ACI 234R-06
(Reapproved 2012)

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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ACI 234R-06 supersedes ACI 234R-96 (Reapproved 2000) and became effective April 13, 2006.

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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 9 is somewhat brief. More details on working with silica-fume concrete in

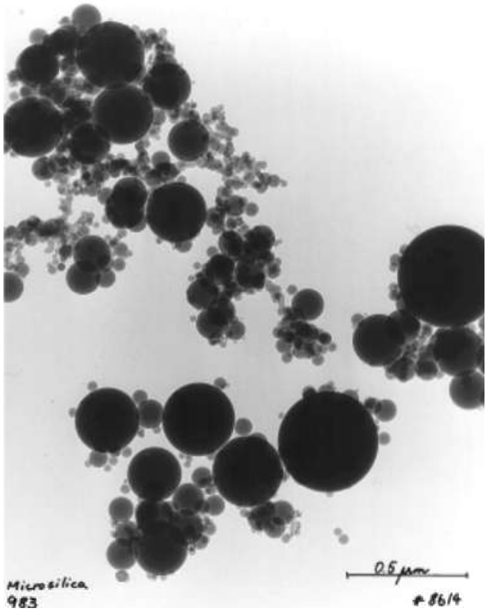

Fig. 1.1—Transmission electron microscope micrograph of silica fume. (Image courtesy of Elkem ASA materials.)

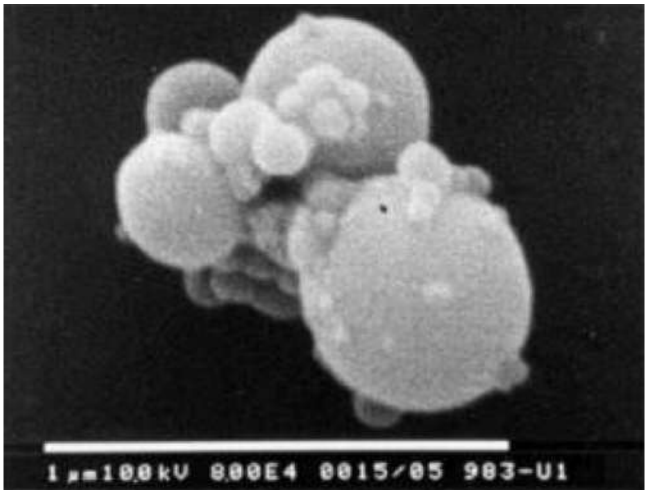

Fig. 1.2—Scanning electron microscope micrograph of silica fume. (Image courtesy of Elkem ASA materials.)

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 × 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 Gjørv and Løland (1982). In 1976, a Norwegian standard permitted the use of silica fume in blended cement. Two years later, the direct addition of silica fume into concrete was permitted by 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

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*Private communication from committee 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. Aïtcin (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 exact amount 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 (Aïtcin 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/m^3 (44 lb/ft^3) dry material versus 130 to 430 kg/m^3 (8 to 27 lb/ft^3) 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 (Wolsiefer et al. 1995) 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 μm (4×10^{-5} in.) with an average diameter of 0.1 to 0.2 μm (4 to 8×10^{-6} 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 2×10^{-6} 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 2×10^{-6} 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/ft^3 (130 to 430 kg/m^3), although it is most common to see values near the middle of this range.

2.3.2 *Slurried silica fume*—Slurried silica fume will typically have a bulk density of approximately 11 to 12 lb/gal. or 83 to 90 lb/ft^3 (1.3 to 1.4 Mg/m^3). 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/ft^3 (200 kg/m^3) to a densified value of 31 lb/ft^3 (500 kg/m^3) 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/ft^3 (400 to 720 kg/m^3).* 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/ft^3 (810 kg/m^3) 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 ft^2/lb (20,000 m^2/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 ft^2/lb (13,000 to 30,000 m^2/kg), nitrogen adsorption
- Fly ash: 1400 to 3400 ft^2/lb (280 to 700 m^2/kg), Blaine air permeability
- Ground-granulated blast-furnace slag:1700 to 2900 ft^2/lb (350 to 600 m^2/kg), Blaine air permeability
- Portland cement: 1500 to 2000 ft^2/lb (300 to 400 m^2/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 ft^2/lb (13,000 to 30,000 m^2/kg) (Malhotra et al. 1987b). One study of Si and FeSi-75% silica fumes reported results between 88,000 and 110,000 ft^2/lb (18,000 and 22,000 m^2/kg) (Elkem 1980). Another study (Nebesar and Carette 1986) reported average surface area values of 98,000 and 84,000 ft^2/lb (20,000 and 17,200 m^2/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 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.

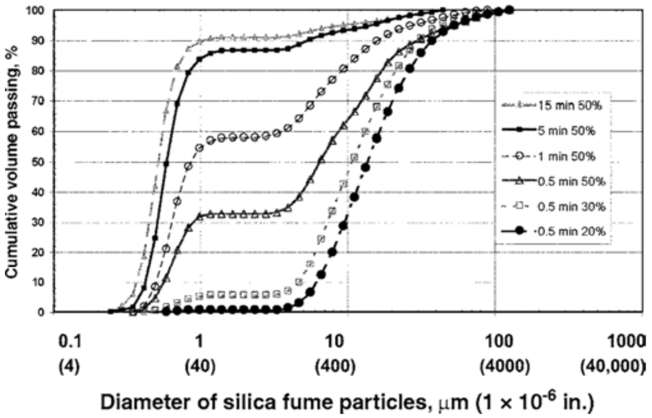

Fig. 2.1—Particle-size distribution of silica fume subjected to varying amounts of dispersion. The set of curves shows the importance of the amount of dispersion on the measured distribution. Varying the intensity and duration of ultrasonic dispersion gives very different results for the same silica 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.)

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.

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*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 n	42		42		32		6		28	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
SiO_2	93.65	3.84	93.22	1.71	92.1	1.29	91.4	0.92	94.22	0.34
Al_2O_3	0.28	0.13	0.31	0.20	0.25	0.12	0.57	0.03	0.36	0.04
Fe_2O_3	0.58	2.26	1.12	0.86	0.79	0.70	3.86	0.41	0.10	0.01
CaO	0.27	0.07	0.44	0.34	0.38	0.11	0.73	0.08	0.27	0.05
MgO	0.25	0.26	1.08	0.29	0.35	0.10	0.44	0.05	0.20	0.02
Na_2O	0.02	0.02	0.10	0.06	0.17	0.04	0.20	0.02	—	—
K_2O	0.49	0.24	1.37	0.45	0.96	0.22	1.06	0.05	—	—
S	0.20[‖]	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 (SiO_2). 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; Aïtcin 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.

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[*] 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 SiO_2 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 SiO_2 of 85%. Published data were not found to show differences in performance in concrete for SiO_2 contents above this minimum. A higher SiO_2 content implies that there are fewer non-SiO_2 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 SiO_2 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 in the presence of fly ash and GGBFS, reactions with different types of portland 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 Radjy (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 exact constituents of portland cement, silica fume, or both that determine the

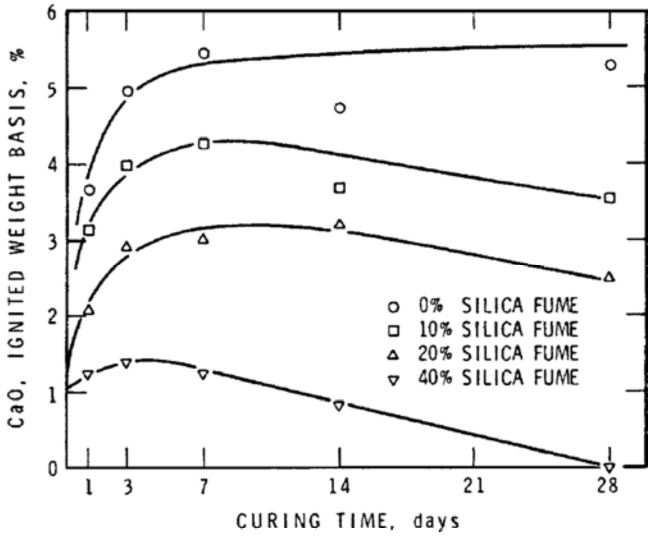

Fig. 3.1—Amount of calcium hydroxide (as CaO) in cement pastes containing different amounts of silica fume (Ono et al. [1985]; as shown in Malhotra et al. [1987b]).

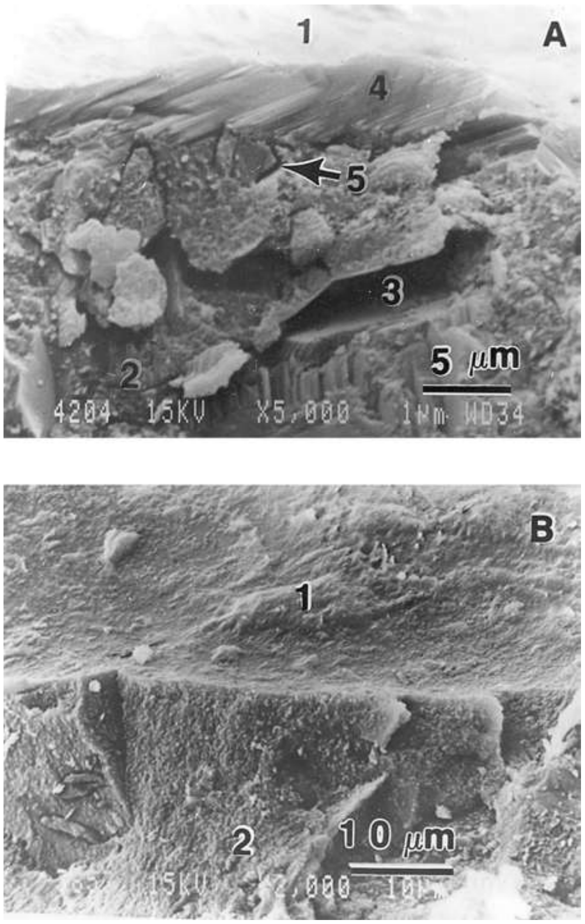

Fig. 3.2—Typical structure of transition zone between the cement paste matrix and aggregate, characterized by scanning electron microscopy (Bentur and Cohen 1987): (a) 28-day system without silica fume; and (b) 28-day system with silica fume. (Note: 1 = aggregate surface; 2 = cement paste; 3 = voids;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

extent of pozzolanic reaction have not been well defined, although studies by Traetteberg (1978) indicate that alkali and silica contents of the silica fume appear to exert some influence. Silica fumes with lower alkali and higher SiO_2 contents 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 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;
- Detwiler et al. (1988) wrote that at the interface itself,

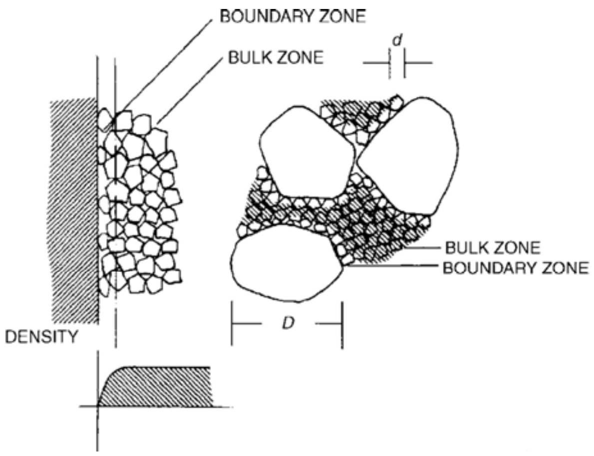

Fig. 3.3—Wall effect and barrier effect are expressions of the fact that particles are packed more loosely in the immediate vicinity of a surface than in the bulk, and of the fact that there is not room for small particles in the narrow zones between large particles.

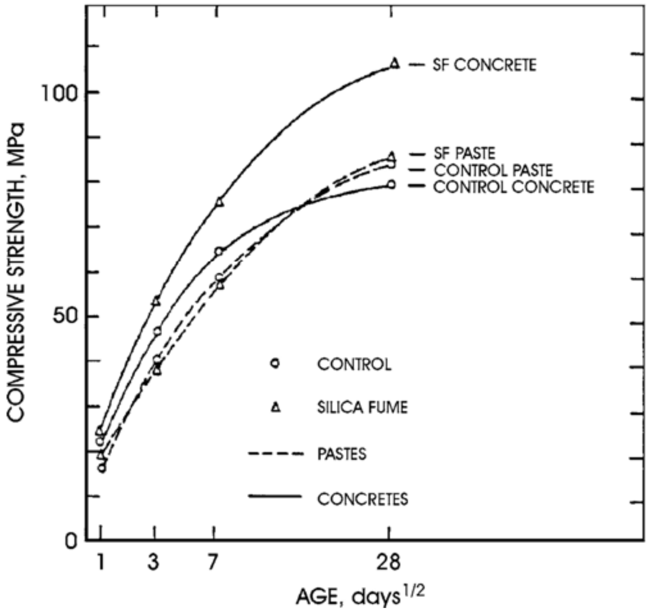

Fig. 3.4—Compressive strength of pastes and concretes with and without silica fume at the same water-cementitious material ratio (Bentur et al. 1988).

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 μm) 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 Gjørv 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.

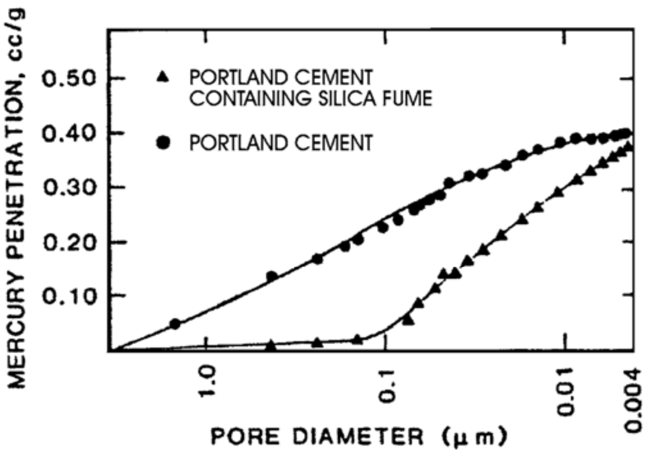

Fig. 3.5—Pore size distribution in pastes of neat portland cement with silica fume (Mehta and Gjørv 1982). (Note: 1 mm = 3.9 × 10^{-5} in.; 1 cc/g = 15.3 fl. oz/lb.)

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

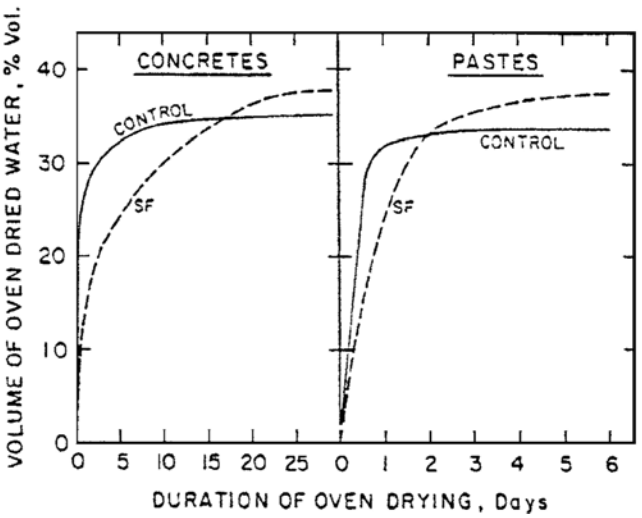

Fig. 3.6—Water loss curves during drying of pastes and concretes with and without silica fume at a water-cementitious material ratio of 0.33. Water loss is presented as volume of water lost relative to paste volume (Bentur et al. 1988).

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 Gjørv (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 of restrained high-strength silica-fume concrete under a sealed condition

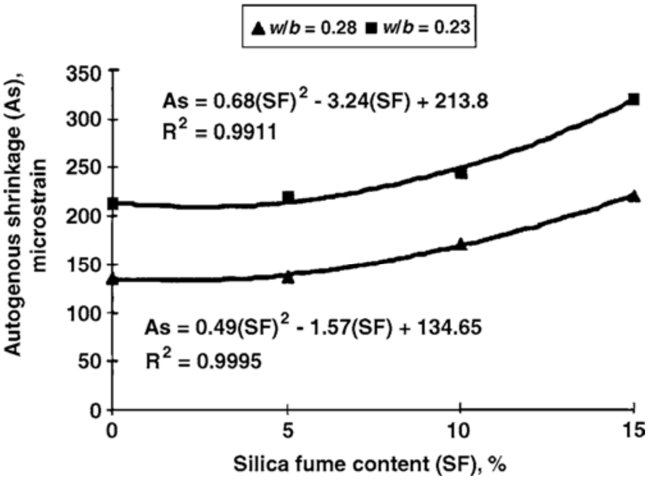

Fig. 3.7—Autogenous shrinkage versus silica fume content and w/cm *(Brooks et al. 1998).*

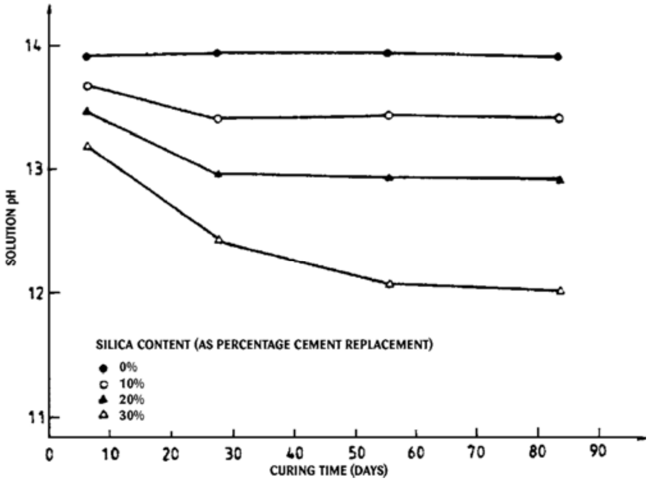

Fig. 3.8—Influence of silica fume on pH values of porewater squeezed from cement pastes. Normal portland cement, water-to-cement-plus-silica-fume ratio of 0.50 (Page and Vennesland 1983).

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 Aïtcin 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 alkalies, 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 alkalies. Diamond (1983) noted that the alkalies 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 alkalies 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 Gjørv (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 Newman (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 Gjørv (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 rate of heat evolution of a 7.5% silica-fume cement paste with that of the

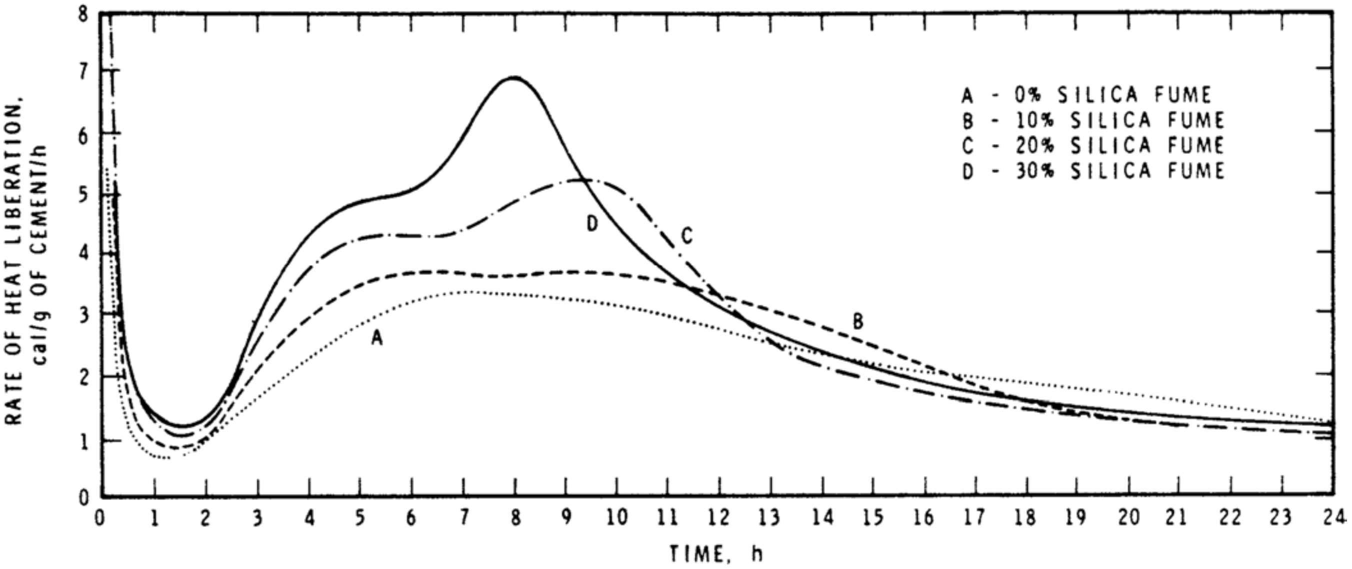

Fig. 3.9—Rate of heat evolution in cement-silica fume pastes (Huang and Feldman 1985a).

