Silica Fume User's Manual

Second Edition

SILICA FUME ASSOCIATION

Photo on front cover: The New Goethals Bridge, spanning Arthur Kill strait between Elizabeth, New Jersey and Staten Island, New York. Silica fume was used to produce 397 high-strength concrete girders. Each girder was 53.6 m long, 1.1 m wide, and weighed 100 metric tons.

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Second Edition

SFA
SILICA FUME ASSOCIATION

DISCLAIMERS

The original edition of the *Silica Fume User's Manual* was produced under Cooperative Agreement DTFH61-99-X-00063 between the Federal Highway Administration and the Silica Fume Association as FHWA-IF-05-016. That document was disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The cost to produce the original edition was financed with federal funds and industry cost share.

The information and data reported in this updated second edition are supported from information in the original document but is produced solely by the Silica Fume Association to provide technical and practical information for users of silica fume that has accumulated since the original manual was published. The content is developed solely by the Silica Fume Association and does not represent the official views of the Federal Highway Administration. This document does not constitute a standard, specification, or regulation, and the United States Government, the Department of Transportation and Federal Highway Administration assume no liability for its contents or use thereof.

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INTRODUCTION

This Manual is intended to provide practical information for individuals working with silica fume and silica-fume concrete. Different chapters of the Manual may be of interest to concrete specifiers, concrete producers, concrete contractors, or concrete inspectors. The Manual is organized as follows:

- **Chapters 1 and 2** provide basic information explaining what silica fume is and how it reacts in concrete.
- **Chapter 3** describes the primary uses of silica fume in concrete.
- **Chapter 4** reviews ACI guidance and standard specifications for silica fume.
- **Chapter 5** presents detailed information on proportioning concrete containing silica fume for different applications.
- **Chapter 6** presents recommendations for working with silica fume in a concrete plant.
- **Chapter 7** presents recommendations for placing and finishing silica-fume concrete on bridge decks and other flatwork.
- **Chapter 8** discusses the role of silica fume in making concrete more sustainable.
- **Chapter 9** discusses health concerns associated with working with silica fume and presents recommendations for personal protection.
- **Chapter 10** is a collection of references from the other chapters.

The contents of this report reflect the views of the Silica Fume Association (SFA), which is responsible for the facts and the accuracy of the data presented herein.

The Silica Fume Association was formed in 1998 to serve as a voice for producers of silica fume. Please visit the SFA website (www.silicafume.org) for additional information.

This first edition of this manual was prepared by Dr. Terence C. Holland with the cooperation of the members of the Silica Fume Association. Dr. Holland also prepared the second edition with the assistance of Eckart Bühler and Robert Lewis, two long-time industry experts on the use of silica fume. Questions or comments regarding this Manual should be addressed to the technical information request portion of the SFA website (www.silicafume.org).

This document may also be downloaded from the SFA website.

Second edition, first printing, June 2022

CONVENTIONS USED IN THIS MANUAL

1. **Water content.** Throughout this manual, the abbreviation w/cm is used for water-to-cementitious materials ratio. This value is the mass of the water divided by the sum of the masses of all cementitious materials. In some instances other than in this manual, this value is referred to as the water-binder ratio.

2. **Standards.** The title of a standard is shown the first time the standard is mentioned in the text. All further references to that standard are made simply using the numerical designation for the standard, such as ASTM C1240. If there is any doubt regarding the full title of a standard, refer to the reference listings in Chapter 10.

3. **Conversion Table.** This document has been prepared using SI units. In a small number of cases, inch-pound units are used to assist users. A conversion table from SI to inch-pound units follows this section. The concrete mixture proportions table and the proportioning examples shown in Chapter 5 using SI units are repeated in Appendix 1 using inch-pound units.

4. **Density, unit weight, and specific gravity.** The density of a material, sometimes referred to as unit weight, is the mass per unit volume. In SI units, the density of water is 1000 kg/m^3 (1Mg/m^3). This value is used when proportioning concrete mixtures. Specific gravity is a unitless value that shows the relationship between the density of a material compared to the density of water. The specific gravity of a material is the same in either SI or inch–pound units. In SI units, the specific gravity may be quickly derived from the density. For example, the density of portland cement is 3150 kg/m^3 and the specific gravity is 3.15.

