hardened concrete can be directly related to the physical and chemical mechanisms by which silica fume functions, as discussed in Chapter 3. The primary changes in the concrete are in pore structure, cement paste-aggregate transition zone, and chemical composition, particularly the content of calcium hydroxide and alkalinity of the pore solution.

- **Pore structure.** As discussed in Chapter 3, silica fume makes the pore structure of the paste and mortar more homogeneous by decreasing the number of large pores and decreasing the entrance radii of the capillary pores. Total porosity, however, appears to remain largely unaffected by silica fume at a given w/cm ;
- **Cement paste-aggregate transition zone.** As also discussed in Chapter 3, the microstructure of the cement paste-aggregate transition zone in all concrete is significantly different from that of the bulk paste. Much of the improvement in silica-fume concrete properties is attributed to improvements in the cement paste-aggregate transition zone. Because of their small size, the silica fume particles, when dispersed with enough HRWRA present to overcome the effects of surface forces, are better able to pack around the

aggregate particles during mixing and placing (Bentur and Cohen 1987). It appears, however, that the enhancing effect of silica fume on concrete compressive strength may also be partly due to improved strength of the paste phase as a whole. The strength of both the bulk paste phase and the paste phase close to aggregate interfaces is improved by the presence of silica fume; and

- **Chemical composition.** Silica fume consumes calcium hydroxide, and also reacts with alkalies in the concrete. This leads to a lower alkalinity in the pore solution and less calcium hydroxide in the matrix. This means that more calcium silicate hydrate and less calcium hydroxide is present. The pH of the pore water is also reduced.

Details of the aforementioned items are presented in Chapter 3. This chapter presents the results of these changes on the performance properties of hardened concrete made with silica fume.

5.2—Mechanical properties

This section reviews the effects of silica fume on the mechanical properties of concrete. Many of the improvements in mechanical properties seem to be related to the improvements in the bond strength between the paste and aggregate (Chapter 3). Therefore, the influence of the properties of the aggregate on the mechanical properties of concrete becomes more important in silica-fume concrete. The size, 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—These properties and their relation to other mechanical properties appear unaffected by the use of silica fume.

Selleveold et al. (1982) found that the dynamic modulus of elasticity increases with increasing silica-fume content in pastes. Helland et al. (1983) concluded that the stress-strain behavior of silica-fume concrete was similar to that of concrete without silica fume. Several other researchers have reported that the static modulus of elasticity of silica-fume concrete is apparently similar to that of concrete without silica fume of similar strength (Luther and Hansen 1989; Løland 1983; Hooton 1993). Burg and Öst (1994), however, reported that concrete incorporating 15% silica fume as an addition had a higher modulus of elasticity than the control concrete without silica fume, regardless of curing conditions (moist curing, moist curing for 28 days followed by air drying, and insulated) and specimen sizes and types (6 x 12 in. [152 x 305 mm] and 4 x 8 in. [102 x 203 mm]) cylinders and 4 x 8 in. [102 x 203 mm] cores).

Wolsiefer (1984) reported a modulus of elasticity of 6250 ksi (43.1 GPa) and a Poisson's ratio of 0.21 for a 14,200 psi (98 MPa) compressive strength silica-fume concrete. Saucier (1984) studied five silica-fume concretes and found Poisson's ratios ranging in value from 0.208 for 13,350 psi (92 MPa) concrete to 0.256 for 16,400 psi (113 MPa) concrete. Iravani (1996) obtained Poisson's ratios ranging from 0.16 to 0.20, including 0.18 for a 15,200 psi (105 MPa) strength, 4640 ksi (31.7 GPa) modulus silica-fume concrete, and 0.19 for a 17,400 psi (120 MPa) strength, 5380 ksi

(37.1 GPa) modulus silica-fume concrete cured for 3 weeks at 100% relative humidity and then for 5 weeks at 50% relative humidity. The range of these values in Poisson's ratio (0.16 to 0.256) is not believed by the committee to be significantly different than for portland-cement concrete without silica fume.

5.2.2 Creep—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. Limited published data and the different nature of the creep tests used by various investigators make it difficult to draw more specific conclusions on the effect of silica fume on the creep of concrete. The only way to compare creep behavior of different concretes (with and without silica fume) is to look at the relative performance at the same stress-strength ratio.

Saucier (1984) tested concrete with compressive strengths ranging from 11,600 to 14,500 psi (80 to 100 MPa). He found essentially no difference in creep between mixtures with and without silica fume (up to 15% by mass of cement). The same conclusion was reached by Buil and Acker (1985) for cement replacement of 25% by volume (that is, 33% 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% in high-strength concrete with 15% silica fume relative to normal-strength concrete without silica fume. Khatri and Sirivivatnanon (1995) reported that, after an initial curing period of 7 days in lime water, the incorporation of 10% silica fume as portland-cement replacement reduced the creep strain of concrete after 100 days by approximately 50% compared with that of the reference portland-cement concrete under a nominal stress of 40% of the compressive strength. Burg and Öst (1994) reported that, the incorporation of 15% silica fume as an addition to the portland cement reduced the creep strain of concrete (by about 30% at 1 year) compared with the control portland-cement concrete after an initial moist curing of 28 days followed by air drying of 6 weeks.

5.2.3 Total shrinkage—Long-term total shrinkage of silica-fume concrete is comparable to that of concrete without silica fume of otherwise similar composition.

ACI 116R defines drying shrinkage as "shrinkage resulting from the loss of moisture." The shrinkage measured for a specimen under drying conditions without being subjected to applied load or temperature change includes both autogenous and drying shrinkage. For normal-strength concrete, combining both types of shrinkage is of minor importance because of its relatively low autogenous shrinkage. For high-strength concrete, however, autogenous shrinkage may not be ignored (Chapter 3). The drying shrinkage discussed in this section includes both autogenous and drying shrinkage.

Data shown in Fig. 5.1 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 w/cm of 0.40 and silica fume contents of 15 and 30%. Carrette and Malhotra (1983a) reported that the drying shrinkage of silica-fume concrete after 28 days of moist curing is generally comparable to that of the control concrete regardless of the w/cm .