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 (Aïtcin 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 (Gjørv 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 to140 °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 (Deutches 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 the 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.

Sellevold 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%. Carette 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*.

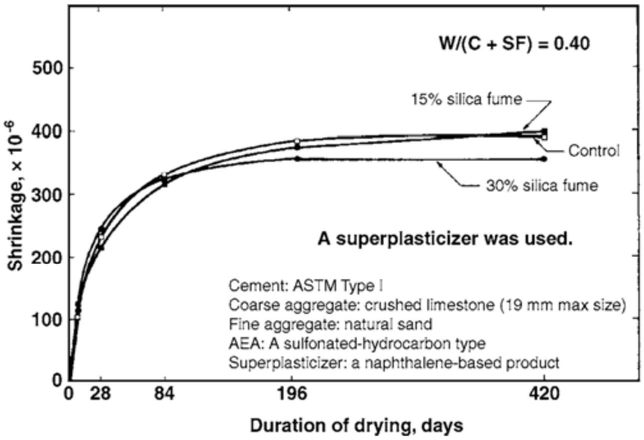

Fig. 5.1—Drying shrinkage of silica-fume concrete with a water-cementitious material ratio of 0.40 (Malhotra et al. 1987b).

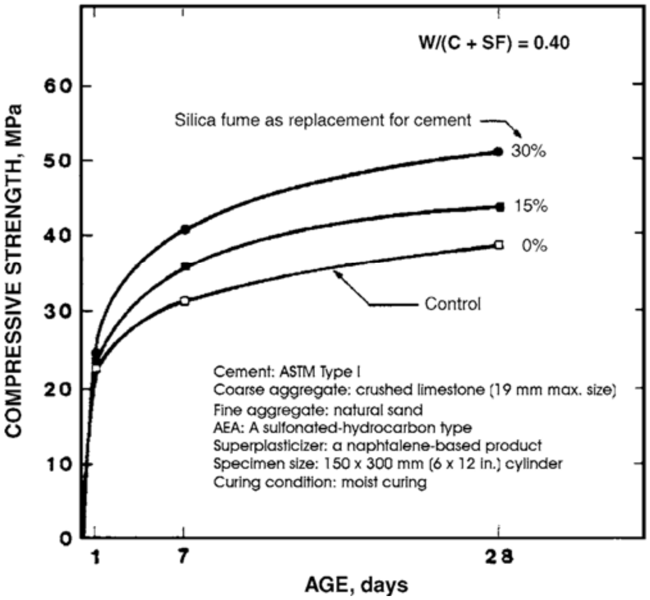

Fig. 5.2—Effect of silica fume on compressive strength of concrete (Malhotra et al. 1987b) (1 MPa = 145 psi).

The amount of silica fume and duration of curing before drying are important factors in the drying shrinkage of concrete. Sellevold and Nilsen (1987) reported that concrete shrinkage is influenced little by silica-fume contents up to 10% by mass of cement.

Hansen (1987) and Luther and Hansen (1989) reported that drying shrinkage of high-strength silica-fume concrete is either equal to or somewhat lower than that of concrete of equal strength without silica fume. Tazawa and Yonekura (1986) also found reduced shrinkage, but for equal strength, the shrinkage per unit volume of paste was similar. Burg and Öst (1994) reported reduced shrinkage of high-strength concrete incorporating 15% silica fume as an addition to the portland cement at ages up to 3 years compared with that of control portland-cement concrete.

Hooton (1993) found that after 28 days of moist curing followed by 64 weeks of drying at 50% relative humidity, a 10% silica fume, 0.35 *w*/*cm* concrete exhibited a small (4%) increase in shrinkage over the control mixture. Shrinkage did increase by 15 and 18% when silica-fume replacements rose to 15 and 20%, respectively.

Drying shrinkage data on concrete containing 20% silica fume and a HRWRA and having a *w*/*cm* of 0.22 have been published by Wolsiefer (1984). This concrete achieved a 28-day compressive strength of 16,200 psi (112 MPa). Shrinkage specimens moist cured for 1 and 14 days showed 1-year drying shrinkages of 730 and 530 microstrain, respectively. The shrinkage values for the specimens moist cured for 14 days were 24% lower than those of a similar high-strength (11,000 psi [79 MPa]) concrete made without silica fume.

Khatri and Sirivivatnanon (1995) reported that the incorporation of 10% silica fume as replacement for portland cement reduced the long-term drying shrinkage of the concrete after 28 days; however, it increased the early-age shrinkage after an initial curing of 7 days in lime water.

5.2.4 *Compressive strength*—For silica-fume concrete:

- Strength development is characterized by higher strength for the same *w*/*cm* than concrete without silica fume. More of the strength is developed at an early age, while late strength gain (beyond 90 days) is normally less than for concrete without silica fume;
- The strength retrogression or reduction reported for silica-fume concrete is marginal and of no structural significance. Strength retrogression is not more of a concern in silica-fume concrete than in concrete without silica fume. Variations of measured concrete strength with time must, for all concrete, be interpreted in light of strength development characteristics and test conditions;[*]
- At low temperatures, silica fume is not as effective as cement for early strength, while high curing temperatures accelerate the effect of silica fume; and
- Silica-fume concrete shows much less reduction in strength due to high temperature curing than does concrete without silica fume.

The main contribution of silica fume to concrete strength development at normal curing temperatures (other than accelerated curing conditions) takes place at early ages up to 28 days. Typical strength-development characteristics of silica-fume concrete are shown in Fig. 5.2 and 5.3. Figure 5.2 shows data for concrete with silica fume as a direct replacement by mass for portland cement (Malhotra et al. 1987b), and Fig. 5.3 refers to concrete with silica fume as an addition to portland-cement fly ash concrete (Carette and Malhotra 1983b). The 1-day compressive strength of silica-fume concrete is about equal to that of the control concrete when the silica fume is used as a direct replacement. When silica fume is used as an addition to the portland cement and fly ash blend, the 1-day strengths may be substantially higher than the control, depending on the amount of silica fume added.

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[*] There is no identified phenomenon, chemical or physical, called strength regression. When compressive strength of concrete at a later age is less than recorded at an earlier age, it usually simply means that the sample at the earlier age came from the upper range of strengths at that age and the later sample came from the lower range. When this is not the case, it is likely due to testing errors. If neither, there is a degradation mechanism that should be identified.

At 28 days, the compressive strength of silica-fume concrete is always higher and, in some instances, significantly so, as shown in Fig. 5.2 and 5.3.

The contribution of silica fume to strength development after 28 days is minimal. This situation is unlike concrete made with ASTM C 618 Class F fly ash in which case the pozzolanic reactions are very slow at early ages, and the contributions to concrete strength development are usually evident after 28 days and then continue for more than 1 year.

There are a limited number of publications where apparent reductions of compressive strength of silica-fume concrete have been reported at later ages (greater than 90 days) (De Larrard and Bostvironnois 1991; Burg and Öst 1994; Persson 1998; Malhotra and Chevrier 1998).

The committee does not believe that there is strength regression of silica-fume concrete. It is believed that some of the reported data were influenced by issues such as:

- Use of testing machines or platens that may have been inadequate for testing high-strength concretes, as currently outlined by ACI 363.2R; and
- The smaller relative strength gain of silica-fume concrete beyond 90 days, compared with concrete without silica fume. This increases the importance of: a) the inherent variation in the test method, including operator dependency and recalibration between tests. In some cases, the differences in strength were within the standard deviation of the results (Burg and Öst 1994; Persson 1998); and b) drying of the test specimens. De Larrard and Bostvironnois (1991) reported that cylindrical test specimens, when cured and tested dry, showed lower strengths. They concluded that self-stresses caused by drying of the specimens were responsible.

Loss of strength has also been found for certain conditions in concrete without silica fume (Wood 1991), where “retrogression,” that is, lower strength measured at, for example, 1 year than at 90 days, was observed.

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

Read et al. (1990) investigated the strength development characteristics of high-strength concrete incorporating 8 and 12% silica fume in comparison to a control portland-cement concrete with the same *w/cm* using cast cylinders and cores drilled from large concrete elements and cured under different regimes. The results indicated that at ages up to 1 year, the silica-fume concrete was affected less by the different curing conditions than the control concrete. The silica-fume concrete had higher early-age strength than the control concrete; however, this advantage appears to be lost at later ages. Regardless of the curing conditions, the silica-fume concrete had faster strength development up to 91 days, after which its strength gains were generally lower than the control concrete.

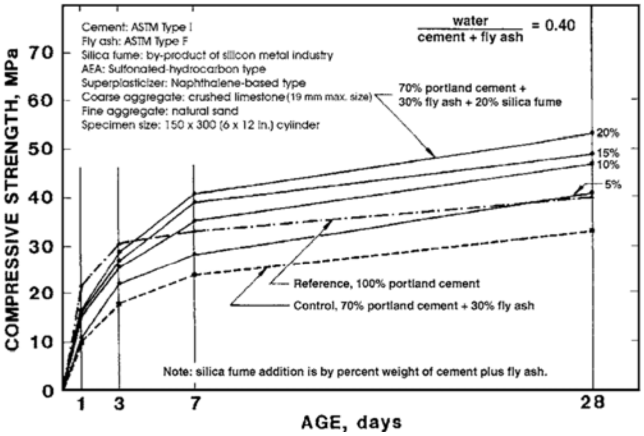


Fig. 5.3—Effect of silica fume on compressive strength of concrete containing fly ash (Carette and Malhotra 1983b) (1 MPa = 145 psi).

5.2.5 *Flexural and splitting tensile strengths*—Development of flexural and splitting tensile strengths of concrete incorporating silica fume are similar to concrete without silica fume.

For both types of concrete, as the compressive strength increases, the tensile strength also increases, but at a gradually decreasing ratio (Goldman 1987). In hardened concrete, the ratio of tensile to compressive strength is strongly affected by the properties of the materials used; therefore, a constant relationship among the various types of strengths does not exist. If tensile strength is important for design, it must be tested for in the project concrete mixture.

Wolsiefer (1984) reported that for 14,200 psi (98 MPa) concrete containing 1000 lb/yd^3 (593 kg/m^3) of cement and 20% silica fume, the ratio of flexural to compressive strength varied from 0.13 to 0.15. Luther and Hansen (1989) found the modulus of rupture of silica-fume concrete made with dolomite coarse aggregate and having compressive strength between 7400 to 15,500 psi (51 to 107 MPa) to be approximately 1.02 times the square root of compressive strength when expressed in megapascals (12.3 times the square root of compressive strength when expressed in pounds per square inch.)

Zhang et al. (1993) reported that for silica-fume concrete with 28-day compressive strengths of approximately 15,200 psi (105 MPa) and containing 674 lb/yd^3 (400 kg/m^3) of cement and 10 or 15% silica fume, the flexural strength increased by 22 to 24% from 7 to 28 days, whereas for concrete without silica fume (28-day compressive strength of 11,600 psi [80 MPa]), the increase in the strength was less than 3% over the same period of time.

Burg and Öst (1994) reported higher flexural- and splitting-tensile strengths at 91 days for concrete incorporating 15% silica fume as an addition to the portland cement compared with those of the control portland-cement concrete.

McDonald (1991) reported that the splitting tensile strength at various ages ranged from 5.8 to 8.2% of the compressive strength at the same age. The higher percentages, 8.2 and 8.0%, were at the ages of 1 and 3 days, respectively. Splitting tensile strengths ranged from 500 psi (3.4 MPa) at an age of 1 day (compressive strength 6080 psi [42 MPa]) to a maximum of 1015 psi (7.0 MPa) at the age of 90 days (compressive strength 14,280 psi [98 MPa]). Luther and Hansen (1989) found the splitting-tensile strength of fly-ash and silica-fume concrete to be similar, ranging between 9.7 and 10.6% of the compressive strength. One 15,500 psi (107 MPa) silica-fume concrete developed a splitting-tensile strength of 1100 psi (7.7 MPa). Zhang et al. (1993) found that the splitting-tensile strengths of concrete with a 10 or 15% silica fume addition did not increase compared with that of a control concrete with a similar *w/cm*, even though the compressive strength of the concrete increased by 30 to 34%. Hooton (1993) found splitting-tensile strengths as a percentage of compressive strength of 10% silica fume concrete (*w/cm* = 0.35) to range from 8.5 to 8.9 at ages of 28 to 182 days, whereas similar concrete without silica fume ranged from 9.4 to 10.7.

5.2.6 *Bond strength*—Silica fume improves bond strength at three types of interfaces: cement paste to aggregate, cement paste to steel reinforcement, and new to old concrete.

Chen and Zhang (1986a) studied the effect of silica fume addition on the properties of the transition zone between marble and cement paste. An addition of 5% silica fume increased the 28-day splitting-bond strength by a factor of approximately 2 compared with that of a sample without silica fume. Odler and Zurz (1988) measured the splitting-bond strength between five different kinds of rocks and cement paste containing up to 10% silica fume. The results showed that, in every case, the bond strength of the samples containing silica fume was higher than that of samples without silica fume. The improved cement-aggregate bond resulting from the use of silica fume was also reported by other investigators. Chen and Wang (1988) found that the splitting-bond strength increased from 290 psi (2.0 MPa) for cement paste without silica fume to 345 psi (2.4 MPa) for cement paste containing 30% silica fume. Wu and Zhou (1988) also reported increased splitting bond strength, but the data in this paper are presented in such a way that it is impossible to provide a single numerical value to characterize the bond improvement.

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

The cleavage strength of a boundary between a pure zinc plate and cement paste was studied by Chen and Zhang (1986b). The results showed that by adding 5% silica fume, the 28-day cleavage strength was increased by approximately 50%. Bürge (1983) showed that concrete-steel reinforcement bond strength in a high-strength, low-density concrete containing silica fume increased three to five times, depending on the proportion of cement replaced by silica fume. A similar improvement in ultimate bond strength for low-density aggregate concrete containing silica fume was reported by Robins and Austin (1986).

The improved bond strength of silica-fume concrete to steel reinforcing bars is reported in numerous papers in the review by Sellevold and Nilsen (1987). Ezeldin and Balaguru (1989) performed a reinforcing bar pullout test on concrete containing up to 20% silica fume. They concluded that the addition of silica fume resulted in bond strength increases that were proportional to the square root of compressive strength, but the use of silica fume led to more brittle behavior. De Almeida (1996) performed a reinforcing bar pullout test for concrete with 8 or 10% silica fume. The results showed that the replacement of cement with silica fume improved the bond compared with that of control specimens.

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

5.3—Durability aspects

As defined in ACI 116R, durability is the ability of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service. Durability is a complex subject, and a number of mechanisms can be involved in the degradation of concrete, concerning both the transport of substances into and out of concrete and the effect of these substances on the concrete.

The most important reason for using silica fume is its contribution to improved durability in concrete.

As will be detailed, silica fume can improve durability of concrete by:

- Reducing rates of transport of aggressive fluids through the pore structure (Section 5.3.1);
- Reducing the rate of chloride-ion ingress (Section 5.3.1);
- Providing equal or improved resistance to freezing and thawing as well as to deicer scaling (Section 5.3.2);
- Improving chemical attack resistance (Section 5.3.3);
- Improving erosion and abrasion resistance (Section 5.3.4);
- Providing similar fire resistance (Section 5.3.5);
- Improving resistance to deleterious expansion due to ASR (Section 5.3.6);
- Improving sulfate resistance (Section 5.3.7); and
- Increasing electrical resistivity (Section 5.4).

5.3.1 *Transport properties*—Many of the deterioration mechanisms that can affect concrete are regulated by the transport properties of the material, be it transport of gas, liquid, or of liquid carrying detrimental substances in solution.

5.3.1.1 *Terminology*—Following are several terms that are used in this section:

- **permeability**—ACI 116R defines the coefficient of water permeability as “the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions, usually 20 ºC.” It is the hydraulic gradient, or hydraulic pressure per unit thickness, that is the transport mechanism;
- Similarly, **gas permeability** results from a gas pressure

gradient across the porous medium;

- **Vapor permeability** results from a gradient in relative humidity (vapor pressure) across the porous medium. It is sometimes referred to as vapor diffusivity because there is a concentration gradient in the water molecules in the air at the different relative humidities;
- **water absorption**—ACI 116R defines absorption as "the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid." It occurs only in concrete that is unsaturated and the rate and magnitude of absorption decrease as the permeable pores in the concrete saturate;
- **diffusion**—a diffusion coefficient, or the diffusivity, is defined as the rate at which a diffusing substance is transported between opposite faces of a unit cross section and depth of a porous medium when there is a unit concentration difference between them. Commonly, chloride diffusion rates in saturated concretes are reported. In practice, the chloride gradient occurs between one surface and the interior of the concrete; and
- **chloride-ion penetration resistance**—the time-dependent resistance of concrete to penetration of chloride ions that may occur due to a number of mechanisms, including absorption, permeability, diffusion, and evaporative transport (wick action). It will also be affected by issues such as chloride binding.

5.3.1.2 *Permeability*—The contribution of silica fume to reduction in water permeability is very large, with the reduction in permeability coefficient being up to one order of magnitude or more depending on the mixture composition and dosage of silica fume. The low-permeability characteristics of silica-fume concrete are responsible for its improved durability in various aggressive environments.

The permeability of concrete is determined by the measurement of the liquid, gas, or vapor flow rate through the pore structure under a pressure gradient. The term permeability is often incorrectly used to describe all forms of fluid penetration, including absorption and diffusion. High concrete permeability is closely linked to poor durability. High-permeability concrete has pore structures that allow freezing-and-thawing damage by water, cement paste deterioration due to the penetration of aggressive chemicals, and corrosion of embedded steel reinforcement by ingress of chloride ions.

The reduction in the size of capillary pores, as explained in Chapter 3, increases the probability of transforming continuous pores into discontinuous ones (Philleo 1986). Because capillary porosity is related to permeability (Powers et al. 1954), the permeability to liquids and vapors is thus reduced by silica fume addition. Hooton's (1986) data for cement pastes of 0.25 *w/cm* indicated water permeability of 3×10^{-13} ft/s (0.9×10^{-13} m/s) and $< 0.3 \times 10^{-13}$ ft/s (0.1×10^{-13} m/s) for 28-day cured pastes containing 10 and 20% by volume of silica fume, respectively. When no silica fume was added, permeability was higher, 12×10^{-13} ft/s (3.8×10^{-13} m/s).

Data for mortar and concrete show a similar trend in that silica fume reduces permeability (Scheetz et al. 1981; Mehta and Gjørv 1982; Delage and Aïtcin 1983). Maage (1984) and Maage and Sellevold (1987) reported a reduction in permeability of about one order of magnitude for silica fume dosages of 5 to 12%; the most improvement was with the lowest dose that was used with the lowest *w/cm*. Measurement of the water permeability for quality concrete (>5800 psi [40 MPa]) is often impossible because of the measuring equipment limitations and leakage around the permeability cells (Hustad and Løland 1981; Hooton 1986, 1993). El-Dieb and Hooton (1995) were able to measure a water permeability of 1.9×10^{-16} m/s for a 0.29 *w/cm* concrete with 7% silica fume plus 25% GGBFS.

Sellevold and Nilsen (1987) concluded that silica fume is more effective in reducing permeability than it is in enhancing strength, and suggested that it is the improved quality of the cement paste-aggregate interfacial transition zone that is largely responsible. As shown previously, however, the permeability of cement paste specimens is also reduced considerably when silica fume is used. Thus, it cannot be that only the interfacial transition zone is improved; the bulk paste phase is also improved. This is indicated by results showing that silica fume lowers the permeability and enhances the strength of both paste and concrete.

5.3.1.3 *Water absorption*—The limited available data indicate less absorption in silica-fume concrete than in concrete of similar *w/cm* without silica fume.