5. **Silica Fume Association.** This manual is produced by the Silica Fume Association. To avoid repetition, this name is abbreviated as SFA throughout the manual.

6. **Abbreviations for organizations.** The following abbreviations for organizations are used in this manual:

   ACI – American Concrete Institute
   ASTM – ASTM International (Formerly the American Society for Testing and Materials)
   AASHTO – American Association of State Highway and Transportation Officials
   CEN – European Committee for Standardization
   DOT – Department of Transportation. This the usual term used for a state organization responsible for roads and bridges in the United States.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

DEDICATION AND SOME SILICA-FUME HISTORY

The successful use of silica fume in concrete has been the result of contributions from two corporations and a great number of individuals across the concrete industry. This Second Edition is dedicated to everyone who has contributed to the use of silica fume.

Silica fume was introduced to the US concrete industry essentially simultaneously by two organizations:

- Elborg Technology, a joint venture of Elkem Metals and Aalborg Portland, began promoting silica fume in the 1970s. When Aalborg left the joint venture, this company became Elkem Chemicals. Today, this organization is known as Elkem Silicon Products.
- Norcem, a joint venture between John Wolsiefer, Sr. and Scancem (a Norwegian cement supplier), also began promoting silica fume at around the same time. This organization became Norchem Concrete Products and later part of the Ferroglobe group, which is the name that it is known by as this edition is prepared.

Following are some of the individuals who have played a major role (if a reader is aware of other individuals who should be recognized, please let the SFA know):

Pierre Claude Aïtcin, Sherbrooke University
Eckart Bühler, Master Builders/Norchem/Ferroglobe
Magne Dåstøl, Elkem
Per Fidjestøl, Elkem
Odd Gjørv, Norwegian Institute of Technology
Terry Holland, Elborg/Elkem Chemicals/Independent consultant
Doug Hooton, University of Toronto
Tony Kojundic, Elkem Chemicals
Robert Lewis, Elkem/Ferroglobe
Mark Luther, Elborg/Elkem Chemicals
Mohan Malhotra, CANMET
Erik Sellevold, SINTEF
John Wolsiefer, Sr., Norcem/Norchem

DEDICATION AND SOME SILICA-FUME HISTORY

Finally, a bit of project history:

- **1946** – First mention of use of silica fume in a cementitious material - US Patent 2,410,954 by J.W. Sharp.
- **1950** – First experiments on the use of silica fume in concrete at the Norwegian Institute of Technology.
- **1978** – Norwegian standard allows use of up to eight percent of silica fume in concrete as long as the w/cm is less than 0.70.
- **Early 1980s** – Many projects where silica fume concrete was placed in parking garages (protection from deicing salts) and chemical resistant concrete applications.
- **1981** – Buck and Burkes (USACE) published the first technical paper in North America on silica fume showing improved resistance to ASR and sulfate attack.
- **1983** – First publically bid silica-fume project in the United States was done by the US Army Corps of Engineers. This project was the repair of a stilling basin slab at Kinzua Dam, located in Pennsylvania. The project is notable because the concrete had a specified compressive strength of 86 MPa at 28 days, which was by far the highest strength specified in the US up to that time. This project is described in Chapter 3 of this manual.
- **1983** –First International Conference on Fly Ash, Silica Fume, Slag, and other Mineral By-Products in Concrete. This conference was held in Montreal and was sponsored by CANMET and ACI. The proceedings were published as ACI SP-79.
- **1984** – Silica-fume concrete with a compressive strength of 90 MPa at 91 days was placed in an experimental column in a high rise in Montreal.
- **1989** – First high-rise structures to use silica fume high-strength concrete in New York City.
- **Late 1980s** – several DOTs in the rust belt and northeast US began specifying silica-fume concrete for the rehabilitation of bridge decks
- **1990s** – Use of ternary blends of portland cement, fly ash, and silica fume in the Storebaelt Bridge in Denmark and portland cement, slag cement, and silica fume in the Tsing Ma bridge in Hong Kong.
- **1990** – One of the first silica-fume concrete bridge deck overlays was placed by the Ohio Department of Transportation. This project was a bridge in Waterford, OH, on Michelle Ave/State Route 339 crossing the Muskingum River.
- **1997** – Ultra-high-performance concrete (UHPC) used for pedestrian bridge at Sherbrook University, Quebec, Canada.
- **2006** – First use of UHPC on a bridge in the US. Three precast UHPC beams 33.5 m long were used for the Mars Hill Bridge in Iowa.
- **2016** – First use of UHPC in the US for a bridge deck overlay in Buchanan County, Iowa.

1 WHAT IS SILICA FUME?

Silica fume is a highly reactive material that is used to enhance the properties of concrete. Depending upon the application, it is typically used between 2 and 20 percent by mass of cementitious material. It is a by-product of producing certain metals in electric-arc furnaces.

This chapter explains what silica fume is and how it is produced.

1.1 DESCRIPTION

The American Concrete Institute (ACI) defines silica fume as "very fine non-crystalline silica produced in electric-arc furnaces as a by-product of the production of elemental silicon or alloys containing silicon" (ACI Concrete Terminology) . It is usually a gray powder, somewhat similar to portland cement or some fly ashes. Figure 1.1 shows a typical silica fume as it appears after being collected from a furnace.

FIGURE 1.1. As-produced silica fume. This is what the material looks like after it is collected.

Silica fume is usually categorized as a supplementary cementitious material. This term refers to materials that are used in concrete in addition to portland cement. These materials can exhibit the following properties:

- **Pozzolanic** — will not gain strength when mixed with water. Examples include silica fume meeting the requirements of ASTM C1240, *Standard Specification for Silica Fume Used in Cementitious Mixtures*, and low-calcium fly ash meeting the requirements of ASTM C618, *Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, Class F.

1.1 DESCRIPTION

- **Cementitious** — will gain strength when mixed with water. Examples include slag cement meeting the requirements of ASTM C989, *Standard Specification for Slag Cement for use in Concrete and Mortars*, or high-calcium fly ash meeting the requirements of ASTM C618, Class C.
- **Pozzolanic and cementitious** — a combination of both properties. Examples include some fly ashes.

Silica fume is frequently referred to by other names. This manual will use the term silica fume, as adopted by the American Concrete Institute. Here are some of the other names for silica fume:

- **Condensed silica fume**
- **Microsilica**

There are several materials that are physically and chemically quite similar to silica fume. These materials may or may not be by-products. Some of these materials may perform well in concrete; however, their cost usually prohibits such use.

- **Precipitated silica**
- **Fumed silica**
- **Gel silica**
- **Colloidal silica**
- **Silica flour and silica dust** — caution: these materials are a crystalline form of silica that will not perform like silica fume in concrete. Because of their crystalline structure, these products may also pose health hazards.

1.2 PRODUCTION

Silica fume is a by-product of producing silicon metal or ferrosilicon alloys in smelters using electric-arc furnaces. These metals are used in many industrial applications to include aluminum and steel production, computer chip fabrication, and production of silicones, which are widely used in lubricants and sealants. While these are very valuable materials, the by-product silica fume is of more importance to the concrete industry.

Figure 1.2 shows a smelter in the days before silica fume was captured for use in concrete and other applications. The "smoke" leaving the plant is silica fume. Today, most environmental guidelines prohibit release of silica fume to the atmosphere. A schematic of silica fume production is shown in Figure 1.3 and a schematic of a smelter is shown in Figure 1.4. The silica fume is collected in very large filters in the baghouse and then made available for use in concrete directly or after additional processing as is described in Chapter 2.

FIGURE 1.2. Smelter before installation of equipment to collect silica fume. The "smoke" is silica fume being released to the atmosphere.