Ramakrishnan and Srinivasan (1983) reported that the water absorption coefficient of silica-fume fiber-reinforced concrete is lower than that of a fiber-reinforced concrete without silica fume. Similarly, Morgan (1988) showed that the water absorption of silica-fume shotcrete is lower than that of shotcrete without silica fume when tested using ASTM C 642. Hooton et al. (1997) reported that the amount of chloride that penetrated due to absorption after 3 days into partly dried concrete with 7% silica fume averaged only 30% of similar concrete without silica fume for *w/cm* of 0.35, 0.40, and 0.45.

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

5.3.1.4 *Chloride-ion penetration resistance*—The reduction in chloride transport is very clear for silica-fume concrete. The use of silica fume delays the onset of corrosion and reduces corrosion rate once it is initiated. As is true for any concrete, chloride transport properties of silica-fume concrete depend on proper mixture proportions, construction procedures, and adequate curing to produce a finished structure with minimal cracking. Silica-fume concrete is commonly used in bridge decks, parking structures, and marine structures because of its ability to slow the ingress of chloride ions.

ASTM C 1202 is a rapid indicator of the ability of concrete to resist the migration of chloride ions and is routinely used

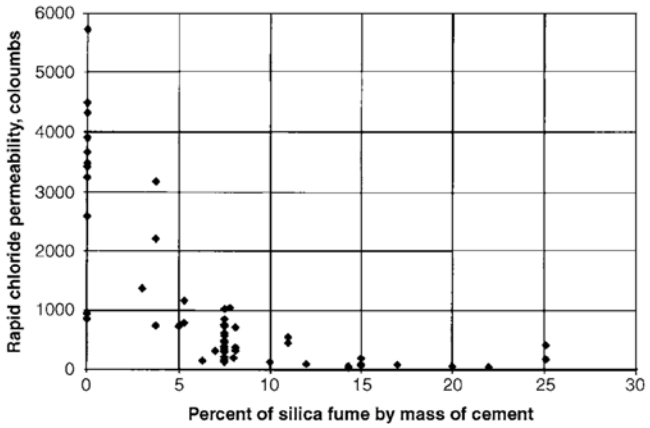
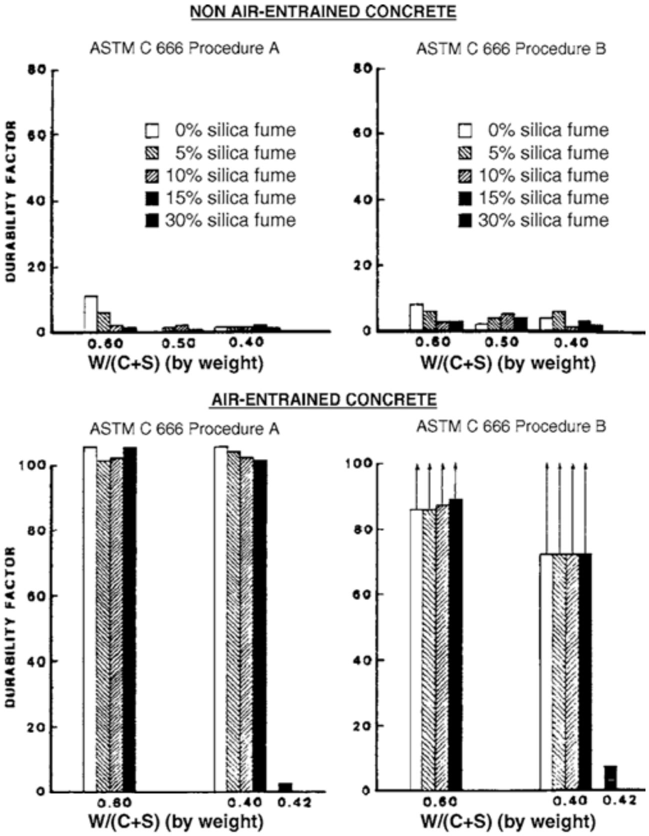


Fig. 5.4—Relationship between rapid chloride permeability (ASTM C 1202) and silica fume content. Scatter in the data is caused by differences in mixture proportions, water-cementitious material ratio, total cementitious material content, specimen curing method and duration, age at testing, inherent variability of the test method, and laboratory-to-laboratory variations. Data are from Perraton et al. (1988); Berke (1989); Plante and Bilodeau (1989); Ozyildirim and Halstead (1988); and Wolsiefer (1991).

both to qualify concrete mixtures and for quality control. This test measures the electrical charge passed through the concrete, which is then related to the chloride-penetration resistance. Work by Whiting (1981, 1988) and McGrath and Hooton (1997, 1999) has shown that this rapid test correlates reasonably well with traditional tests of concrete transport properties. When tested using ASTM C 1202, the electrical charge passed through concrete was reduced with increasing silica fume replacement levels, as is shown in Fig. 5.4, which is compiled from several references.[*]

Detwiler et al. (1994) compared the chloride-ion transport of concrete with and without 5% silica fume and cured at different temperatures to the same degree of hydration. They found that while all of the concrete was adversely affected by curing at elevated temperatures, the silica-fume concrete performed better than the comparable control concrete for any given curing temperature. The use of 5% silica fume substitution by mass of cement was more effective than reducing the *w/cm* from 0.50 to 0.40 in improving the resistance to chloride-ion penetration. Hooton et al. (1997) found an increase in chloride penetration resistance for concrete containing 7% silica fume by AASHTO T 259, ASTM C 1202, and bulk diffusion tests for both ambient-temperature and 160 °F (70 °C) curing.

McGrath and Hooton (1997) found beneficial effects of silica fume on chloride diffusion coefficients for concrete having a *w/cm* of 0.40 and 0.30. For the 0.40 *w/cm* concrete, the substitution of 8% silica fume by mass of cement reduced the diffusion coefficient by a factor of 7. Whiting and Detwiler (1998) studied optimum silica-fume concrete mixtures for bridge decks. They found that the use of silica fume reduced the chloride diffusivity by a factor of 3 or more compared with similar concrete not containing silica fume. Increased dosages of silica fume above 6 to 8% by mass provided little additional benefit.



Cement: ASTM Type I
Coarse aggregate: crushed limestone (19 mm max. size)
Fine aggregate: natural sand
AEA: A sulfonated-hydrocarbon type
Superplasticizer: a naphthalene-based product

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

Fig. 5.5—Summary of durability factors for air-entrained concretes (Malhotra 1986).

In a field survey of bridge deck overlays in Illinois, Detwiler et al. (1997) found that the depth of penetration of chlorides after 8 years of exposure was considerably less for a silica-fume concrete overlay than for a dense concrete overlay without silica fume. Results for ASTM C 1202 testing were consistent with those determined in detailed chloride concentration profiles on companion cores.

5.3.2 *Freezing-and-thawing resistance*

5.3.2.1 *Freezing-and-thawing resistance*—When silica-fume concrete is air entrained at typically recommended levels, there is no difference in performance compared with concrete without silica fume. The data for silica-fume concrete without entrained air are conflicting. This committee recommends that all silica-fume concrete be air entrained if exposed to freezing-and-thawing conditions; it could become critically saturated unless testing with project-specific materials indicates otherwise.

Numerous investigators have shown that it is possible to produce freezing-and-thawing-resistant, air-entrained concrete containing silica fume (Aïtcin and Vezina 1984; Caldarone et al. 1994; Cohen and Olek 1989; Malhotra 1986; Sonebi and Khayat 1993). From these data it appears that satisfactory

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[*] ASTM C 1202 and AASHTO T 277 describe the same test method. The ASTM designation is used in this report.

freezing-and-thawing durability factors were obtained up to a *w*/*cm* of 0.60. Also, to ensure adequate freezing-and-thawing resistance, there are data that support limiting the silica fume content to a maximum of 15% (Yamato et al. 1986; Malhotra et al. 1987b). It is vital to check admixture compatibility and to perform tests with the actual materials to be used to be sure that the air-entraining admixture is effective and that a stable air-void system can be produced (Saucier et al. 1991). Therefore, for properly air-entrained concrete with a *w*/*cm* as high as 0.50, up to 15% silica fume by mass of cement should have no detrimental effects on resistance to freezing and thawing.

The situation for non-air-entrained concrete containing silica fume is not as straightforward, as is evident in Fig. 5.5. The following conclusions can be drawn from the published results:

- It is not possible to consistently create freezing-and-thawing-resistant, non-air-entrained concrete containing silica fume at a *w*/*cm* above 0.45 (Malhotra 1986; McGrath and Hooton 1991; Yamato et al. 1986);
- In the *w*/*cm* range of 0.35 to 0.45, several investigations present conflicting results (Cohen et al. 1992; Hooton 1993; Luther and Hansen 1989; Malhotra 1986; Malhotra et al. 1987a; McGrath and Hooton 1991); and
- Many non-air-entrained concretes with satisfactory durability factors (DF > 60%, according to Neville [1996]) have been produced at a *w*/*cm* below 0.35 with up to 10% silica fume replacement (Buck et al. 1987; Nasser and Ghosh 1994; McGrath and Hooton 1991; Mohktarzadeh et al. 1995; Saucier 1984; Sonebi and Khayat 1993). Malhotra et al. (1987a), concluded that even at the extremely low *w*/*cm*, non-air-entrained concrete containing silica fume does not have adequate freezing-and-thawing resistance when tested according to ASTM C 666.

5.3.2.2 *Scaling resistance*—The data on scaling resistance of silica-fume concrete with and without entrained air are also mixed. The committee recommends that silica-fume concrete exposed to deicing salts in service be air entrained.

Adequate scaling resistance can be obtained for air-entrained concrete mixtures incorporating up to 10% silica fume with a *w*/*cm* as high as 0.45. This guidance is supported by work reported by Gagne et al. (1996), Pigeon et al. (1987), and Sørensen (1983).

Good deicing chemical scaling resistance has also been achieved with silica-fume concrete that was not air entrained. Good results have been reported at low *w*/*cm* of 0.38 with 10 and 20% silica fume, 0.35 with 7.5% silica fume, and 0.30 with 10% silica fume by Sørensen (1983), Marchand et al. (1992), and Gagne et al. (1996), respectively.

5.3.2.3 *Air-void system parameters*—The committee is aware of specifications for silica-fume concrete that require the hardened concrete to show the traditional parameters for the air-void system: a spacing factor equal to or less than 0.008 in. (0.2 mm), and a specific surface greater than 600 $\text{in.}^2/\text{in.}^3$ ($24\ \text{mm}^2/\text{mm}^3$). These traditional parameters may be difficult to achieve for any concrete, with or without silica fume, which contains high dosages of HRWRA. Concretes without silica fume containing HRWRAs with air-void parameters outside the traditional range have been found to perform well in freezing and thawing (ACI 212.4R). The Canadian Standard (CSA A23.1-04) annex on high-performance concrete allows a spacing factor not to exceed 0.009 in. (230 μm), with no single test exceeding 0.010 in. (250 μm). If the *w*/*cm* is 0.36 or less, the spacing factor must not exceed 0.010 in. (250 μm), with no single test exceeding 0.012 in. (300 μm).

5.3.3 *Chemical attack resistance*—Silica fume will increase the resistance of concrete to chemical attack through reduced permeability and through reduced content of calcium hydroxide.

Silica-fume concrete is not completely impervious to all aggressive chemicals, especially in the case of acid attack on the surface; however, research and field performance show that at a low *w*/*cm*, silica-fume concrete can be used effectively to prevent significant damage by many types of chemical attack. Before using silica-fume concrete for projects involving exposure to aggressive chemicals, the mixture proportions should be optimized and, if necessary, concrete specimens tested to the specific project conditions (type and concentration of chemicals, pH level, ambient temperature, and consideration of wetting-and-drying cycles).

Wolsiefer (1984) investigated the chemical resistance of silica-fume concrete to fertilizer and explosive-grade ammonium nitrate, which is known to be very aggressive to concrete. The test mixture contained a 550 lb/yd^3 ($325\ \text{kg/m}^3$) cementitious material content, with and without 104 lb/yd^3 ($62\ \text{kg/m}^3$) of silica fume and a *w*/*cm* of 0.28. Durability was determined by compressive strength measurements of silica fume and control concrete exposed to the aggressive chemicals. The test specimens were submerged (57 weeks) to half their height in plain water (as a control) and in a saturated solution of ammonium nitrate at laboratory ambient temperatures. The control concrete lost 74% of its average compressive strength in the ammonium nitrate solution when compared with the control concrete submerged in water. The silica-fume concrete specimens did not lose any strength, and had an average final compressive strength (57 weeks) of 13,100 psi (90 MPa). The tests were also conducted in a more severe, elevated temperature environment at 150 °F (63 °C), with daily wetting-and-drying cycles for 240 days. The control concrete lost 62% of its average compressive strength in the ammonium nitrate solution, while the silica-fume concrete lost only 3.4% of its compressive strength.

Feldman and Huang (1985) investigated the resistance of mortars to attack by 4% $MgCl_2$ solution for 150 to 170 days followed by exposure to a solution containing a mixture of magnesium, calcium, and sodium chlorides. The *w*/*cm* of the mortars was 0.45 and 0.60, and they contained silica fume at 0, 10, and 30% by mass of cement. The results showed that the addition of silica fume substantially increased the resistance to the attack of the chemicals of the mortars.

Mehta (1985) tested the chemical resistance of low *w*/*cm* concrete exposed to 1% hydrochloric acid, 5% acetic acid, 1% lactic acid, and 1% sulfuric acid solutions. The specimens were 7 weeks old before the exposure and included concrete without silica fume with a *w*/*cm* of 0.35, latex-modified concrete with a *w/cm* of 0.33, and silica-fume concrete containing 15% silica fume by mass of cement with a *w/cm* of 0.33. Mehta concluded that concrete containing silica fume showed better resistance to the chemical attack than did the other two types of concrete.

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

Yamato et al. (1989) studied the chemical resistance of silica-fume concrete to 5% sulfuric acid, 5% hydrochloric acid, and 10% sodium sulfate solution. The concrete specimens were immersed in the aggressive chemical solutions for 340 days, with the solutions replenished every 1 to 2 weeks. At 2-week intervals, the specimen masses and dynamic moduli of elasticity were determined. Concrete specimens containing 0, 10, and 20% silica fume showed mass losses of 1.3, 0.8, and 0%, respectively, when exposed to the 10% sodium sulfate solution. For concrete exposed to 5% hydrochloric acid, the comparative mass loss was reduced by 50% with a 10% silica fume dosage, and 50% more with a 20% silica fume dosage. The mass loss and decrease in modulus of elasticity values of the specimens subjected to 5% sulfuric acid were much more pronounced than that of the specimens exposed to other chemicals. The mass loss at 100 days for the silica-fume concrete, at a 30% dosage, was 20 to 23% at 90 days, while the mass loss for the control concrete was 35%. Although this study showed improved chemical resistance of silica-fume concrete exposed to hydrochloric acid and sodium sulfate solution, the improvement in performance of the specimens exposed to 5% sulfuric acid was not significant. As the concrete used for this study had a high *w/cm* of 0.55, however, it would be expected that its chemical resistance would be improved by lowering the *w/cm*.

Durning and Hicks (1991) and Berke et al. (1992) studied the chemical resistance of concrete with and without silica fume to 5% acetic acid and 5% formic acid. Various silica fume addition rates from 7.5 to 30% were used with ASTM C 150 Type I and I/II cements. The concrete cylinders were immersed in the aggressive chemicals (1 week wet/1 week dry). The samples were then wire brushed, and their mass determined at the end of each wet cycle. The specimens of concrete without silica fume had 25% mass loss within 10 cycles. The chemical resistance increased with an increase in silica fume percentage, and the addition of 30% silica fume decreased the mass loss of the test cylinders by a factor of 4.5 in the case of the formic acid and by at least 15 in the case of the acetic acid. Durning and Hicks (1991) studied the chemical resistance of silica-fume concrete to 1 and 5% sulfuric acid, and 5% phosphoric acid; this is in addition to the investigation previously reported on acetic and formic acid. Using the same wet and dry chemical ponding exposure, they reported that the addition of 30% silica fume doubled the time-to-failure for the exposure to 1% sulfuric acid. The addition of 25% silica fume improved the mass loss factor by only 1.3 for 5% sulfuric acid and 1.4 for the specimens exposed to 5% phosphoric acid. This study's findings are consistent with that of Yamato et al. (1989), which showed no significant improvement for exposure to sulfuric acid.

5.3.4 *Abrasion-erosion and abrasion resistance*—Silica fume will increase the abrasion-erosion and abrasion resistance of concrete through increased strength of the matrix and the improved bond between matrix and aggregates.

The excellent resistance of silica-fume concrete to abrasion-erosion damage was reported by Holland (1983; 1986a,b) and McDonald (1991) based on investigations performed at the U.S. Army Corps Engineers WES. The abrasion-resistance test method used was developed by the WES (Liu 1981), which is now ASTM C 1138. This method uses steel balls in water stirred by paddles at 1200 rpm to simulate the abrasive action of waterborne particles such as silt, sand, gravel, and boulders. High-strength silica-fume concrete with limestone aggregate was shown to have abrasion-erosion resistance similar to that of a concrete without silica fume with a *w/cm* of 0.40, and containing hard chert aggregates. The improved abrasion-erosion resistance was attributed to the very high compressive strength of the paste fraction of the concrete.

Berra et al. (1989) investigated the abrasion-erosion resistance of mortar made with rapid-hardening portland and blast-furnace slag cement, with and without silica fume. The mortars were to be used for the repair of hydraulic structures in an Italian hydroelectric power plant. The mortars tested also contained different types of fibers and a HRWRA. The abrasion-resistance test used was ASTM C 1138. Test results showed that the abrasion resistance of the mortar samples increased as the dosage of the silica fume was increased up to 15%. The best comparative abrasion resistance was achieved by the combination of 30% GGBFS, 15% silica fume, steel fibers, and a low *w/cm*.

Horiguchi et al. (1998) studied the effects of silica fume (5, 10, and 15%) on the abrasion-erosion resistance of concrete. Abrasion resistance was measured both by ASTM C 1138 and a nonstandard surface fatigue wear test. The wear depth, as measured by the ASTM test method, decreased by 25 to 35% compared with the control concrete for the silica-fume concrete at 5% dosage. The wear depth decreased by 49% for the concrete containing 15% silica fume. The nonstandard surface fatigue wear test method showed similar performance, wherein wear depth decreased by 20% for 5% silica-fume dosage and by 52% for the 15% silica-fume concrete.

5.3.5 *Fire resistance*—Silica-fume concrete will perform similarly to other low-permeability concrete when exposed to fire. In some cases of extremely low permeability, silica-fume concrete, explosive spalling has been reported. While silica fume content as such is not the governing parameter, the low permeability often associated with a low *w/cm* and silica fume may require preventative measures, such as fiber addition.

A number of researchers have demonstrated that the fire performance of silica-fume concrete is little different from that of conventional concrete (Jensen and Aarup 1996; Dumuolin and Behloul 1998). Properties such as thermal conductivity and specific heat do not change significantly, and there is evidence that properties during the fire and residual properties are actually better for silica-fume concrete. Research (Phan and Carino 2002) indicates that for high-strength concrete, the relative amount of residual strength may be less than that in conventional-strength concrete, but the presence of silica fume does not appear to have a significant effect. This is in part due to the reduced content of CH in concrete with pozzolans, which means that less water is released at high temperatures (Chan et al. 1996, 1999; Saad et al. 1996).

There has been some concern regarding one particular aspect of fire resistance, namely the tendency to spall and the possible correlation to the use of silica fume. Researchers have indicated that there is a greater tendency for spalling and, in some cases, explosive spalling, for concrete containing silica fume with a low *w/cm* (Oredsson 1997; Hertz 1992). Others have reported no increased risk of spalling for silica-fume concrete (Shirley et al. 1988; Jahren 1989; Lennon and Clayton 1999; Hertz 2003). This type of study is complicated because there are a number of parameters influencing the risk of explosive spalling; the more significant of these are permeability, moisture content, stress-strength ratio, and section size. Thus, some of the incidents of explosive spalling reported have been observed on very special concrete with a *w/cm* of less than 0.18, strength in excess of 150 MPa, and with more than 20% silica fume by mass of cement (Hertz 1982). The permeability of this concrete is very low as there are practically no capillary pores, which means that vapor from free water can introduce high stresses during a fire. A similar type of behavior has not been observed on concrete with higher a *w/cm* and, thus, a higher permeability.