1.2 PRODUCTION

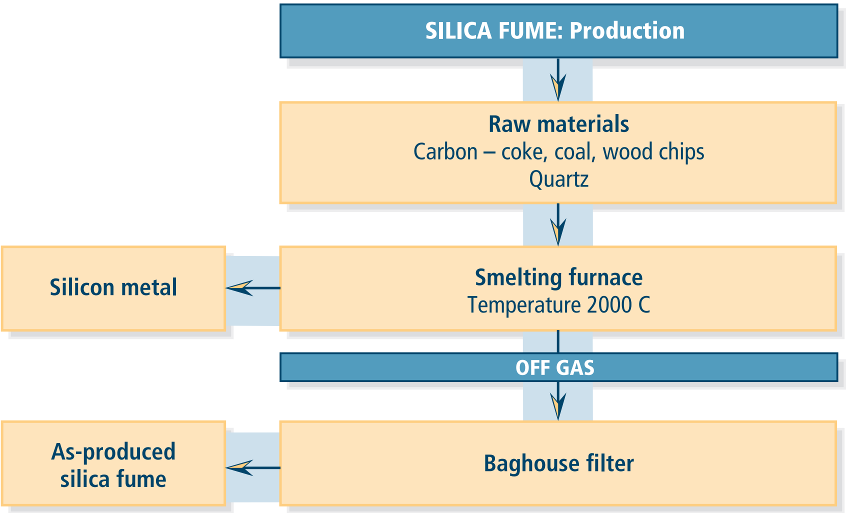

FIGURE 1.3. Schematic of silica fume production.

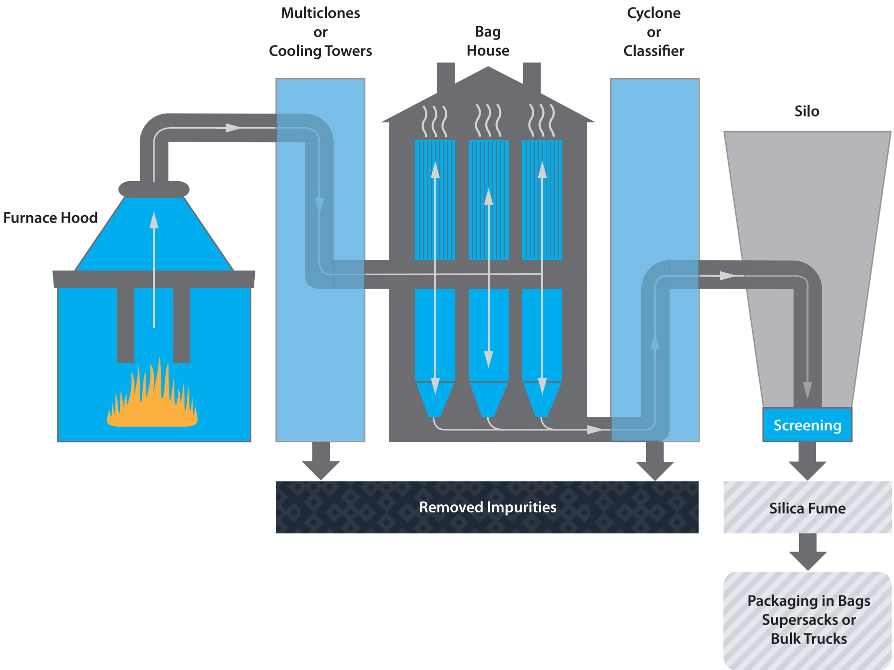

FIGURE 1.4. Schematic of a smelter and silica fume processing and cleaning system. Specific equipment and layout may vary at actual plants.

2 SILICA FUME PROPERTIES AND REACTIONS IN CONCRETE

The physical and chemical properties of silica fume affect the properties of concrete. These properties are described in this chapter.

Additionally, available silica-fume products and how silica fume contributes to the improvements in fresh and hardened concrete are discussed.

Finally, silica fume is compared to other supplementary cementitious materials.

2.1 CHEMICAL PROPERTIES

The primary chemical properties of silica fume are shown in Table 2.1. Following is a discussion of each of these properties. The major chemical properties are included in the standard specifications for silica fume as discussed in Chapter 4.

TABLE 2.1

CHEMICAL PROPERTIES OF SILICA FUME
Amorphous
Silicon dioxide > 85 percent
Trace elements depending upon type of fume

- **Amorphous.** This term simply means that silica fume is not a crystalline material. A crystalline material will not dissolve in concrete, which must occur before the material can react. There is a crystalline material in concrete chemically similar to silica fume. That material is sand. While sand is essentially silicon dioxide (SiO_2), it does not react because of its crystalline nature.

- **Silicon dioxide (SiO_2).** This is the reactive material in silica fume. How silica fume reacts in concrete is discussed in Section 2.4.

- **Trace elements.** There may be additional materials in the silica fume based upon the metal being produced in the smelter from which the fume was recovered. Usually, these materials have no impact on the performance of silica fume in concrete. Standard specifications may put limits on some of the materials in this category as is discussed in Chapter 4.

2.2 PHYSICAL PROPERTIES

The primary physical properties of silica fume are shown in Table 2.2. Following is a discussion of each of these properties. The major physical properties are included in the standard specifications for silica fume as discussed in Chapter 4.

TABLE 2.2

PHYSICAL PROPERTIES OF SILICA FUME	
Particle size (typical):	< 1 µm
Bulk density:	
(as-produced):	200 to 350 kg/m^3
(densified):	450 to 700 kg/m^3
Specific gravity:	2.2
Specific surface:	15,000 to 30,000 m^2/kg

- **Particle size.** Silica fume particles are extremely small, with more than 95 percent of the particles being less than 1 µm (one micrometer). Particle size is significant for both the physical and chemical contributions (discussed below) of silica fume in concrete. A photomicrograph of portland cement grains and silica fume particles is shown in Figure 2.1.

- **Bulk density.** This is another term for unit weight. The bulk density of the as-produced fume depends upon the metal being made in the furnace and upon how the furnace is operated. Because the bulk density of the as-produced silica fume is usually very low, it is not economical to transport it for long distances. See Section 2.3 for a discussion of the various product forms of silica fume.

- **Specific gravity.** Specific gravity is a unitless relative number that tells how silica fume compares to water, which has a specific gravity of 1.00. This number is used in proportioning concrete as is discussed in Chapter 5. Silica fume has a specific gravity of about 2.2, which is somewhat lighter than portland cement, which has a specific gravity of 3.15. Thus, adding silica fume to a concrete mixture will not increase the density (unit weight).