There are concerns regarding the fire safety of high-strength, low-permeability concrete (particularly those containing low-density aggregates) in applications where the concrete may not be dry in service. A European research project investigating fire resistance of high-performance concrete (Khoury et al. 1998; Juvas et al. 1999) has indicated that it is the low permeability of this concrete rather than the use of silica fume as such that adds to the risk of explosive spalling. There has been a tradition of comparing concrete with and without silica fume, with little regard for the fact that there is a significant difference in permeability between the concretes. The difference in behavior has, in some cases, been attributed to the difference in silica fume content rather than to the more fundamental parameter of permeability. The aforementioned research project (Khoury et al. 1998; Juvas et al. 1999) compared concretes where equivalent permeability had been achieved with and without silica fume; no increased risk of spalling was observed in concretes with silica fume. Similar observations were made in an extensive Swedish research project (Oredsson 1997), where silica fume contents of up to 7% made no difference to the fire resistance of concrete in the range of *w/cm* tested.

When very low-permeability concrete is used, several measures can reduce the risk of spalling, such as a reduction in moisture content. The beneficial effect of this has been observed (Shirley et al. 1988) for one of the 21,700 psi (150 MPa) concretes mentioned previously, where drying the concrete eliminated the risk of explosive spalling. This reduction in moisture content will also be achieved with normal aging, as the binder content in the concrete is so high that the concrete will self-desiccate.

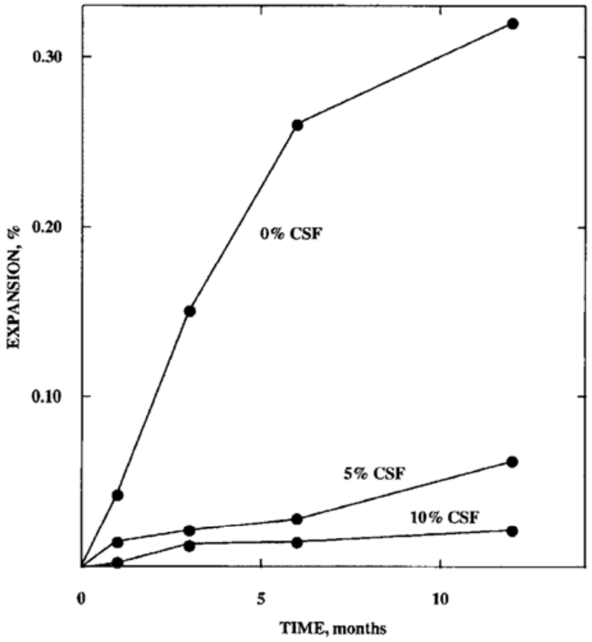

Fig. 5.6—ASR expansion in Iceland (Gudmundsson and Olafsson 1996). (Note: CSF = consolidated silica fume.)

The addition of synthetic fibers is a preventative measure that is being increasingly recommended and used (Breitenbücher 1996; Lennon and Clayton 1999; Nishida et al. 1995). This approach is especially used in off-shore structures, in high-rise buildings, and in tunnels and mines. These types of structures are also typically ones where high-strength, low-permeability concrete is used extensively, and where fire loading is more severe than for a standard building fire. With respect to spalling, it should be noted that fire test standards such as ASTM E 119 do not have spalling (or lack thereof) as a criterion for establishing fire ratings and that the use of fibers to prevent spalling may make it more difficult to achieve high compressive strengths. Refer to ACI 216.1 for more information on fibers and fire resistance of high-strength concrete.

5.3.6 *Alkali-aggregate reaction expansion*—The use of silica fume in sufficient quantity and properly dispersed in concrete, either on its own or in combination with other pozzolans or GGBFS, can be an effective means of combating ASR, as evidenced by decades of field experience in addition to laboratory tests. There is limited evidence, primarily for concrete made in the laboratory, that if not properly dispersed, clumps of silica fume can act as reactive aggregates. Silica fume is not effective in controlling alkali-carbonate reaction (ACR). It is recommended that each source of silica fume be tested with the particular reactive aggregate before use.

The beneficial effects of silica fume on ASR are thought to be largely due to the ability of silica fume to rapidly combine with alkalies present in the pore solutions (Diamond 1983; Page and Vennesland 1983) and incorporate the alkalies as substitutes for calcium in the CSH matrix. The concentration of alkalies in solution is then not sufficient to raise the pH of the pore solution high enough that a reaction

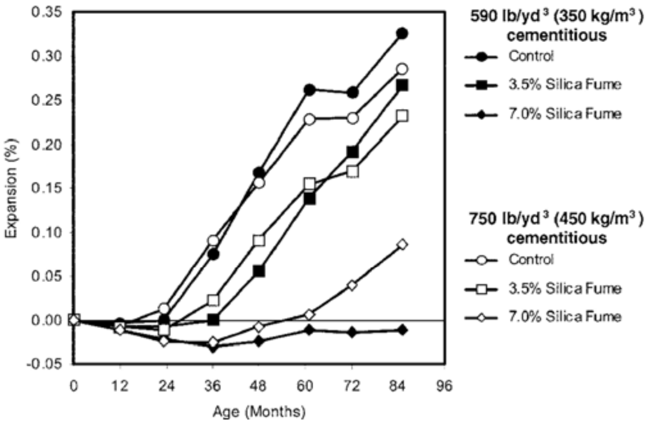

Fig. 5.7—Results of field exposure tests in South Africa (Oberholster 1989).

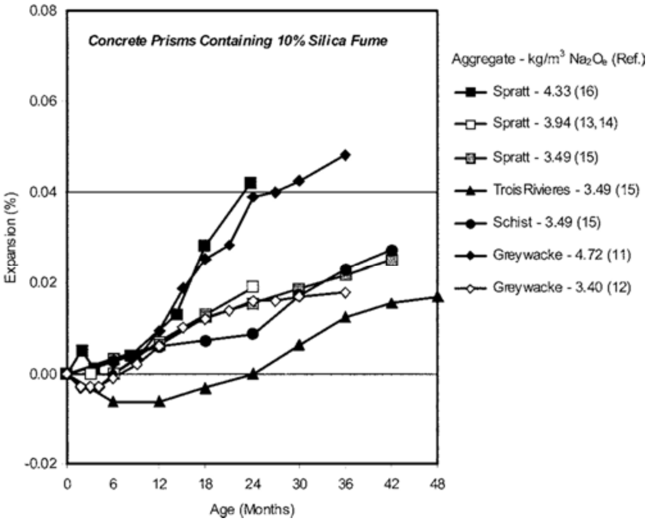

Fig. 5.8—Results of concrete prism tests with Canadian aggregate (Thomas and Bleszynski 2000).

occurs on the reactive silica in the aggregates, resulting in the production of a reactive product that can take up water, swell, and cause damaging expansion. Uchikawa et al. (1989) showed that 10% by mass replacement of portland cement with silica fume tied up almost three times more alkali in the CSH than does portland cement without silica fume. They also found the diffusion rates of alkalies through the pores of concrete incorporating silica fume to be approximately an order of magnitude lower, which would restrict the ability of dissolved alkalies to migrate to reactive aggregate sites.

Since 1979, blended cement containing silica fume interground with high-alkali portland cement (~1.5% Na_2O-equivalent) has been used in Iceland for the purpose of controlling ASR (Asgeirsson and Gudmundsson 1979). Initial production contained 5% silica fume; this was later increased to 7.5%. Figure 5.6 shows the effect of silica fume on the expansion of mortars bars in the ASTM C 227 test with local Icelandic materials (Gudmundsson and Olafsson 1996). The use of silica fume was very effective in reducing expansion in this test, although the expansion eventually exceeded 0.10% (after 4 years). The implication of the long-term expansion in this test is not known, although it is noteworthy that recent surveys indicated no evidence of damage due to ASR in silica-fume concrete after 16 years in field exposure (Gudmundsson and Olafsson 1996).

The National Building Research Institute (NBRI) in the Republic of South Africa conducted a series of field exposure tests with silica fume using 300 mm (12 in.) concrete cubes (Oberholster and Davies 1986; Oberholster 1989). Two series of mixtures were cast with cement contents of approximately 590 and 760 lb/yd^3 (350 and 450 kg/m^3). Within each series, 5 or 10% of the portland cement by mass was replaced with an equal volume of silica fume, resulting in silica fume levels of 3.5 and 7.0% by mass. The active alkali content was maintained at a constant level within a given series by addition of alkali hydroxide (using the same Na_2O/K_2O as the cement), assuming the silica fume to contribute no alkali. The active alkali content for a given mixture is equal to the sum of the active portland-cement alkali (according to ASTM C 311) and the admixed alkali hydroxide. Results of these tests up to 7.4 years are given in Fig. 5.7. The use of 3.5 or 7% silica fume (by mass) delayed the onset of expansion and time to cracking in all cases. Both mixtures with 3.5% silica fume and the higher cement content mixture with 7% silica fume eventually showed deleterious expansion and cracking. The expansion of control specimens with 760 lb/yd^3 (450 kg/m^3) cementitious material exceeded 0.05% after 870 days, whereas specimens from the same series with 7.5% silica fume did not reach this value until 2300 days. Once the onset of expansion was realized, however, the silica-fume specimens appeared to exhibit similar expansion rates as the control specimens. Only the mixture at the lower cement content with 7.5% silica fume failed to expand after 2700 days.

Figure 5.8 (Thomas and Bleszynski 2001) shows expansion data for concrete prisms containing 10% silica fume and a range of reactive Canadian aggregates; the data are compiled from four separate studies. It is apparent that silica fume becomes less effective in controlling expansion due to ASR as the cement content and hence, the alkali content of the concrete increases. These laboratory data are in broad agreement with the field data of Oberholster (1989).

Thomas and Bleszynski (2001) presented a synthesis of published data from laboratory and field studies for the purpose of developing a rational approach for specifying silica fume for controlling expansion due to ASR. They demonstrated that as the alkali content of the concrete increased, a higher level of silica fume was required to control expansion (or pore solution alkalinity). Consequently, they proposed that the minimum level of replacement should be based on the availability of alkalies in the concrete using the following equation:

$$\text{SF (\%)} = k \times \text{alkali contributed by the portland cement}$$
$$\text{(kg } Na_2O\text{-equivalent per cubic meter of concrete)}^*$$

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[*] If alkalis are expressed in pounds per cubic yard, multiply by 0.5933 to get an approximate k value to determine the percentage of silica fume required by this approach.

A value of $k = 2.5$ was suggested as a suitable value for Canadian aggregates (Thomas and Bleszynski 2001). This approach has been adopted by the Canadian Standards Association (CSA A23.1), although the value of k varies (in the range 2.0 to 3.0) depending on the nature of the aggregate, size of the concrete element, exposure conditions, and required service life.

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

Duchesne and Bérubé (1994) showed that silica fume with a relatively low silica content (74.6% SiO_2) was much less effective in controlling ASR expansion than silica fume with a higher silica content (94.2% SiO_2). The low-SiO_2 silica fume also had a much higher alkali content (3.63% Na_2O_e) than the high-SiO_2 silica fume (0.77% Na_2O_e), and thus it is not possible to ascribe differences in performance solely on the basis of the silica content.

The use of silica fume in combination with GGBFS has been found to be effective in reducing both accelerated mortar bar and concrete prism expansions of reactive aggregates as well as reducing pore solution alkalinity (Bleszynski et al. 2000). Similarly, blends of silica fume and both ASTM C 618 Class F and C fly ash have been found to be effective in controlling expansion caused by ASR (Thomas et al. 1999.)

The use of overdensified or pelletized silica fume can result in undispersed agglomerates of silica fume particles, which have been reported to act either as reactive aggregates (Marusin and Shotwell 2000) or to reduce silica fume's effectiveness at a given level of replacement (Hooton et al. 1998).

Caution is urged when mixing silica-fume concrete in laboratory mixers, particularly if the densified form of silica fume is being used. Committee member experience and laboratory research (Lagerblad and Utkin 1993; Pettersson 1992; Rangaraju and Olek 2000; Boddy et al. 2000) have shown problems with satisfactory dispersion of the densified silica fume in paste, mortar, and concrete. Juenger et al. (2004) reported their unsuccessful efforts to produce expansion in mortars using sintered silica fume particles. The mixing and grinding action in many laboratory mixers does not seem to be adequate to ensure dispersion. One method to overcome this tendency when making concrete in the laboratory is to premix the densified silica fume with coarse aggregate for several minutes before batching the remainder of the concrete ingredients. Detailed information on mixing silica-fume concrete in a laboratory mixer may be found in the reference by Holland (2005).

While agglomerates of undispersed silica fume appear far more common in laboratory-mixed specimens, such agglomerates have been reported in hardened field concrete incorporating densified silica fume. Marusin and Shotwell (2000) documented silica-fume agglomerates that had reacted with the pore solution. Gundmudsson and Olafsson (1996, 1999) found agglomerates in cores taken from several structures, but no evidence of ASR occurring in these regions. Baweja et al. (2003) found the presence of silica-fume agglomerates was sporadic and not representative of the concrete as a whole, and did not appear to have had a detrimental effect on the concrete. St. John and Freitag (1996) reported finding agglomerates in high-strength silica-fume concrete, but did not report any expansion.

While some of the data reported shows expansive reaction in the presence of silica-fume agglomerates, no clear evidence exists as to why such expansion occurs on a sporadic basis. It is not surprising that some undispersed silica fume would be present in some hardened concrete. Care needs to be taken to ensure adequate mixing and grinding during concrete production to minimize undispersed material.

Perry and Gillott (1985) reported that silica fume was much less effective in controlling expansion caused by ACR than that caused by ASR. Neither low-alkali cement nor other pozzolans are effective in combating ACR (Rogers and Hooton 1992).

5.3.7 *Sulfate resistance*—Silica fume is very effective in reducing or preventing the attack from sodium sulfate. The primary mechanism by which silica fume improves sodium sulfate resistance is by reduction of permeability, and it may be augmented by reduced calcium hydroxide contents due to pozzolanic reaction. Performance of silica-fume concrete exposed to ammonium sulfate is mixed. Performance when exposed to magnesium sulfate is less than that of paste without silica fume.

The reduced permeability and diffusivity of silica-fume concrete, made possible as a result of pore refinement caused by both the pozzolanic effect and the filler effect of silica fume, would be expected to reduce the transport of sulfate ions into concrete. Because silica fume replacement levels are generally 15% or less, the dilution effect on C_3A would be small. Sellevold and Nilsen (1987) cite 20-year field performance results from Norway. Specimens were placed in a tunnel in alum shale where groundwater sulfate-ion concentrations reached 4 g/L (4000 ppm) with pH of 2.5 to 7.0. In this case, the performance of concrete with a conventional portland cement and a 15% silica fume addition with a w/cm of 0.62 was equal to that of a sulfate-resistant portland-cement concrete with a w/c of 0.50. Khatri et al. (1997), in their work on the role of permeability in sulfate attack, determined that the relative performance of concrete in sulfate attack can be estimated accurately only by combining the effect of permeability with the chemical resistance of the binder. Thus, it is very important to consider that the chemical reactions in sulfate attack can be altered by the presence of silica fume.

When exposed to sodium sulfate solution, performance of concrete is improved by addition of silica fume (Mather 1982; Mehta 1985; Hooton 1993; Cohen and Bentur 1988). Mather (1982) reported tests using mortar bars exposed to sodium sulfate. Three high C_3A cements (14.6, 13.1, and 9.4% C_3A) were used alone and with 30% replacement of

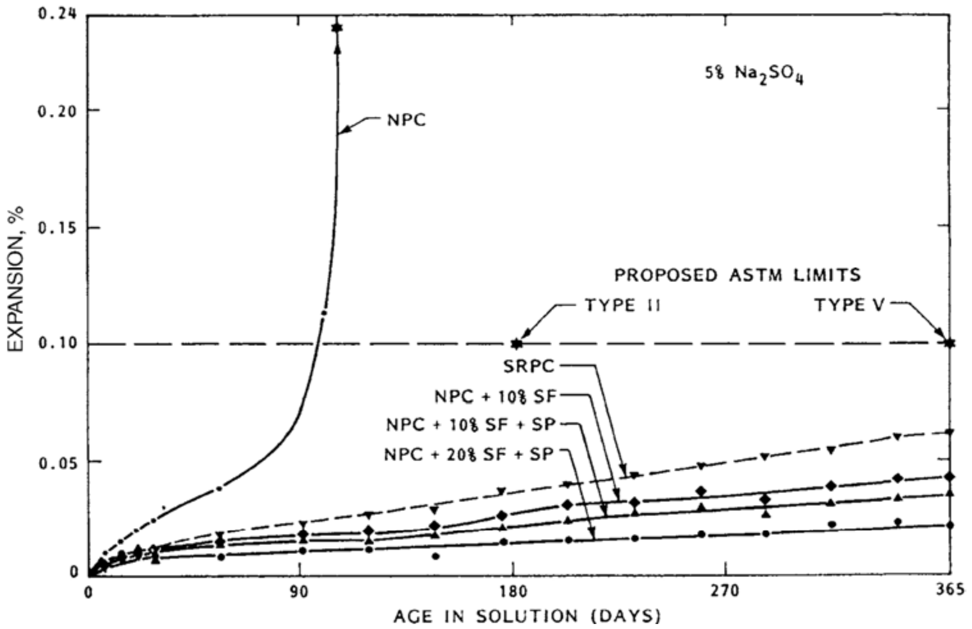

Fig. 5.9—ASTM C 1012 sulfate resistance of silica fume mortar bars, flow 115 ± 5 (Hooton 1993). (Note: SRPC = sulfate-resisting portland cement; NPC = normal portland cement; SF = silica fume; SP = superplasticizer [HRWRA]).

various pozzolans. The greatest sodium sulfate resistance was obtained with silica fume. The use of silica fume with ASTM C 150 Type I portland cement has the effect of improving its performance to levels similar to those of ASTM C 150 Type V portland cement (Mather 1982; Hooton 1993; Cohen and Bentur 1988). In Fig. 5.9, mortar bars containing 10% silica fume tested using ASTM C 1012 employing sodium sulfate as the sulfate source are shown to be as resistant as those containing a sulfate-resistant portland cement, even though the C_3A content of the cement was 11.8% (Hooton 1993). Similar results were obtained by Buck (1988) for a cement containing 15% C_3A.

Carlsson et al. (1986) examined the use of 5% silica fume in concrete mixtures intended for use in pipes. They exposed the specimens to a 10% sodium sulfate solution for 92 weeks. The silica-fume concrete exhibited less mass loss, leading the authors to conclude that pipes made from the silica-fume concrete would have two to three times the life expectancy of the same concrete without silica fume.

Performance of silica fume exposed to ammonium sulfate is mixed. Popovic et al. (1984) showed improved resistance of silica-fume mortars, whereas Mehta (1985) showed no improvement in concrete.

In very high concentrations of magnesium sulfate (equivalent to a 4.5% SO_3 solution), silica fume impaired the performance of the pastes made with both ASTM C 150 Types I and V portland cements (Cohen and Bentur 1988). Apparently, the consumption of calcium hydroxide due to reaction with silica fume is detrimental to the durability of samples exposed to high concentrations of magnesium sulfate. In the initial stages of attack, the reaction of calcium hydroxide with magnesium sulfate forms a layer of brucite (magnesium hydroxide) on the surface of the mortar/concrete, reducing further ingress of the sulfate solution. Reduction in the quantity of calcium hydroxide by silica fume results in a thinner brucite layer or, sometimes, the complete absence of the layer. Under these circumstances, the sulfate solution is able to attack the CSH gel directly, leading to a decomposition of its structure. This process is known as decalcification (Cohen and Bentur 1988; Bonen and Cohen 1992), primarily because it is characterized by a significant reduction (below 1.0) in the $CaO:SiO_2$ ratio of the CSH gel. In extreme cases, a conversion of CSH to the reportedly non-cementitious magnesium silicate hydrate is also possible (Bonen 1993).

5.4—Miscellaneous properties

5.4.1 *Electrical resistivity*—Using silica fume increases the electrical resistivity of concrete, with the increase being related to the amount of silica fume used. The increase in resistivity can be expected to decrease or eliminate corrosion current.

Corrosion of reinforcement in concrete is an electrochemical process, and concrete containing moisture is a semiconductor. Corrosion currents are encountered in steel-reinforced concrete under chloride attack in deicing and marine environments. Generally, the likelihood of corrosion occurring varies with the inverse of resistivity: as resistivity increases, the rate of corrosion decreases (Gannon and Cady 1992).