2.2 PHYSICAL PROPERTIES

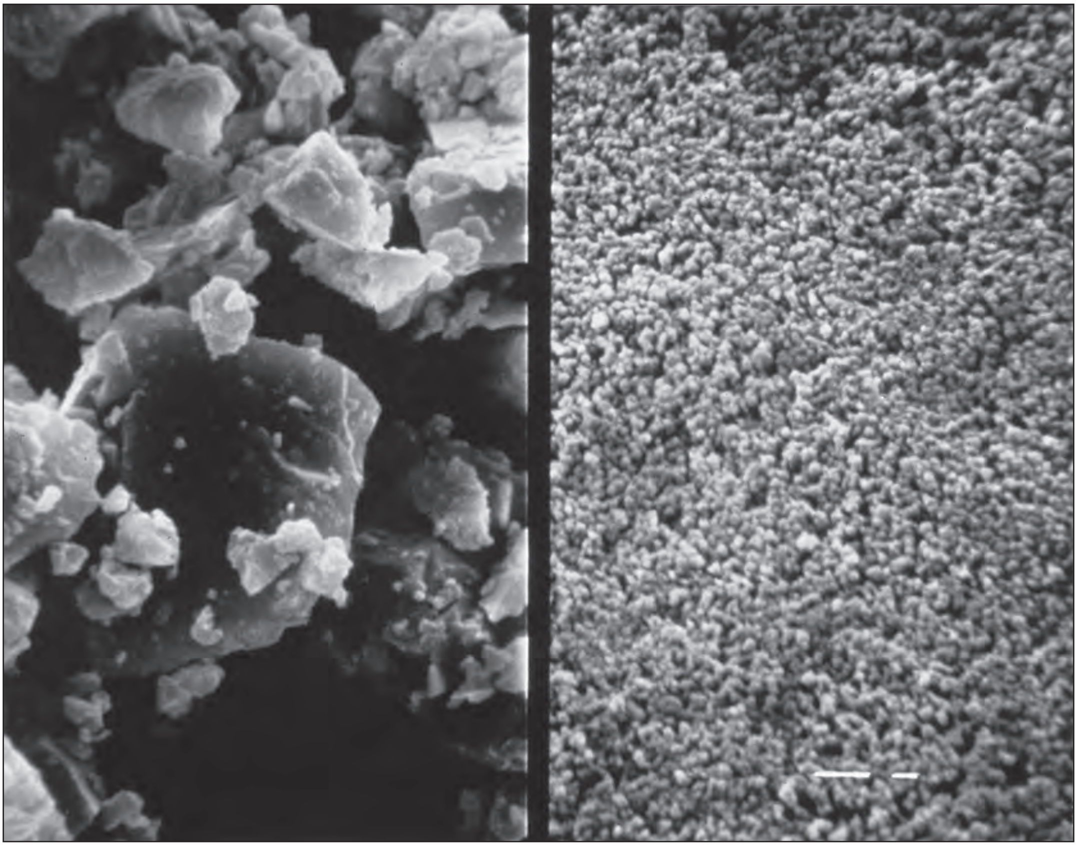

FIGURE 2.1. Photomicrograph of portland cement grains (left) and silica-fume particles (right) at the same magnification. The longer white bar in the silica fume side is 1 micrometer long. For commonly used dosages of silica fume, there will be a very large number of silica-fume particles for each cement grain.

- **Specific surface.** Specific surface is the total surface area of a given volume of a material. Because the particles of silica fume are very small, the surface area is very large. We know that water demand increases for sand as the particles become smaller; the same happens for silica fume. That's why it is necessary to use silica fume in combination with a water-reducing admixture or a superplasticizer. A specialized test called the "BET method" or "nitrogen adsorption method" must be used to measure the specific surface of silica fume. Specific surface determinations based on sieve analysis or air-permeability testing are meaningless for silica fume because of the extremely small particle size.

2.3 PRODUCT TYPES

Silica fume has historically been available in four basic product forms: undensified, slurried, densified, and pelletized. After many years of testing and producing silica-fume concrete around the world, there is no evidence to show that, in a well-designed, properly produced concrete mixture, any of the forms gives better results than the others.

Slurried silica fume is no longer available in the U.S. market; it may be available outside the U.S. Undensified silica fume is available, but it is not frequently used in ready-mixed or precast concrete. Undensified silica fume is primarily used in pre-bagged products such as grouts or repair mortars. Pelletized silica fume is primarily used in blended cements. Slurried, undensified, and pelletized silica fume are not discussed in detail in this manual.

Figure 2.2 shows densified silica fume and Table 2.3 shows some of the characteristics of this product form. Densified silica fume is produced by treating undensified silica fume to increase the bulk density to between 450 and 700 kg/m^3. This increase in bulk density is usually accomplished by tumbling the silica-fume particles in a silo, which causes surface charges to build up. These charges draw the particles together to form weak agglomerates. Because of the increased bulk density, this material is more economical for truck transportation.

FIGURE 2.2. Densified silica fume.

2.3 PRODUCT TYPES

TABLE 2.3

PRODUCT CHARACTERISTICS OF DENSIFIED SILICA FUME*
■ Reversible agglomeration process
■ Flows well pneumatically
■ Bulk transportation is economical: 20 metric tons in a bulk tanker
■ Product bulk density can be controlled for handling conditions and applications

**This is the form of silica fume that is most frequently used in concrete construction.*

Densified silica fume works very well in concrete. However, one caution when working with this product form is to ensure that the mixing is adequate to break up the particle agglomerations. Mixing in some types of mixers such as those that are used in dry-mix shotcrete, roof tiles, or other applications where coarse aggregate is not present may not be adequate to break up the agglomerations. In those situations, undensified silica fume may be more appropriate. Contact the SFA for assistance in these types of applications. Additional information on mixing densified silica fume is presented in Chapter 6.

Densified silica fume is available as shown in Table 2.4. In bulk, the densified silica fume may be stored and dispensed like any other cementitious material in a concrete plant. Additional information on storing and dispensing densified silica fume is presented in Chapter 6.

TABLE 2.4

SILICA FUME PRODUCT AVAILABILITY

PRODUCT FORM	BULK	22.7 kg (50 Lb) BAGS	11.4 kg (25 Lb) BAGS	BIG BAGS
Undensified	Yes	Yes	No	Yes*
Densified	Yes	Yes	Yes	Yes*

**Mass in these bags as agreed upon with suppliers.*

2.4 REACTIONS IN CONCRETE

The benefits seen from adding silica fume are the result of changes to the microstructure of the concrete. These changes result from two different but equally important processes. The first of these is the physical aspect of silica fume and the second is its chemical contribution. Here is a brief description of both of these aspects:

- **Physical contributions** — Adding silica fume brings millions of very small particles to a concrete mixture. Just like fine aggregate fills in the spaces between coarse aggregate particles, silica fume fills in the spaces between cement grains. This phenomenon is frequently referred to as particle packing or micro-filling. Even if silica fume did not react chemically, the micro-filler effect would bring about significant improvements in the nature of the concrete. Table 2.5 and Figure 2.3 compare the size of silica-fume particles to other concrete ingredients to help understand how small these particles actually are.

- **Chemical contributions** — Because of its very high amorphous silicon dioxide content, silica fume is a very reactive pozzolanic material in concrete. As the portland cement in concrete begins to react chemically with water, it forms calcium silicate hydrates and releases calcium hydroxide. The silica fume reacts with this calcium hydroxide and water to form additional calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from the portland cement. It is this essentially additional binder that gives silica-fume concrete its improved hardened properties.

TABLE 2.5

COMPARISON OF SIZE OF SILICA FUME PARTICLES AND OTHER CONCRETE INGREDIENTS

MATERIAL	SI UNITS	NOMINAL SIZE
Silica fume particle	0.5 µm	—
Cement grain	45 µm	No. 325 sieve
Sand grain	2.36 mm	No. 8 sieve
Coarse aggregate particle	19.0 mm	3/4 inch sieve