The resistivity of concrete depends primarily on the pore structure within the material, the moisture and ion content within the pores, and temperature (Gannon and Cady 1992). The saturated, 73 °F (23 °C) resistivity of well-cured concrete used in construction can vary by more than a factor of 10. A typical 4000 psi (27.5 MPa) concrete without silica fume has a saturated, 73 °F (23 °C) resistivity in the range of 1600 to 3900 ohm-in. (4000 to 10,000 ohm-cm), while specialty concrete, especially very low *w*/*cm* concrete containing more than 9% silica fume by mass of cement, has a saturated, 73 °F (23 °C) resistivity in excess of 39,000 ohm-in.

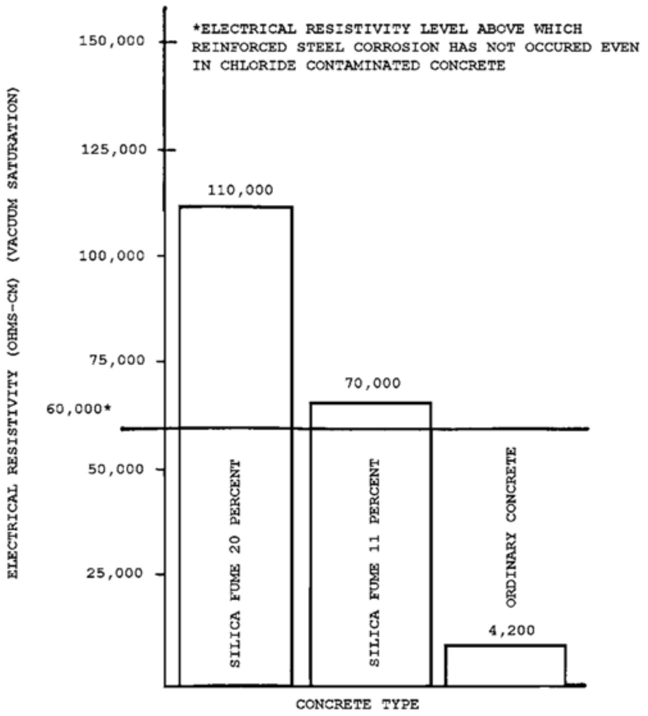

Fig. 5.10—Electrical resistivity as measured during AASHTO T 277 (ASTM C 1202) testing for various silica fume contents (Wolsiefer 1991). (Note: 1 ohm-cm = 0.394 ohm-in.)

(100,000 ohm-cm) (see data in the next paragraph). Tremper et al. (1958) noted that field concrete with resistivity in excess of approximately 24,000 ohm-in. (60,000 ohm-cm) showed little corrosion-induced distress after long-term exposure to severe salt environment, and Broomfield et al. (1994) defined concrete with low corrosion rates as those with resistivity in excess of 20,000 ohm-in. (50,000 ohm-cm).

At present, there is not an ASTM standard resistivity test for concrete. Data have, however, shown that resistivity is inversely proportional to the ASTM C 1202 values (Berke and Roberts 1989). Figure 5.10 shows electrical resistivity data, as measured by the ASTM C 1202 test, for a silica-fume concrete at 11 and 20% addition of silica fume by mass of cement. The concrete without silica fume yielded a saturated 73 °F (23 °C) resistivity of 1700 ohm-in. (4200 ohm-cm), the 11% silica-fume concrete yielded 28,000 ohm-in. (70,000 ohm-cm), and the 20% silica fume dosage showed a resistivity of 43,000 ohm-in. (110,000 ohm-cm) (Wolsiefer 1991). After 90 days of moist curing, other 20% silica-fume concretes exhibited 73 °F (23 °C) resistivity in excess of 120,000 ohm-in. (300,000 ohm-cm) (Wolsiefer and Clear 1995).

Other published data indicating that silica-fume concrete has high electrical resistance to the passage of corrosion current include Berke and Roberts (1989), Berke (1989), and Berke and Weil (1988). Berke et al. (1991) presented resistivity data for concrete containing silica fume or silica fume and fly ash. At 28 days, a concrete with 600 lb/yd^3 (355 kg/m^3) of cement, 75 lb/yd^3 (44.5 kg/m^3) of silica fume (12.5%), and a *w/cm* of 0.47 had a resistivity of 20,300 ohm-in. (51,750 ohm-cm).

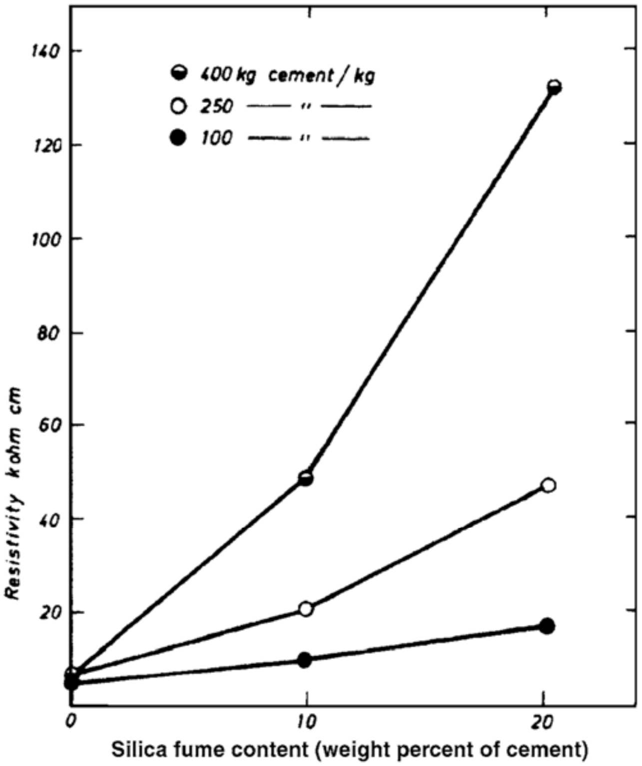

Fig. 5.11—Effect of silica fume on the electrical resistivity of concrete (Vennesland and Gjørv 1983). (Note: 1 ohm-cm = 0.394 ohm-in.)

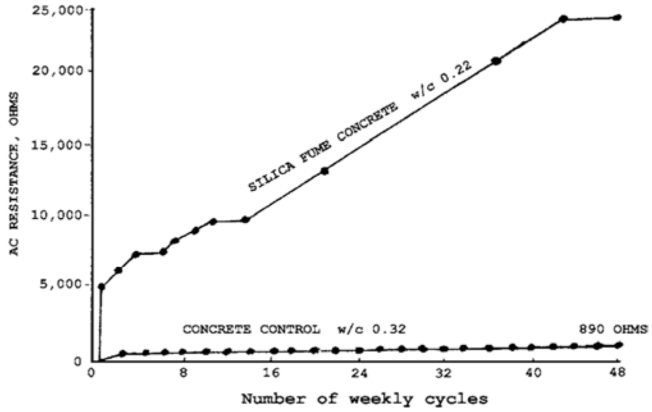

Fig. 5.12—Alternating-current resistance of concrete containing 20% addition of silica fume (Wolsiefer 1991).

Vennesland and Gjørv (1983) measured electrical resistivity by embedding an isolated steel plate in the middle of an insulated concrete cylinder. The test cylinder was immersed in water with counter electrodes, and an AC bridge was used to measure electrical resistivity. Figure 5.11 shows the resistivity data for three concrete mixtures each with 0, 10, and 20% silica fume addition by mass of cement. Correlation with Vennesland and Gjørv's data is seen with an electrical resistivity of 50,000 ohm-in. (127,000 ohm-cm) for a comparable mixture (675 lb/yd^3 [400 kg/m^3] cement, 143 lb/yd^3 [85 kg/m^3] silica fume, 21% by mass of cement.) Electrical resistivity is improved, and the increased resistivity is more pronounced at high strengths. The improvement is due to the effect of silica fume in lowering the ion concentration in the pore solutions and providing a more discontinuous capillary pore structure (Sellevold and Nilsen 1987).

Figure 5.12 shows that the AC resistance for a silica-fume concrete sample (prepared with a dry silica-fume admixture, at 20% addition by mass of cement), increased from 5000 ohms to 25,000 ohms during the course of the 48-week exposure to a 15% sodium chloride solution. The corresponding control concrete remained constant at 890 ohms. These data, along with simultaneous corrosion current measurements, tend to indicate that the silica-fume concrete was not a conductor of corrosion current (Wolsiefer 1991). Converting resistance to resistivity, the aforementioned 20% silica-fume concrete exhibited a resistivity after 23 southern-exposure cycles of 50,000 ohm-in. (673,000 ohm-cm). Macrocell corrosion currents were zero (Wolsiefer and Clear 1995).

Wolsiefer and Clear (1995) found that 7-year-old, 12 to 22% silica-fume concrete (very low *w*/*cm*) exposed to weathering (including freezing and thawing) in Northern Virginia exhibited saturated, 73 °F (23 °C) resistivity values in the range of 177,000 to 612,000 ohm-in. (449,000 to 1,554,000 ohm-cm) as silica fume dosage increased. These 7-year exposure resistivity values were more than double those measured after 42 days of moist curing.

Christensen et al. (1992a) measured the electrical properties of cement paste using impedance spectroscopy. They found that additions of silica fume to cement paste substantially increased the electrical resistivity. Christensen et al. (1992b) found only modest increases in bulk resistance due to the addition of silica fume to cement paste for the first 100 hours of hydration, after which the silica fume cement pastes exhibited substantial increases in resistance. The effect was more pronounced with increased dosages of silica fume. The authors attributed this observation to the development of discontinuity of the pore structure.

5.4.2 *Thermal properties*—Published data on thermal properties are scarce. The committee is not aware of any effect of silica fume on thermal properties because such properties depend primarily on the thermal characteristics of the aggregate. One study (Van Geem et al. 1997) found that the values of thermal conductivity, thermal diffusivity, and specific heat for high-strength concretes containing silica fume were generally similar to the values for conventional-strength normalweight concretes. Heat of hydration is covered in Chapter 3.

5.4.3 *Silica-fume concrete and cracking*—Silica-fume concrete is usually high strength and has a low *w*/*cm*. Such concrete can be susceptible to two basic types of cracking. First, there is early-age cracking relating to the material itself and to construction practices. This form of cracking is reasonably well understood, and appears to be controlled by adopting appropriate construction practices. Second, there is later-age cracking that is apparently related to performance under load. This form of cracking is not well understood.

5.4.3.1 *Early-age cracking*—The ability of concrete to perform its intended function may be compromised by excessive cracking. The tendency for early cracking of concrete—with or without silica fume—depends on a number of factors. Volume changes in concrete caused by autogenous shrinkage, plastic shrinkage, drying shrinkage, temperature change, and creep are extremely important because of their effects on its tendency to crack. Prediction and control of early-age cracking are difficult because of complex interactions among the factors mentioned above and the degree of restraint, the developing stiffness, and the developing tensile strength.

Concrete cracks when and where the tensile stress exceeds the tensile strength. Thus, high tensile strength increases resistance to cracking. The tensile stresses that cause cracking in the first few days after placement can be reduced by reducing the modulus of elasticity; by reducing the strains due to temperature change and autogenous, plastic, and drying shrinkage; or by controlling the temperature of the hardening concrete or the temperature difference between the new structure and the substrate.

As is discussed in Chapter 3, silica fume results in a refinement of the pore structure with a consequent increase in the number and reduction in size of the menisci, thus increasing the early-age autogenous shrinkage. Sellevold et al. (1995) observed that even with good curing, cracks might develop because of chemical shrinkage and self-desiccation with low *w*/*cm* concrete.

The work of Springenschmid et al. (1995) indicated that silica-fume concrete may be more susceptible to cracking at a moderate *w*/*cm* of approximately 0.50 because of self-desiccation.

Kanstad et al. (2001) measured the tensile strength, modulus of elasticity, thermal expansion, and autogenous shrinkage for concrete with and without silica fume and incorporated their results into a mathematical model to predict the cracking behavior. They found that the autogenous shrinkage of silica-fume concrete within the first 2 or 3 days is greater than for concrete without silica fume, consistent with the findings of Springenschmid et al. (1995). When the other factors contributing to cracking were taken into account, however, such as development of tensile strength, they found that silica-fume concrete is no more likely to crack than concrete without silica fume.

Whiting and Detwiler (1998) and Whiting et al. (2000) studied the effects of *w*/*cm* and silica fume content on the tendency of concrete to crack under conditions of full restraint. The concrete mixtures were typical of concrete for full-depth bridge decks and bridge deck overlays. The *w*/*cm* ranged from 0.35 to 0.45 for the full-depth concrete, and from 0.30 to 0.40 for the overlay concrete. Silica fume contents ranged from 0 to 12% replacement of cement. They found that the concrete's tendency to crack was highly sensitive to the length of the curing period. For concrete that was moist cured for only 1 day, the tendency to crack increased with the silica-fume content. For concrete that was moist cured for 7 days, there was no relationship between silica fume content and tendency to crack. They recommended that specifications for silica-fume concrete bridge decks require 7-day, continuous moist curing.

There are several means for reducing the tendency of silica-fume concrete to crack. The specifier should select those that are most appropriate for the application, considering the importance of minimizing cracks and the cost. Air entrainment reduces the cracking sensitivity by increasing the tensile strain capacity and reducing the modulus of elasticity in the hardened concrete; thus, it both increases the resistance to stress and reduces the stress. For this reason, Springenschmid et al. (1995) recommended entraining 4 to 6% air even in concrete not subjected to freezing. The selection of an aggregate with a low coefficient of thermal expansion will minimize thermal strains. Aggregate with the largest possible maximum size and optimized particle-size distribution will minimize the paste content, minimizing the strains due to autogenous, plastic, and drying shrinkage and heat of hydration. The use of sufficient ASTM C 618 Class F fly ash or ASTM C 989 GGBFS can reduce both the heat of hydration and the modulus of elasticity at early ages. The specified strength of the concrete should be no higher than necessary and should not develop earlier than necessary to minimize the modulus of elasticity at early ages and reduce the early-age volume changes. Construction practices for minimizing cracking are discussed in Chapter 9.

5.4.3.2 *Later-age cracking*—The committee is aware of instances in which cracking in silica-fume concrete has been seen after the concrete has been placed into service. This type of cracking has been particularly prevalent in long-span steel bridges, both in full-depth placements and in overlays with high-durability and high-strength concrete. The committee is not aware of research or publications in this area. The cracking may be a function of the increased modulus of the concrete, which will change the structural response of the structure under dynamic loading.

5.5—Use of silica fume in combination with fibers

Silica fume has been used in combination with a wide variety of fibers used in concrete. The consensus of the data reported is that the combination produces positive results. Given the many different types of fibers used and the various concrete properties evaluated, however, it is difficult to draw specific conclusions. The reader is cautioned to examine the data for a specific application. The following is a sampling of reported findings.

Bentur and Diamond (1985) demonstrated that pretreatment of alkali-resistant glass fibers with a silica-fume slurry before their incorporation in a cementitious matrix was an effective means of improving the resistance to alkali (hydroxyl) attack of glass-fiber-reinforced composite. The improvement was found to be dependent on the extent of penetration of the silica-fume slurry into the spaces between the glass fiber filaments during the slurry pretreatment. Composites prepared after such treatment did not lose any flexural strength over an accelerated alkali attack period of 5 months, and the usual decline in toughness resulting from akali attack was arrested.

Naaman and Al-Khairi (1994) conducted an extensive study on high early-strength (at least 5000 psi [35 MPa] in 24 hours) fiber-reinforced concrete made with silica fume and either steel or polypropylene fibers or hybrid combinations of the two fiber types. Optimized mixtures satisfied the minimum strength criteria and provided enhanced values of flexural strength, toughness in bending, and fatigue life in the cracked state. Such mixtures were considered suitable for applications in repair and rehabilitation as well as construction of transportation structures.

Chern and Chang (1994) carried out an investigation into the long-term deformation of steel fiber-reinforced concrete containing silica fume. They demonstrated that the combined effects of fibers and silica fume resulted in a reduction in creep and shrinkage and enhanced development of compressive strength.

Igarashi and Kawamura (1994) demonstrated that the addition of short carbon fibers to mortar containing silica fume and steel fibers was effective in producing greater flexural strength and toughness in the composite.

Kawamura and Igarashi (1995) conducted a study of the fracture of the interfacial zone between steel fiber and the cementitious matrix under pullout loading. They demonstrated that the incorporation of silica fume in the mixture resulted in a reduction in the number of areas containing local failures along the fiber/matrix interface.

Denarie and Houst (1995) studied the effects of additions of silica fume, polypropylene fibers, and a HRWRA on moisture diffusivity of repair mortars. They found that the addition of these products, in conjunction with air entrainment, had a positive combined effect in reducing moisture diffusivity.

Jamet et al. (1995) conducted a study on high compressive strength (10,000 psi [70 MPa]) concrete made with silica fume and hooked-end steel fibers. They found that 1% by volume of steel fiber addition significantly increased the fracture energy of high-strength concrete.

Balaguru and Folden (1996) conducted a study on fiber-reinforced structural low-density concrete incorporating silica fume and various lengths and addition rates of steel fibers. Fiber lengths included 2 and 2.4 in. (50 and 60 mm) long fibers, and fiber addition rates were 75, 100, and 150 lb/yd^3 (45, 60, and 90 kg/m^3). They demonstrated that low-density concrete with a density of 100 lb/ft^3 (1650 kg/m^3) attained a compressive strength of about 6000 psi (42 MPa). The combination of silica fume and fibers was found to substantially increase flexural and splitting tensile strengths and produce concrete with increased ductility.

Morgan et al. (1998) carried out repairs to deteriorated shipping berth faces at the Port of Montreal, Quebec, using combinations of silica fume and steel or polyolefin fiber-reinforced shotcrete. The steel fiber was added at 0.75% volume and the polyolefin fiber at 1.26% volume. Both systems produced tough, durable, pseudoductile shotcrete repairs.

5.6—Use of silica fume in ternary blends

The use of ternary blends (incorporating portland cement, silica fume, and either fly ash or GGBFS) has been on the increase in the last few years. This section reviews performance of these blended materials.

5.6.1 *Use of silica fume in conjunction with fly ash*—Silica fume is being used extensively in combination with fly ash. Data from both research and applications indicate that this combination performs well, with some reports indicating that the combination works better than either material alone.

A number of researchers have studied combinations of fly ash and silica fume. The primary research objectives have been two-fold: to offset the reduced early strength typical of ASTM C 618 Class F 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 3.)

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

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

Mehta and Gjørv (1982) and Carette and Malhotra (1983b) found that the combination of pozzolans could offset the reduction of early strength caused by the use of ASTM C 618 Class F fly ash alone.

Maage (1986) examined combinations of portland cement, fly ash, and silica fume for influence on strength and heat development. He also investigated the effect of these combinations on the maturity functions of the concrete. Silica fume was used as a replacement material in concrete in which the cement content was reduced to maintain essentially constant 28-day compressive strength. He reported that the early-age strength of the concrete containing silica fume was reduced, with increasing fly-ash contents resulting in greater early-age strength reductions. For concrete with silica fume, heat generation per unit mass of cement plus silica fume was higher than without silica fume. For concrete cured at 68 ºF (20 °C), maturity calculations were found to be valid for up to 2 to 3 days of equivalent curing time. Concerning the durability of this concrete, Maage (1987) investigated water permeability, frost resistance, sulfate attack, carbonation, chloride diffusion, pH of pore water, and electrical resistivity. He concluded that silica fume worked in combination with the blended cements in approximately the same manner as with concrete containing only portland cement.

Thomas et al. (1999) found the combination of silica fume and low-CaO (<8%) ASTM C 618 Class F fly ash complementary, with the silica fume improving the early-age performance of concrete and the fly ash refining the properties of the hardened concrete as it matures. The shortcomings of high-CaO fly ash, in terms of controlling ASR and sulfate resistance, can be compensated for by adding relatively small quantities (5%) of silica fume. It was further reported that combinations of 3 to 5% silica fume with 20 to 30% high-CaO (>20%) ASTM C 618 Class C fly ash showed satisfactory performance in both ASR and sulfate expansion tests. These combinations produced concrete with generally excellent properties and offset the problems associated with using increased amounts of high-CaO fly ash or silica fume required when these materials are used independently. Many of these benefits are attributed to reductions in permeability and ionic diffusivity in the system. Indeed, the ternary cement system showed dramatically increased resistance to chloride-ion penetration compared with either a binary cement system (with either fly ash or silica fume), or especially a system with only portland cement (Thomas et al. 1999).

Gautefall (1986) examined the chloride-diffusion rates in pastes made from portland cement and a blended cement containing 10% fly ash, both with silica fume contents ranging from 0 to 15%. He found that the addition of silica fume led to a marked decrease in chloride diffusivity, more so for the portland cement than for the blended cement. McGrath and Hooton (1997) found that diffusion coefficients of silica-fume mixtures alone could be reduced with ternary blends of fly ash and silica fume. Streeter (1996) developed bridge deck mixtures for the state of New York containing 20% ASTM C 618 Class F fly ash and 6% silica fume by mass of cementitious materials. In addition to the increase in ultimate strength, the resultant concrete showed a 70 to 80% reduction in ASTM C 1202 results over the control mixture. In 1998, the New York State Department of Transportation began using this mixture, combining cement, fly ash, and silica fume, in all new bridge decks and deck rehabilitation projects.

When used with fly ash, silica-fume concrete mixtures have been found to be more resistant to sulfate attack than sulfate-resisting cement (Carlsen and Vennesland 1982; Fidjestøl and Frearson 1994).

Wakeley and Buck (1986) examined grouts containing American Petroleum Institute (API) Class H cement (similar to a coarsely ground sulfate-resisting portland cement), an expansive agent, fly ash (an ASTM C 618 Class C and Class F ash were tested), and silica fume. They examined compressive strength, volume change, phase composition, and microstructure. They found some differences in performance with the different ashes, but concluded that the properties of the grouts were markedly similar. Seabrook (1987) has described the use of fly ash and silica fume in a grout for use in ducts in post-tensioned concrete. He developed a grout that was superior in absorption, shrinkage, bleeding, and corrosion resistance over the neat cement grout.

5.6.2 *Use of silica fume in conjunction with GGBFS—* Silica fume is also being used increasingly in combination with GGBFS. Data indicates that this combination is also performing well.

In Ontario, widespread use of GGBFS resulted in commercial use of ternary systems of GGBFS with silica fume as early as 1986 in high-strength concrete applications (Thomas et al. 1998).

Silica fume and GGBFS ternary systems have been demonstrated in laboratory testing to exhibit reduced chloride diffusivity (McGrath and Hooton 1997), produce lower ASTM C 1202 values (Ozyildirim 1994), and very low permeability to water (El-Dieb and Hooton 1995).

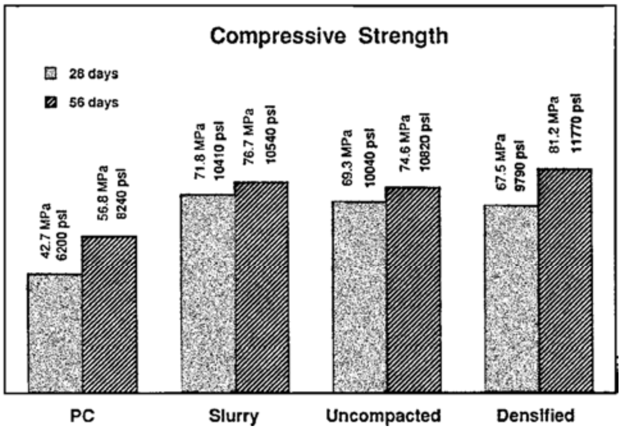

Fig. 5.13—Twenty-eight- and 56-day compressive strengths of plain concrete and concretes containing various forms of silica fume (Cohen and Olek 1989).

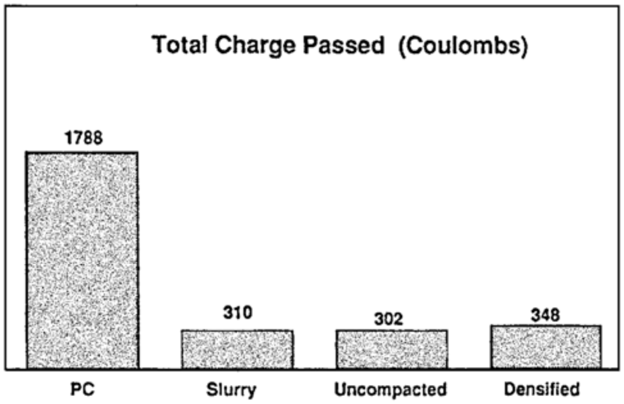

Fig. 5.14—Total electric charge passed during ASTM C 1202 testing of plain concrete and concretes containing various forms of silica fume (Cohen and Olek 1989).

Such ternary systems have been effective in preventing deleterious expansion due to alkali-silica reactivity (Bleszynski et al. 2000).

When used with GGBFS, silica-fume concrete mixtures may be more resistant to sulfate attack than sulfate-resisting cement (Carlsen and Vennesland 1982; Fidjestøl and Frearson 1994).

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

The product form of silica fume (as-produced, slurried, and densified) used in concrete does not seem to affect the performance of the concrete. No product form appears to outperform any other product form.

Cohen and Olek (1989) studied the effects of the form of silica fume (as-produced, slurried, and densified) on properties of unreinforced concrete containing 9% silica fume, while Fidjestøl et al. (1989) used 11 and 15% silica fume by mass of portland cement. Results from both studies indicated that at the age of 28 days, the slurried and as-produced silica fumes provided somewhat more compressive strength than did the densified material. The 56-day compressive strength of the concrete containing the densified silica fume somewhat exceeded those of the concrete containing the other forms of silica fume, as shown in Fig. 5.13 (Cohen and Olek 1989).

Results from measurements made in accordance with ASTM C 1202 indicate that all forms of silica fume tend to increase resistance to chloride ingress to about the same level as shown in Fig. 5.14 (Cohen and Olek 1989; Fidjestøl et al. 1989).

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

Wolsiefer et al. (1995) reported that there were no significant differences in the mechanical and durability characteristics of concrete incorporating different silica fume product forms (undensified, densified, slurry or incorporated in blended cements). The mechanical properties tested included compressive and flexural strengths and drying shrinkage. The durability-related properties included depth of carbonation and ASTM C 1202 tests.

Hooton et al. (1998) found that the effectiveness of densified (39 lb/ft^3 [630 kg/m^3]) silica fume in reducing expansion due to ASR using ASTM C 1260 was about the same as for undensified silica fume, but that unground, pelletized silica fume (not normally used in concrete) was far less effective. Similar results were reported for ASTM C 1260 and C 1293 expansions except that both slurried and undensified silica fume were effective at about 2% less cement replacement then for densified silica fume (Boddy et al. 2000).

CHAPTER 6—APPLICATIONS OF SILICA FUME IN CONCRETE

Silica fume was introduced to the concrete market in the mid to late 1970s. The use of the material increased during the 1980s and 1990s. During this period, silica-fume concrete became recognized for high strength and low diffusivity. Silica fume is currently widely used to produce high-performance concrete. The committee estimates that nearly 8,000,000 yd^3 (more than 6,000,000 m^3) of silica fume concrete are produced globally each year. This large volume of concrete placed annually is used in a variety of applications. This chapter presents a few of the more significant projects where silica-fume concrete has been used. 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.

6.1—Tsing Ma Bridge, Hong Kong

The Lantau Link is composed of the Tsing Ma suspension bridge (Fig. 6.1) linking Tsing Yi to Ma Wan; viaducts crossing Ma Wan; and the Kap Shui cable-stayed bridge linking Ma Wan to Lan Tau. The Tsing Ma Bridge has become a major Hong Kong landmark. Its main span of 4500 ft (1377 m) is the world's longest, carrying both road and rail, and its concrete towers are 675 ft (206 m) tall. Construction of Tsing Ma Bridge began in May 1992, and was completed in May 1997. Other statistics for this bridge are:

Fig. 6.1—Tsing Ma Bridge, Hong Kong.

Fig. 6.2—311 South Wacker Dr., Chicago, Ill.

- Total length: 7200 ft (2200 m);
- Shipping clearance: 203 ft (62 m); and
- Volume of concrete: 650,000 yd^3 (500,000 m^3)

All of this concrete contains GGBFS and silica fume for fresh and hardened concrete properties.

6.2—311 South Wacker Drive, Chicago

Built between 1988 and 1990, 311 South Wacker Drive (Fig. 6.2) in Chicago has 65 floors above ground, for a total height of 961 ft (293 m). When completed, it was the world's tallest reinforced concrete building. The complete plan for the block of 311 South Wacker featured three identical towers, all facing inward. Currently, there is only one tower, with the two side plots reserved for future development. Silica-fume concrete was used mainly to provide 12,000 psi (83 MPa) (Robison 1988).

Fig. 6.3—Kuala Lumpur City Center, Malaysia.

6.3—Kuala Lumpur City Center, Malaysia

Kuala Lumpur City Center (Fig 6.3), also known as Petronas Towers, were, at the time of completion in 1997, the tallest buildings in the world at 95 stories and 1480 ft (452 m). Each tower building contains 2.3 million ft^2 (218,000 m^2) of development space. The buildings used high-performance silica-fume concrete of 11,600 psi (80 MPa) in the lowest levels of columns, core walls, and ring beams to minimize column and wall size. The mixture proportions were:

- Portland cement: 473 lb/yd^3 (260 kg/m^3);
- Blended cement (20% fly ash): 437 lb/yd^3 (260 kg/m^3);
- Silica fume: 50 lb/yd^3 (30 kg/m^3); and
- HRWRA: 2 gal./yd^3 (10 L/m^3).

The design cube compressive strength was 11,600 psi (80 MPa) at 56 days; the average field cube strength was 15,000 psi (105 MPa) at 56 days (Thornton et al. 1997).

6.4—Kinzua Dam Stilling Basin, United States

One of the first major applications of silica-fume concrete in the United States was for repair of hydraulic structures subjected to abrasion-erosion damage. The concrete in the stilling basin slab of Kinzua Dam (Fig. 6.4) in western Pennsylvania was severely damaged by abrasion erosion and was repaired with 18% silica-fume concrete with a compressive strength over 13,000 psi (90 MPa) at 28 days (Holland et al. 1986). A 10-year performance assessment (Luther and Halczak 1995) indicated that the silica-fume concrete was performing well and projected a 20-plus year service life, as opposed to the previous 7-year life of conventional portland-cement steel-fiber reinforced concrete. Recent diver inspections found up to 8 in.(200 mm) wear in some areas of the slab after 18 years. Thus, the anticipated 20-year service life will likely be exceeded.

6.5—Stolma Bridge, Norway

A number of lightweight aggregate bridges have been built in Norway over the last decade. A common denominator is the use of silica fume to prevent segregation of the fresh concrete and to increase the chloride resistance of the hardened concrete. Stolma Bridge (Fig. 6.5), built in 1998, has the world's longest span of 988 ft (301 m) built by the balanced cantilever construction method. Located on the West Coast of Norway, the bridge links two islands in an archipelago southwest of Bergen.

Fig. 6.4—Kinzua Dam, Pennsylvania.

6.6—Highway bridges, United States

A Federal Highway Administration (FHWA) program designed to introduce state department of transportation engineers to the long-term benefits of high-performance concrete has incorporated the use of silica-fume concrete for precast bridge elements. The following are several examples of these bridges.

In Colorado, silica-fume concrete was used to produce pretensioned box beams for the I-25 Yale Avenue overpass (Leonard 1999) (Fig. 6.6). The concrete compressive strength was 10,000 psi (69 MPa) at 56 days. The high-strength concrete allowed a reduction in required number of spans compared with conventional technology and reduced the depth of the beams, resulting in an increase in headroom. The composition of the concrete is shown below:

- Portland cement, Type I: 730 lb/yd^3 (433 kg/m^3);
- Silica fume: 35 lb/yd^3 (21 kg/m^3);
- *w/cm*: 0.29;
- HRWRA: 0.3 to 1.0 gal./yd^3 (1.7 to 5.1 L/m^3);
- WRA: 0.1 to 0.4 gal./yd^3 (0.6 to 2.2 L/m^3); and
- Required strength: 10,000 psi (70 MPa).

The New Hampshire Department of Transportation used silica-fume concrete to produce 8000 psi (55 MPa) at 28 days, and a chloride-ion penetration value of less than 1000 coulombs (ASTM C 1202) for Type III AASHTO prestressed concrete I-girders and New England bulb-tee girders (Waszczuk and Juliano 1999). In this case, the high-strength concrete allowed a reduction in the number of girders required for the bridge.

The Ohio Department of Transportation designed a single-span 117 ft (36 m) prestressed concrete box-beam bridge composed of 12 side-by-side 48 x 42 in. (1219 x 1067 mm) deep beams. The beams were designed for 6000 psi (41 MPa)

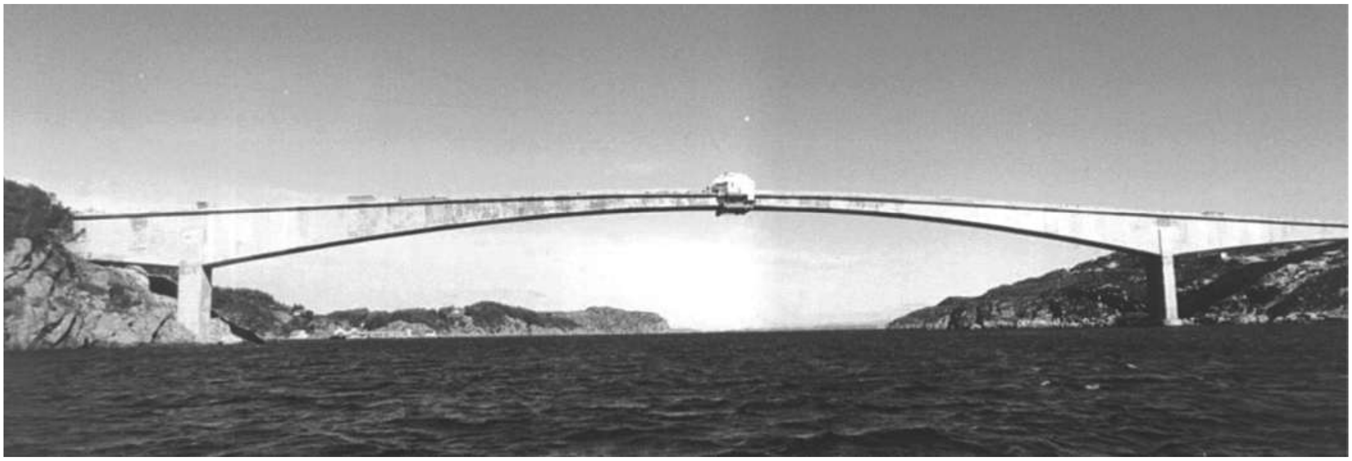

Fig. 6.5—Stolma Bridge, Norway. (Photo courtesy of Bergens Tidende, photographer: J. M. Lillebø.)

Fig. 6.6—I-25 Overpass, Denver, Colo.

Fig. 6.7—Administration Parking Garage at University of Cincinnati, Ohio.

Fig. 6.8—Town Pavillion Parking Garage, Kansas City, Mo.

release and 10,000 psi (69 MPa) 56-day strengths and less than 1000 coulomb ASTM C 1202 results (Miller 1999). The single-span bridge replaced a three-span bridge, and eliminated the requirement for construction of piers in the river.

The Nebraska Department of Roads used silica-fume concrete to produce 12,000 psi (83 MPa) at 56 days, bulb-tee girders for three equal spans of 75 ft (22.9 m) having a total width of 84.7 ft (25.8 m). The high-performance concrete ($w/cm = 0.28$) used a ternary blend of cement, fly ash, and silica fume (Beacham 1999). This bridge opened to traffic in 1996. Silica-fume concrete was used in the girders and on the deck of this bridge. An identical bridge using conventional concrete was constructed nearby this project. The two bridges will be monitored to determine the benefits of the high-performance concrete.

6.7—Parking structures, United States

A major application of silica-fume concrete for corrosion protection is in parking structures, both for cast-in-place and precast concrete. Specifications for silica-fume concrete parking structures have often included testing for resistance to chloride-ion penetration according to ASTM C 1202. The Administration Parking Garage at the University of Cincinnati, Ohio (Fig. 6.7), and Town Pavilion Parking Garage, Kansas City, Mo. (Fig. 6.8), serve as examples of this type of structure.

CHAPTER 7—SPECIFICATIONS

7.1—General

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

7.2—Specifying silica fume

7.2.1 *Properties of silica fume*—At this time there are no universally accepted requirements for specifying silica fume for use in concrete. Initially, specifications for silica fume in concrete were developed to meet specific project requirements based primarily on recommendations from the suppliers. More recently, a number of consensus standards have been developed worldwide to address silica fume. A report prepared by the International Union of Testing and Research Laboratories and Materials and Structures (RILEM) Technical Committee 73-SBC (1988) states that, to ensure quality mineral additions[*] for use in concrete, it is necessary to test the following: loss on ignition, moisture content, fineness, water requirement for standard consistency, and activity index. Currently available standards typically include these elements, as well as others of national origin. At present, the standards available specify silica fume in a manner similar to that used for other pozzolanic materials. Several of the standards available for specifying silica fume are described in the following sections.

7.2.2 *United States standards*—The first specifications in the United States were those developed for specific projects. Typically, these specifications called for the use of silica fume meeting certain minimum chemical and physical requirements, such as SiO_2 content, loss on ignition, and surface area.

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[*] The term “mineral addition” is used by RILEM for inorganic materials, both natural minerals and industrial by-products, that are used in quantities of 5% or more by mass of the cement. Mineral additions may be blended or interground with portland cement, or added directly to concrete before or during mixing (RILEM Technical Committee 73-SBC 1988).

Table 7.1—Comparison of North American silica fume standards: ASTM C 1240-04, CSA A23.5-M98, and AASHTO M 307-03

Test	ASTM	CSA	AASHTO
SiO_2 (silicon dioxide) (minimum)	85% (M)[*]	85% (M)[†]	85% (M)
SO_3 (sulfur trioxide) (maximum)	N/A	1.0% (M)	N/A
Loss on ignition (maximum)	6.0% (M)	6.0% (M)	6.0% (M)
Moisture content (maximum)	3.0% (M)	3.0% (OPT)	3.0% (OPT)
Available alkalies as Na_2O (maximum)	Report only (M)	N/A	Report only (M)
Oversize (fineness), percentage retained on 45 m (No. 325) sieve (maximum)	10% (M)	10.0% (M)	5% (M)[‡]
Oversize (maximum variation from average)	5% (M)	N/A	5% (M)
Density (specific gravity)	Report only (M)	Must be available	Report only (M)
Accelerated pozzolanic strength activity index (minimum percentage of control)	105% at 7 days (M)	85.0% at 7 days (OPT)	105% at 7 days (M)
Soundness (autoclave expansion) (maximum)	N/A	0.2% (M)	N/A
Drying shrinkage (mortar bars) (maximum)	N/A	0.03% at 28 days (OPT)	N/A
Specific surface area, BET (minimum)	73,000 ft^2/lb (15,000 m^2/kg) (M)	N/A	73,000 ft^2/lb (15,000 m^2/kg) (M)
Sulfate resistance expansion (maximum)	Varies; refer to specification (OPT)	Required for blended cement only	Varies; refer to specification (OPT)
Uniformity of air-entraining admixture demand in mortar (maximum variation from average)	20% (OPT)	20% (OPT)	20% (OPT)
Reactivity with cement alkalies, reduction of expansion (minimum)	80% (OPT)	N/A	80% (OPT)
Tendency to entrap air	N/A	No visible foam (M)	N/A
Expansion due to alkali-silica reactivity (maximum)	N/A	0.10% mortar expansion at 14 days (OPT)	N/A
Bulk density	Report only (M)	N/A	Report only (M)

[*] (M) = mandatory test; (OPT) = optional test.

[†] CSA A23.5-M98, silica fume with less than 85% SiO_2 falls outside the scope of this standard. Acceptance should depend on the results of comprehensive testing covering their uniformity and their chemical and physical properties.

[‡] This requirement is currently the only difference between ASTM C 1240-04 and AASHTO M 307-03.

AASHTO published the first standard in the United States for silica fume in 1990. The current version is AASHTO M 307-03; the requirements established by this standard are shown in Table 7.1. The 2003 version of the AASHTO document also carries the ASTM C 1240-01 designation. There is only one difference between the requirements in the two documents (Table 7.1). Readers are cautioned that the most current versions of the two documents may not be identical because of differences in balloting cycles.

In 1993, ASTM Committee C-9 developed a standard for silica fume: ASTM C 1240. The original thought was that silica fume would become a part of ASTM C 618, but this idea was rejected by the ASTM subcommittee, thus silica fume is covered in a separate standard. The current version is ASTM C 1240-04; the requirements established by this standard are shown in Table 7.1.

7.2.3 *Canadian standards*—A Canadian standard for silica fume was first issued in 1986. This standard covered natural pozzolans, low-calcium fly ash, high-calcium fly ash, GGBFS, and silica fume in a common document. The current version is CSA A23.5-M98; the requirements established by this standard are shown in Table 7.1.

7.2.4 *Standards from outside North America*—Standards have been developed in a number of countries. The mandatory requirements from several international standards are shown in Table 7.2.

Conformance to Norwegian and European standards is assessed by means of statistical control procedures. The European standard, EN 13263, is likely to be released by the time this document is released. This standard will replace national European standards.

7.2.5 *Standard reference silica fume*—A standard reference material (SRM) for silica fume has been developed in the United States for use in calibrating testing for conformance to various standards. This material has been designated SRM 2696, and it is available from the National Institute of Standards and Technology (NIST). Established properties of this material include SiO_2 content, specific surface area by Brunauer-Emmet-Teller method (BET), moisture content, loss on ignition, and the amount of several trace elements that may be present.

7.3—Specifying silica-fume admixtures

As described in Chapter 1, silica fume is commercially available in three forms: solid (or powdered), densified solid, and slurry. Each of these forms may or may not be marketed in conjunction with chemical admixtures. Typically, specifications have treated these products as individual components. The silica fume has been required to meet project-specific or national standards, if available, and the chemical admixtures, if present, have been required to meet the requirements of an appropriate standard, such as ASTM C 494.

To prevent minor variations in fresh or hardened concrete performance that may result from changes in silica-fume source or product form, Holland (1989) has recommended that changing products during a project be avoided unless

Table 7.2—Comparison of silica fume standards from outside North America

Test	Australia[*]	Europe[†]	Japan[‡]	China[§]	South Africa[‖]	Brazil[#]
SiO_2 (silicon dioxide) (minimum)	85% (M)[**]	85% (M)	85% (M)	85% (M)	85% (M)	85% (M)
SO_3 (sulfur trioxide) (maximum)	3% (M)	2.0% (M)	3.0% (M)	N/A	2.5% (M)	N/A
Loss on ignition (maximum)	6% (M)	4.0% (M)	5.0% (M)	6.0% (M)	5.0% (M)	6.0% (M)
Moisture content (maximum)	2% (M)	N/A	3.0% (M)	3.0% (M)	3.0% undensified (M) 1.0% densified (M)	3.0% (M)
Available alkalies as Na_2O (maximum)	To be reported (OPT)	To be reported (OPT)	N/A	N/A	1.5% (OPT)	1.5% (M)
Oversize (fineness), percentage retained on 45 μm (No. 325) sieve (maximum)	N/A	N/A	N/A	N/A	N/A	N/A
Oversize (maximum variation from average)	N/A	N/A	N/A	N/A	N/A	N/A
Density (specific gravity)	N/A	N/A	N/A	N/A	N/A	N/A
Accelerated pozzolanic strength activity index (minimum percentage of control)	N/A	N/A	Required	Required	N/A	N/A
Soundness (autoclave expansion) (maximum)	N/A	N/A	N/A	N/A	N/A	N/A
Drying shrinkage (mortar bars) (maximum)	N/A	N/A	N/A	N/A	N/A	N/A
Specific surface area, BET (minimum)	N/A	73,000 ft^2/lb (15,000 m^2/kg) (M)	73,000 ft^2/lb (15,000 m^2/kg) (M)	73,000 ft^2/lb (15,000 m^2/kg) (M)	N/A	N/A
Sulfate resistance expansion (maximum)	N/A	N/A	N/A	N/A	N/A	N/A
Uniformity of air-entraining admixture demand for mortar (maximum variation from average)	N/A	N/A	N/A	N/A	N/A	N/A
Reactivity with cement alkalies, reduction of expansion (minimum)	N/A	N/A	N/A	N/A	N/A	N/A
Tendency to entrap air	N/A	N/A	N/A	N/A	N/A	N/A
Expansion due to alkali-silica reactivity (maximum)	N/A	N/A	N/A	N/A	N/A	N/A
Bulk density	N/A	N/A	N/A	N/A	N/A	N/A
Magnesium oxide (maximum)	N/A	N/A	5.0% (M)	N/A	N/A	N/A
Chloride as Cl (maximum)	N/A	0.3% (M)	N/A	N/A	N/A	N/A
Calcium oxide (maximum)	N/A	1.0% (M)	N/A	0.2% (M)	N/A	N/A
Silicon metal (maximum)	N/A	0.4% (M)	N/A	N/A	N/A	N/A

[*] Standards Association of Australia (1994).
[†] EN 13263 (under approval).
[‡] Japanese Standards Association (2000).
[§] China General Administration (2002).
[‖] South African Bureau of Standards (1989).
[#] Brazilian Technical Standards Association (1997).
[**] (M) = mandatory test; (OPT) = optional test.

appropriate testing has been done to verify mixture proportions and concrete performance using the alternate material.

7.4—Specifying silica-fume blended cement

Silica-fume blended cement was first used on a large scale in Iceland, where all cement produced has contained at least 7% silica fume since 1979. This was done to combat alkali-silica reactivity. The first silica-fume blended cement in North America was produced in 1982 by a Canadian cement producer. Silica fume was interground with Type 10 cement to produce a blended cement with 6% silica fume by mass (Thomas et al. 1998). Today, a number of silica-fume blended cements (typically 8% silica fume by mass of cement) are available in Canada. Blending is accomplished by either intergrinding silica fume with cement clinker in the grinding mill or by air blending finished cement and silica fume.

It is worth distinguishing between blended cements made from undensified or densified silica fume and those made from pelletized silica fume. In the former case, the end result should be the same as adding that silica fume separately. In the latter case, the water or water-cement bound pellets must be broken down by intergrinding, and the particle size of the silica fume will depend on the characteristics of the milling process.

Applicable standards have been developed by both ASTM and CSA for this product. In the United States, ASTM C 595 is a prescriptive standard, while ASTM C 1157 is a performance standard. In Canada, both specifications CSA A362 and CSA A23.5-M98 apply. The Canadian standard CSA A362 lists several types of blended cement, including ternary blends with slag or fly ash. This standard limits the silica fume content to not more than 10% of the total mass.

7.5—Specifying silica-fume concrete

Silica-fume concrete has usually been specified as a separate section within Division 3 of a project specification following the format established by the Construction Specifications Institute. The section of the project specification on silica-fume concrete usually contains requirements for the silica fume itself, requirements for the silica-fume concrete, and any procedural requirements that differ from those for concrete not containing silica fume. Sections 7.5.1 through 7.5.5 address procedural topics that should be covered in the project specifications for silica-fume concrete.

7.5.1 *Measuring, batching, and mixing*—Concrete containing silica fume has been batched in all of the acceptable methods currently available for production of concrete. In some cases, the dry powder has been added to the mixer after mixing the other materials. In other cases, the dry powder has been mixed with portland cement before batching. Generally, the slurried admixtures have been added at the time and manner in which other liquid admixtures have been added. The volume of silica-fume slurry used per unit volume of concrete is generally much greater than that of other liquid admixtures. For example, a typical WRA may require use of 12 fl oz/yd^3 (650 mL/m^3); a typical HRWRA may require use of 130 fl oz/yd^3 (5 L/m^3); and a silica-fume slurry may require use of 11 gal./yd^3 (55 L/m^3) (Holland 1988). Automated dispensing equipment is commonly used for efficient handling of large volumes of silica fume slurry. All dispensing equipment for silica fume should be required to meet the accuracy requirements of ACI 304R and ASTM C 94.

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

Project specifications for silica-fume concrete may require extra mixing of the concrete to ensure uniform dispersion of the silica fume. If there is a question of whether mixing is adequate, mixer uniformity testing as outlined in ASTM C 94 should be specified. Note, however, that mixer uniformity testing may not indicate whether silica fume is being uniformly distributed or whether silica fume agglomerations are being properly dispersed. If there is a question regarding distribution or dispersion, testing of specific concrete properties beyond those required for the mixer uniformity testing may be required.

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

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

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

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

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

CHAPTER 8—PROPORTIONING SILICA-FUME CONCRETE MIXTURES

8.1—General

Most silica fume is used to provide concrete with high strength, high durability, or both. To achieve the desired levels of these properties of the concrete, significant modifications of the proportioning methods outlined in ACI 211.1 are required when silica fume is used.

8.2—Cement and silica fume content

Mixture proportions for high-strength concrete typically contain 600 to 850 lb/yd^3 (350 to 500 kg/m^3) of cementitious materials that may include 5 to 10% silica fume by mass. This concrete may have a w/cm as low as 0.20. Concrete for increased durability and reduced chloride diffusivity in parking structures and bridge decks typically has cementitious material contents from 590 to 725 lb/yd^3 (350 to 430 kg/m^3), with a w/cm of 0.35 to 0.45. This concrete typically contains 3 to 10% silica fume by mass. Fly ash or GGBFS may also be included in this concrete for either high-strength or high-durability applications. Where available, silica fume may be introduced as part of a blended cement, typically at approximately 7% by mass of cement.

8.3—Water content

For silica fume contents above approximately 5%, the use of silica fume will typically increase the water demand of the concrete in proportion to the amount of silica fume added. Therefore, the recommendations for approximate mixing water requirements contained in ACI 211.1 are invalid. The increase in water demand may be equal to the mass of silica fume added. HRWRAs are commonly used to adjust the water content to attain the desired *w*/*cm* and workability of the concrete. Different silica fume product forms and sources and characteristics of other concrete materials may alter the water demand. Depending on the characteristics of the materials being used, the use of fly ash or GGBFS may offset, to some degree, the increased water demand of the silica fume.

Typically, the mass of the silica fume is added to the mass of all other cementitious materials present to determine the *w*/*cm*. In some instances, however, an apparent *w*/*cm* is calculated by multiplying the mass of silica fume by a specified factor. The European standard (EN 206) requires a multiplier of twice the actual mass of silica fume to calculate the *w*/*cm*, depending on the exposure. Because North American practice has not been to use a multiplier for any cementitious material when calculating *w*/*cm*, a multiplier for the mass of silica fume is not used in this document.

When using slurried silica fume, the water portion of the slurry should be accounted for during the proportioning process. This is similar to making adjustments to the batch water content for free moisture on coarse and fine aggregates. Silica-fume slurry contains approximately 48 to 52% silica fume solids by mass. The slurry silica-fume manufacturer should be consulted for exact water content contributed by the slurry being used. When proportioning mixtures with slurried silica fume, the calculated batch water should be reduced by the amount of water contributed by the slurry.

8.4—Aggregate

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

8.5—Chemical admixtures

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

Silica-fume concrete mixtures may also contain corrosion-inhibiting admixtures for protection of reinforcing steel. Some corrosion-inhibiting admixtures are added to silica-fume concrete in large dosages, such as 6 gal./yd^3 (5 L/m^3). The amount of water contributed by these admixtures to the silica-fume concrete should be accounted for during the proportioning process, and should be subtracted from water added during batching.

8.6—Proportioning

There is no empirical method for proportioning silica-fume concrete. This means that there is no chart or document that can be used to derive the mixture ingredients to meet a specified level of performance. There are simply too many variables for such a chart to be developed. Local materials will determine the mixture proportions. A mixture that was developed and used elsewhere may not provide the same results when local materials are used. Mixtures used elsewhere are excellent starting points, but the influence of local materials on the results obtained must be determined.

Testing should be done at both the laboratory and truck scale during mixture development. The process is too complex to predict what the outcome will be without appropriate testing. Testing should be started early enough in the planning process to develop all data that may be required for project submittals.

Although an empirical method is not available, the following step-by-step procedure should help:*

Step 1—Determine project requirements. Read the specifications carefully. Look for requirements not only for concrete performance, but also for concrete proportioning. Items to look for include:

- Compressive strength;
- Chloride exposure;
- Freezing-and-thawing exposure, including specified air content;
- Aggregate requirements, including nominal maximum size;
- Chemical exposure;
- Abrasion resistance;
- Temperature restrictions;
- Maximum water content;
- Cementitious materials contents;
- Percentages of fly ash, slag, and silica fume;
- Silica fume product form, dry or wet, or blended cement; and
- Slump.

Step 2—Coordinate with the contractor who will be placing the concrete. Get input from the contractor early in the process. Knowing what the contractor needs to get the concrete into place will also help to price the concrete correctly. An overall approach to developing mixture proportions for silica-fume concrete is to determine project requirements; select a previously developed concrete mixture that matches, as closely as possible, the current requirements; conduct laboratory and field testing using project materials; and adjust the mixture as necessary (Holland 2005). The following is a step-by-step procedure based on this general approach:

- Special constructibility requirements;
- Placing and finishing methods;
- Nominal maximum allowable aggregate size;
- Slump requirements—increase the slump for silica-fume concrete (Section 9.4); and
- Responsibility for adding chemical admixtures on the site, if necessary.

Note that nominal maximum aggregate size and slump requested by the contractor may not be the same as in the specifications. This issue may have to be addressed by the specifier.

Step 3—Select starting mixture. Tables 8.1 and 8.2 contain a number of silica-fume concrete mixtures that have been

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*This procedure is taken from a document currently being prepared by the Silica Fume Association.

Table 8.1—Representative silica-fume concrete mixture proportions (SI units)

	Mixture proportions, kg/m^3											Compressive strength, MPa				
Mixture ID	Reference[*]	Cement	Silica fume	Fly ash GGBFS	Fine aggregate	Coarse aggregate	Water	HRWRA, L/m^3	w/cm	Slump, mm	Air, %	7 days	28 days	56 days	90 days	ASTM C 1202, Coulombs
Kinzua	1	386	70	0	708	971	130	6.5[†]	0.29	250	3.2	68.7	94.6	—	103.2	—
Mom column	2	498	30	0	700	1098	135	14.0	0.26	255	—	70.8	85.4	—	89.7[‡]	—
LAR-1983	1	356	53	53 fly ash	801	1109	111	5.3[§]	0.24	—	—	—	72.5	—	—	—
LAR-1984	1	380	42	0	756	1092	147	—	0.35	85	1.5	—	55.2	—	—	—
LAR-1985	1	356	50	65 fly ash	635	1151	135	4 to 8[‖]	0.29	125	2.0	42.6	60.0	—	—	—
MP1	3	390	30	0	964	964	156	3.1	0.37	100	6.8	—	60.5	—	—	468 at 35 days
MP2	3	390	39	0	964	964	160	3.3	0.37	135	7.0	—	64.3	—	—	471 at 35 days
MP3	3	390	20	0	964	964	152	3.3	0.37	165	8.7	—	58.6	—	—	592 at 35 days
NY DOT HPC	4	297	24	80 fly ash	—	—	160	—	0.40	75 to 100	6.5	—	>37	—	—	<1600 at 35 days
Petronas Towers	5	440	31	70 fly ash	775	945	147	8.3	0.27	205	—	—	97	—	—	—
Key Corp. Tower	5	406	47	169 GGBFS	—	—	149	1.25	0.24	250	—	87	98	104	—	—
Denver Airport Parking Garage	5	380	29	—	—	—	109	5.3	0.35	205	7.0	34	54	—	—	533 at 28 days
Test High Strength	6	475	74	104 Class C	593	1068	151	16.4	0.23	240	1.4	—	107	—	126 at 3 years	—
Handford Canister Storage	7	232	35	90 fly ash	743	1144	102	8.1	0.37	205	4.5	—	43	—	52	—
Toronto Subway	8	305[#]	8%	145 GGBFS	—	—	140	—	0.31	—	—	—	75	—	—	<500 at 28 days
Scotia Plaza Tower	9	314	38	118 GGBFS	—	—	145	—	0.31	—	—	—	—	—	93.5	—
Wacker Dr., Chicago	10	311	16	37 fly ash 47 GGBFS	676	1068	151	—	0.27	200	7	—	41	—	—	<2000 at 28 days

[*] *References*:
1. Holland and Gutschow (1987).
2. Aïtcin and Riad (1989).
3. Unpublished data from Braun Intertec Corp., Minneapolis, Minn., on a Minneapolis parking structure.
4. Alampalli and Owens (2000).
5. Unpublished data provided by committee members.
6. Burg and Öst (1994).
7. Holland (1998).
8. Hart et al. (1997) and unpublished data provided by committee members.
9. Bickley et al. (1991).
10. Kaderbek et al. (2002).

[†] Silica fume added as slurry that contained 11 lb/yd^3(6.5 kg/m^3) of admixture solids.

[‡] Compressive strength at 1 year: 14,150 psi (97.6 MPa); and at 2 years: 13,660 psi (94.2 MPa).

[§] Silica fume added as slurry that contained 9 lb/yd^3 (5.3 kg/m^3) of admixture solids.

[‖] Silica fume added as slurry that contained 7 to 14 lb/yd^3 (4 to 8 kg/m^3) of admixture solids.

[#] Blended silica-fume cement.

developed for a variety of applications. These tables should be used to find a concrete mixture that meets requirements that are similar to the current project.

Account for the water in the slurried form of silica fume, if appropriate. The values in the starter mixtures in the tables include all water, regardless of the source. Failure to account for the water in the slurry will result in concrete not achieving the performance requirements.

Step 4—Determine volume of entrained air required. It is essential that silica-fume concrete that will be exposed to freezing and thawing while saturated contains entrained air. Use an industry standard table such as found in ACI 201.2R to determine the volume of air required.

Step 5—Incorporate local aggregates into the starting mixture. There are two considerations:

- Calculate a total aggregate volume that will yield the correct amount of concrete. Not everyone proportions concrete to yield the same volume—many producers proportion slightly more than 1 m^3 (or 1 yd^3) to provide a some margin of error; and
- Use a fine-to-coarse aggregate ratio that works well for local materials. This ratio can always be adjusted once trial mixtures are made in the laboratory. While the ratio of fine to coarse aggregate will have an influence on the workability, small changes will not seriously affect hardened concrete properties.

Step 6—Prepare laboratory trial mixtures. There are a few points to keep in mind:

- Ensure that the silica fume is adequately dispersed in the concrete. Remember that a very small amount of

Table 8.2—Representative silica-fume concrete mixture proportions (in.-lb units)

Mixture proportions, lb/yd^3												Compressive strength, psi				
Mixture ID	Reference[*]	Cement	Silica fume	Fly ash GGBFS	Fine aggregate	Coarse aggregate	Water	HRWRA, fl. oz/yd^3	*w/cm*	Slump, in.	Air, %	7 days	28 days	56 days	90 days	ASTM C 1202, Coulombs
Kinzua	1	650	118	0	1194	1637	219	11[†]	0.29	9.75	3.2	9970	13,270	—	14,970	—
Mom column	2	840	50	0	1180	1850	227	362	0.26	10	—	10,270	12,380	—	13,010[‡]	—
LAR-1983	1	600	90	90 fly ash	1350	1870	187	9[§]	0.24	—	—	—	10,250	—	—	—
LAR-1984	1	641	71	0	1275	1840	247	—	0.35	3.25	1.5	—	8000	—	—	—
LAR-1985	1	600	85	110 fly ash	1070	1940	228	7 to 14[‖]	0.29	5	2.0	6180	8700	—	—	—
MP1	3	658	50	0	1155	1625	263	79	0.37	4	6.8	—	8780	—	—	468 at 35 days
MP2	3	658	66	0	1155	1625	270	86	0.37	5.25	7.0	—	9330	—	—	471 at 35 days
MP3	3	658	33	0	1155	1625	257	86	0.37	6.5	8.7	—	8500	—	—	592 at 35 days
NY DOT HPC	4	500	40	135 fly ash	—	—	270	—	0.40	3 to 4	6.5	—	>5400	—	—	<1600 at 35 days
Petronas Towers	5	742	52	118 fly ash	1306	1593	248	265	0.27	<8.0	—	—	14,000	—	—	—
Key Corp. Tower	5	685	80	285 GGBFS	—	—	252	420	0.24	10	—	12,600	14,200	15,100	—	—
Denver Airport Parking Garage	5	640	48	—	—	—	241	193	0.35	8.0	7.0	4980	7830	—	—	533 at 28 days
Test High Strength	6	800	125	175 Class C	1000	1800	254	425	0.23	9.5	1.4	—	15,520	—	18,230 at 3 years	—
Handford Canister Storage	7	391	60	150 fly ash	1257	1928	225	210	0.37	8.0	4.5	—	6300	—	7500	—
Toronto Subway	8	514[#]	8%	244 GGBFS	—	—	236	—	0.31	—	—	—	10,900	—	—	<500 at 28 days
Scotia Plaza Tower	9	529	64	200 GGBFS	—	—	244	—	0.31	—	—	—	—	—	13,560	—
Wacker Dr., Chicago	10	525	27	53 fly ash 79 GGBFS	1140	1800	254	—	0.27	8	7	—	6000	—	—	<2000 at 28 days

[*] *References*:
1. Holland and Gutschow (1987).
2. Aïtcin and Riad (1989).
3. Unpublished data from Braun Intertec Corp., Minneapolis, Minn., on a Minneapolis parking structure.
4. Alampalli and Owens (2000).
5. Unpublished data provided by committee members.
6. Burg and Öst (1994).
7. Holland (1998).
8. Hart et al. (1997) and unpublished data provided by committee members.
9. Bickley et al. (1991).
10. Kaderbek et al. (2002).

[†] Silica fume added as slurry that contained 11 lb/yd^3(6.5 kg/m^3) of admixture solids.

[‡] Compressive strength at 1 year: 14,150 psi (97.6 MPa); and at 2 years: 13,660 psi (94.2 MPa).

[§] Silica fume added as slurry that contained 9 lb/yd^3 (5.3 kg/m^3) of admixture solids.

[‖] Silica fume added as slurry that contained 7 to 14 lb/yd^3 (4 to 8 kg/m^3) of admixture solids.

[#] Blended silica-fume cement.

silica fume is being used with respect to the other ingredients. For the silica fume to perform, it must dispersed throughout the concrete. Sometimes it is difficult to get adequate dispersion when using a laboratory concrete mixer. This is particularly true for the densified form of silica fume (Lagerblad and Utkin 1993). Laboratory mixers simply do not have enough mixing action to break down and disperse the silica fume;

- Batch the concrete at the maximum allowed water content. Remember that there may not be any slump resulting from the mixing water. Use chemical admixtures to achieve the necessary workability;
- Review the properties of the fresh concrete and make adjustments as necessary to get the desired workability, air content, and other properties. Once the fresh properties are established, make specimens for hardened concrete testing;
- Based on the results of testing the hardened concrete, adjust the mixture proportions as necessary; and
- Detailed information on mixing silica-fume concrete in a laboratory mixer may be found in the reference by Holland (2005).

Step 7—Conduct full-scale testing. There are always minor differences between proportions developed in the laboratory and those used for concrete production, particularly in chemical admixture dosages. Making truck-sized batches of the concrete is the best way to work out the variances. Keep in mind:

- This is not a time to economize by making very small batches. Make enough concrete to be representative of what will be made during the project. Remember that it takes a lot of paste to coat the inside of a truck drum or a central mixer. If too small a batch of concrete is made, a significant amount of paste can be lost to the drum. Make at least 3 yd^3 (2 m^3) for most truck or central mixers;

- Test to determine whether the concrete meets the fresh and hardened requirements for the project. Because the mixture has already been fine tuned in the laboratory, major adjustments at this point should not be required. If it appears that the performance is not the same as in the laboratory, examine the process carefully—there is no reason to expect major differences; and
- Make more than one batch to ensure that the performance of the concrete mixture can be repeated.

8.7—Ternary mixtures

Combinations of three different cementitious materials are commonly referred to as ternary mixtures. Silica fume has been combined with portland cement and either fly ash or GGBFS to produce ternary mixtures. Examples of ternary mixtures featuring silica fume are shown in Tables 8.1 and 8.2. Such combinations have been selected for high-strength concrete and for durability. When ternary mixtures are used, the amount of silica fume is typically somewhat less than would be used without the fly ash or GGBFS.

CHAPTER 9—WORKING WITH SILICA FUME IN FIELD CONCRETE

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

Handling procedures for silica-fume materials depend on the form of the product being used—either dry or slurry. Within these two general product forms, silica fume can be provided with or without chemical admixtures. Because silica fume products are available in dry bulk, dry super sack, dry paper sack, liquid bulk, and liquid drums, the material handling systems and the equipment used in transportation, discharge, storage, batching, and mixing of the silica fume depend on the specific product form.

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

9.1.1 *Dry silica fume*—Dry silica fume products may be further categorized into two forms: as-produced silica fume with a typical bulk loose density of 8 to 27 lb/ft^3 (130 to 430 kg/m^3), and densified silica fume with a typical bulk loose density of 25 to 45 lb/ft^3 (400 to 720 kg/m^3).

Silica fume in the as-produced form tends to be dusty, prone to lumping, and difficult to move in cement-handling equipment. Bulk silica fume in the as-produced form is being used for premixed mortar production and for concrete where the silica-fume source is close to the concrete plant.

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

In cement tankers, bulk densified silica fume load size is 12 to 17 tons (11 to 15 Mg) for a 1000 ft^3 (28 m^3) tank truck, and 18 to 25 tons (16 to 23 Mg) for a 1400 ft^3 (40 m^3) tank truck. A 100 ton (90 Mg) cement rail car can typically hold 60 to 80 tons (55 to 73 Mg) of densified material. The bulk load size for as-produced fume is significantly less, at 7 to 10 tons (6 to 9 Mg) for a 1400 ft^3 (40 m^3) tanker because of decreased density.

Loading of densified silica fume is accomplished with an air slide or gravity feed, and normally requires 15 to 20 minutes to transfer 25 tons (23 Mg) to a bulk tank truck. As-produced silica fume is blown pneumatically into bulk tank trucks, and typically takes 3 to 5 hours of loading time.

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

Because silica-fume concrete mixtures are usually proportioned by mass of cement (typically 5 to 10%, with occasional applications to 20%), the densified silica fume silo can be smaller than the concrete producer's normal cement silo. The silo should have a capacity of at least 3000 ft^3 (85 m^3) to hold two full truckloads so that the schedule of silica fume deliveries is not critical for placements. Storage silos for undensified silica fume are much larger, as the bulk densities are 1/3 to 1/2 that of densified silica fume.

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

Dry silica fume (both as-produced and densified) is also available in small paper bags, 50 or 55 lb (23 or 25 kg), with or without dry chemical admixtures. Densified silica fume is additionally available in 25 lb (11 kg) repulpable paper bags. These bags are also available with dry chemical admixtures. The entire bag is generally placed into the mixer after the other ingredients have been mixed for some time. The bags break down as a result of the mixing action and the exposure to water. Problems have been reported with inadequate dispersion of these bags, particularly for mixtures containing small aggregates or very low water contents. If there are any doubts about dispersion of the paper bags, testing should be conducted. Additional information on using these bags is available in the reference by Holland (2005).

Paper bagged products are normally shipped on shrink-wrapped pallets and, depending on the density of the product, 18 to 22 tons (16 to 20 Mg) of material can be shipped on a standard truck trailer. The advantage of using silica fume in paper bags is that it lends itself to relatively small projects or remote locations. The product form that contains HRWRA may eliminate the need to handle the HRWRA separately, thus simplifying batching and mixing of silica-fume concrete for applicable field projects.

9.1.2 *Slurried silica fume*—Several manufacturers supply silica-fume slurries. This practice allows silica fume to be stored and dispensed in liquid form. Transportation costs are reduced relative to those of as-produced silica fume because over twice as much silica fume can be shipped in a given container volume. Slurry transportation cost is typically higher than that of densified silica fume due to the requirements of shipping the water portion of the slurry.

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

The plain slurry material and formulated slurry containing chemical admixtures products are pumped, or moved by gravity, into 4000 gal. (15,000 L) tank trucks or 20,000 gal. (76,000 L) rail tank cars for transportation to permanent or mobile dispensers located at concrete production plants. If weather conditions warrant, the tank trucks or cars should be insulated.

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

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

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

9.2—Producing concrete

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

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

9.2.2 *Slurried silica fume*—At the concrete production plant, the slurry products are typically stored in steel or fiberglass 2000 to 6000 gal. (7500 to 23,000 L) tanks. These tanks usually have recirculation, mechanical agitation capability, or both, that are used intermittently as required to liquefy the material for dispensing. Typically, the slurry is pumped from the storage tank through a flow meter and a hose into the mixer or into the water weigh hopper. Some systems dispense the slurry by mass, but volumetric dispensers are more commonly used.

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

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

9.3—Transporting

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

9.4—Placing

It is absolutely essential to adhere to good concrete placement practices as outlined in ACI 304R to achieve a high level of concrete performance. Before placing silica-fume concrete, the contractor should be prepared. Adequate manpower, backup equipment (vibrators, vibratory screeds, and power sprayers), and the proper curing materials should all be on hand. Generally, with silica-fume concrete, the placing, finishing, and curing procedures should all be performed in a continuous operation.

Silica-fume concrete should be placed at the highest practical slump that is suitable for the placing conditions. Because silica-fume concrete is much more cohesive, it should be specified with a slump that is 1 to 2 in. (25 to 50 mm) higher than normally allowed (Holland 1989). It may also be advisable to redose with additional HRWRA on site to maintain the slump. Silica-fume concrete is very cohesive and resists segregation at high slumps. Although silica-fume concrete flows well, vibration is needed for good consolidation, even at high slumps. The use of a vibratory screed is recommended when placing slabs and concrete overlays.

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

9.5—Finishing

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

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

A general approach to finishing silica-fume concrete is to underfinish, as opposed to overfinish, the concrete surface (Holland 1987). Although it may not always be aesthetically pleasing, the minimum required finish is the best approach because it provides the most resistance to aggressive freezing-and-thawing and aggressive chemical environments.

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

Contractors have frequently been urged by suppliers of silica fume or required by project specifications to use the chart presented in ACI 305R or in 308R that allows estimates to be made regarding the rate of evaporation from fresh concrete. For instances in which the chart predicts that plastic-shrinkage cracking is likely, contractors have been referred to the preventative steps included in ACI 305R and 308R. Cohen et al. (1990) suggested that the potential for plastic-shrinkage cracking of silica-fume concrete is greater than that predicted by the ACI chart. The potential for such cracking increases with increasing dosages of silica fume because of the further reductions in the rate of bleeding. The Virginia Department of Transportation (1991) requires that measures to reduce moisture loss be taken when the predicted rate of evaporation of surface moisture from silica-fume concrete exceeds 0.05 $\mathrm{lb/ft^2/h}$ (0.25 $\mathrm{kg/m^2/h}$) during the placement.

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

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

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

9.6—Curing

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

As with any concrete, the most effective curing method for silica-fume concrete slabs is to cover them with wet burlap and plastic sheeting. If wet curing is used, however, the concrete should still be protected against plastic shrinkage because there is usually a time delay associated with beginning wet curing that could allow cracking. Protection against plastic shrinkage should be done using one of the techniques mentioned previously, such as fog misting or using an evaporation retardant until the concrete has enough strength to support the placement of the wet burlap and plastic. The burlap and plastic should be left in place and the concrete kept wet for at least 3 days, and preferably for 5 to 7 days. Some agencies, such as the New York State Department of Transportation (Streeter 1999), require that concrete containing silica fume be wet-cured. Formed surfaces should be coated with a curing compound or, if feasible, covered with wet burlap and plastic after form removal.

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

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

9.7—Accelerated curing

There is synergy between silica-fume concrete and steam- or heat-accelerated curing. Manufacturers of precast concrete products have achieved impressive gains in early-age compressive strength when using mixtures containing silica fume and HRWRA instead of their traditional concrete mixtures. In many cases, the economics of fuel cost savings compared with the cost of the silica fume were favorable (Johnston 1989; Hooton et al. 1997).

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

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

CHAPTER 10—RESEARCH NEEDS

During the last decade, the use of silica fume in high-strength and high-performance concrete has become an increasingly accepted practice. As more laboratory- and field-generated data become available, the knowledge of silica fume properties and the confidence in its usage reduces the need for additional research. Nevertheless, to derive the maximum short- and long-term benefits from the use of this material in concrete, some topics still remain that can benefit from additional research efforts. These issues are discussed in the following sections.

10.1—Frost resistance

As discussed in Chapter 5 of this document, numerous studies of air-entrained silica-fume concrete have shown that such concrete is frost resistant for a wide range of *w/cm* (as high as 0.5 to 0.6) and for up to 15% silica fume replacement of cement.

The freezing-and-thawing resistance of non-air-entrained concrete containing silica fume requires further research, as several existing investigations present conflicting results. Some of the reported inconsistencies may be related to differences in mixture proportions, curing conditions, degree of saturation of the specimens, and the details of the test method used. There is a concern that the general, standard freezing-and-thawing test method that is used for plain concrete (ASTM C 666) may not be applicable to silica-fume concrete, and may require some modifications (Sellevold and Nilsen 1987; Feldman 1986; Gudmundsson and Asgeirsson 1983; Huang and Feldman 1985c). The use of ASTM C 671 for assessing resistance to freezing and thawing of high-strength silica-fume concrete should be investigated as a possible replacement or extension of ASTM C 666. The effectiveness of the air-entraining admixtures in terms of their ability to produce a stable air-void system, especially in the presence of some of the polycarboxylate HRWRA, and the feasibility of commercial production of non-air-entrained frost-resistant silica-fume concrete at a low (below 0.35) *w/cm*, require additional studies.

10.2—Scaling resistance

Some of the existing literature (Zhang et al. 1997) and the discussion presented in Chapter 5 of this report indicate that further research is needed on the scaling resistance of silica-fume concrete with a low (below 0.4) *w/cm*, especially if such concrete is not air entrained. Reduced scaling resistance of silica-fume concrete subjected to steam curing has also been reported (Soeda et al. 1999), and additional studies in this area should be considered to determine the exact mechanism of the observed damage.

10.3—Sulfate attack

The issue of resistance to sulfate attack of concrete containing silica fume has been extensively studied over the last decade, and a comprehensive review of the pertinent publications is presented in Chapter 5. The majority of data available in the literature deal with the resistance of silica-fume concrete to either sodium or magnesium sulfate solutions, and show improvements in performance with an increase in the amount of silica fume added.

As discussed in Chapter 5, the results regarding the resistance of silica-fume concrete to ammonium sulfate solutions are still conflicting and require further investigation.

10.4—Drying shrinkage and creep

Although significant progress has been made in developing information on the drying shrinkage of concrete containing silica fume, the information on creep of such concrete is relatively scarce and often difficult to draw a specific conclusion from because of differences in creep test procedures used by various investigators (Section 5.2.2). The committee feels further research may be warranted on the issues of autogenous shrinkage, stress relaxation-creep relationships, and tensile creep, which is critical for concrete subjected to a high degree of restraint.

10.5—Steel corrosion

Corrosion of steel reinforcement is one of the most critical durability problems for concrete exposed to chloride ions. Laboratory tests of silica-fume concrete show that they have low diffusivity to chlorides and high electrical resistivity (Chapter 5). Both of these properties are important in protecting the embedded reinforcement from depassivation and the resulting corrosion. As reported in Chapter 3 of this document, however, further research is needed to clarify the issue of the chloride-binding capacity of cement paste and concrete containing silica fume.

10.6—Long-term durability

While most of the existing information on the durability of concrete containing silica fume was derived from short-term or accelerated laboratory tests, data on the long-term performance of such concrete in the field are becoming more available as existing structures age. Although the currently available durability data indicate that silica-fume concrete performs satisfactorily and typically better than concrete without silica fume (Sarkar 1993; Lachemi et al. 1998), a concentrated effort is needed to document and analyze the long-term field information and to correlate it with the results of laboratory tests. Such studies would help improve the process of mixture proportioning with respect to expected service conditions and help identify the best construction practices with respect to placing and curing silica-fume concrete.

10.7—Rheology of fresh concrete

As mentioned in Chapter 4, silica-fume concrete frequently requires a higher slump to achieve the same workability as concrete without silica fume. This difference illustrates one of the limitations of the slump test as a measure of workability. Test methods have been developed that measure both yield and plastic flow parameters of fresh concrete (Wallevik 1990). These can provide more meaningful data on workability, but will require more research before they can be used with confidence in the field. Additional research is also required in the area of rheology of cement-based materials made with combinations of silica fume and other supplementary materials and fillers.

10.8—Mechanism of strength development

As discussed in Chapter 5, the presence of silica fume in concrete increases its strength. This increase appears to be due to a combination of physical and pozzolanic effects in the bulk matrix and at the interfaces between the matrix and inclusions (Detwiler 1988; Cong et al. 1992). As discussed in Chapter 3, however, some controversy still exists regarding this issue, and the relative contribution of each of these mechanisms to strength development still needs to be quantified. If successfully developed, such quantitative data could be used to optimize mixture proportioning of silica-fume concrete with respect to strength development.

10.9—Role of silica fume in special concretes

Research is needed to study the influence of silica fume on the properties of specialized concrete. In particular, the role of silica fume in self-leveling, self-consolidating, and expansive cementitious systems needs more detailed documentation.

10.10—Effect of silica fume on hydration

Chapter 3 describes the physical and chemical effects of silica fume on the hydration of portland cement. Considerable progress has been made in recent years in documenting the role of silica fume in the cementitious system as that of a highly reactive pozzolan that combines with CH to form CSH. The exact constituents of the silica fume-portland cement system that determine the extent of this reaction still need to be defined.

10.11—Later-age cracking

As discussed in Chapter 5, there have been instances in which cracking of silica-fume concrete at later ages have been seen; this cracking does not seem to be related to improper protection and curing during the construction process. This type of cracking has mainly been seen in long-span steel bridges, both in full-depth placements and in overlays with made high-durability and high-strength concrete. The committee is not aware if this is a general problem with high-performance or specifically related to silica-fume concrete. The committee is also not aware of research or publications in this area. The cracking may be a function of the increased modulus of the concrete, which will change the structural response of the structure under dynamic loading. Work is needed in this area to establish the cause or causes of this cracking and develop the appropriate preventative measures.

CHAPTER 11—REFERENCES

11.1— Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Association of State Highway and Transportation Officials

M 307-03	Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout
T 259	Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration
T 277	Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete (refer also to ASTM C 1202)

American Concrete Institute

116R	Cement and Concrete Terminology

201.2R	Guide to Durable Concrete
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
212.4R	Guide for the Use of High-Range Water-Reducing Admixtures (Superplasticizers) in Concrete
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
305R	Hot Weather Concreting
308R	Guide to Curing Concrete
309R	Guide for Consolidation of Concrete
363R	Report on High-Strength Concrete
363.2R	Guide to Quality Control and Testing of High-Strength Concrete
517.2R	Accelerated Curing of Concrete at Atmospheric Pressure

ASTM International

C 94	Standard Specification for Ready-Mixed Concrete
C 150	Standard Specification for Portland Cement
C 227	Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C 309	Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 311	Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete
C 494	Standard Specification for Chemical Admixtures for Concrete
C 595	Standard Specification for Blended Hydraulic Cements
C 618	Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
C 642	Standard Test Method for Density, Absorption, and Voids in Hardened Concrete
C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 671	Standard Test Method for Critical Dilation of Concrete Specimens Subjected to Freezing
C 989	Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
C 1012	Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C 1138	Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)
C 1157	Standard Performance Specification for Hydraulic Cement
C 1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
C 1240	Standard Specification for Silica Fume used in Cementitious Mixtures
C 1240-01	Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout
C 1240-03a	Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout
C 1260	Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
C 1293	Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction
E 119	Standard Test Methods for Fire Tests of Building Construction and Materials
E 1156-87	Practice for Health Requirements for Occupational Exposure to Synthetic Amorphous Silica

Canadian Standards Association

A23.1	Concrete Materials and Methods of Concrete Construction
A23.5-M98	Supplementary Cementing Materials
A362	Blended Hydraulic Cement

European Committee for Standardization (CEN)

EN 206	Concrete—Performance, Production, Placing and Conformity Criteria
EN 13263	Silica Fume for Concrete

The aforementioned publications may be obtained from the following organizations:

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

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

ASTM International
100 Barr Harbor Drive
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Canadian Standards Association
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European Committee for Standardization
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Brussels, Belgium

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