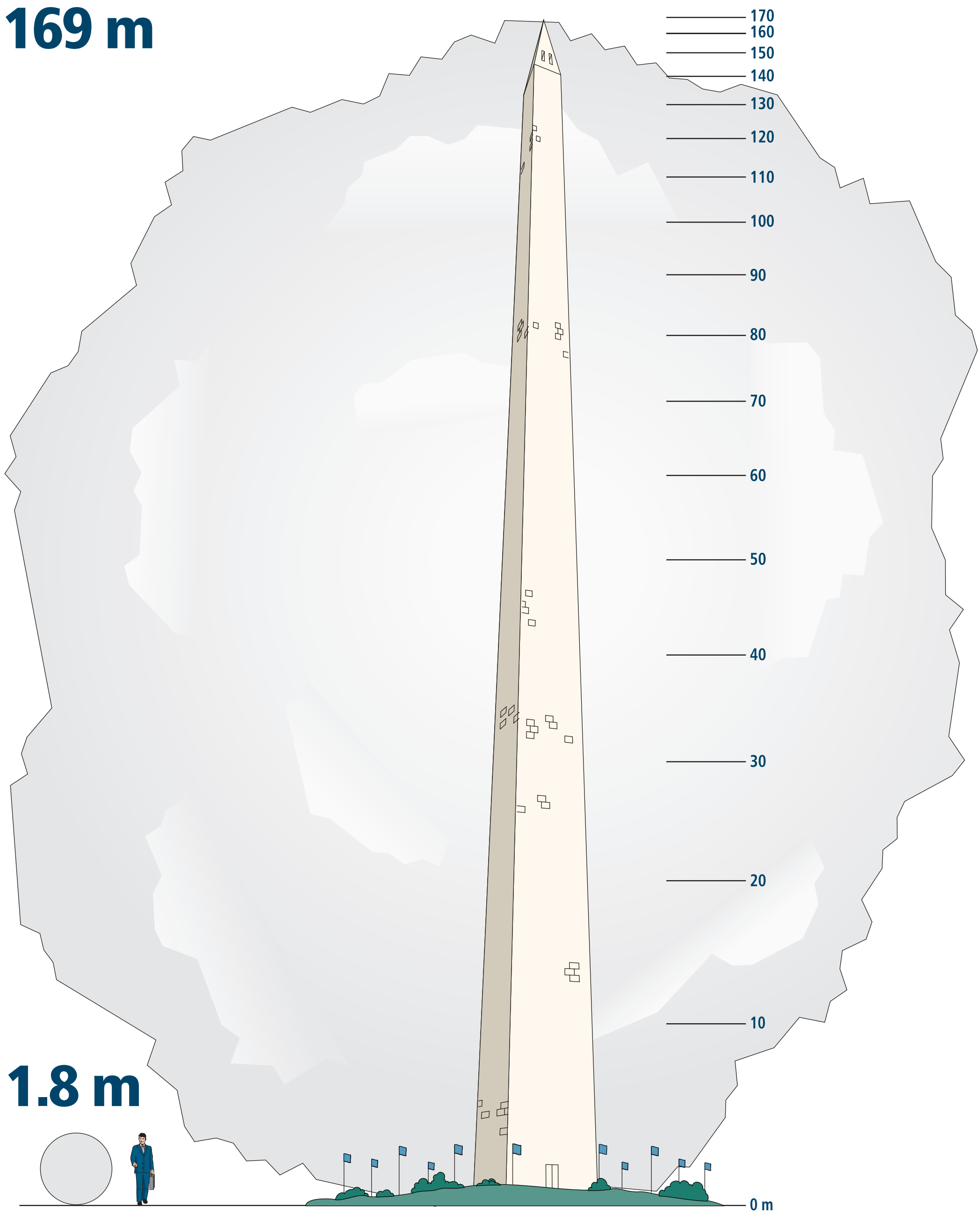

FIGURE 2.3. General size comparison of silica-fume particles. If a person (1.8 m) were the size of a silica-fume particle, then a cement grain would be approximately the size of the Washington Monument (169 m).

2.5 COMPARISON WITH OTHER SUPPLEMENTARY CEMENTITIOUS MATERIALS

Silica fume is rarely used as a direct replacement material for portland cement. It is instead used to enhance the properties of the concrete, through the combined particle packing and pozzolanic effects. Fly ash or slag cement are used as cement replacement materials. Both of these materials are frequently used in combination with portland cement and silica fume. In this usage, cement can be replaced by moderate to large volumes of slag cement or fly ash, and the performance of the concrete is enhanced by the addition of the silica fume. This practice reduces the use of portland cement, which also reduces the carbon footprint of the concrete.

Table 2.6 presents a comparison of silica fume and other commonly used supplementary cementitious materials. Silica fume is typically much more reactive, particularly at early ages, because of its higher silicon dioxide content and its very small particle size.

TABLE 2.6

COMPARISON OF CHEMICAL AND PHYSICAL CHARACTERISTICS — PORTLAND CEMENT, FLY ASH, SLAG CEMENT, AND SILICA FUME

Note that these are approximate values. Values for a specific material may vary from what is shown. (Note 1)

PROPERTY	PORTLAND CEMENT	CLASS F FLY ASH	CLASS C FLY ASH	SLAG CEMENT	SILICA FUME
SiO_2 content, percent	21	52	35	35	85 to 97
Al_2O_3 content, percent	5	23	18	12	—
Fe_2O_3 content, percent	3	11	6	1	—
CaO content, percent	62	5	21	40	< 1
Fineness as surface area, m^2/kg *(Note 2)*	370	420	420	400	15,000 to 30,000
Specific gravity	3.15	2.38	2.65	2.94	2.22
General use in concrete	Primary binder	Cement replacement	Cement replacement	Cement replacement	Property enhancer

Note 1. Information from SFA and Kosmatka, Kerkoff, and Panarese (2016).

Note 2. Surface area measurements for silica fume by nitrogen adsorption method. Others by air permeability method (Blaine).

3 WHY IS SILICA FUME USED IN CONCRETE?

Silica fume is used in concrete because it significantly improves the properties of fresh and hardened concrete. More recently, the benefits of using silica fume to increase sustainability have been recognized. The potential for using silica fume in concrete was known in the late 1940s, but the material did not become widely used until the development of another concrete technology. This parallel technology is the use of powerful dispersants known as high-range water-reducing admixtures or superplasticizers. Once these chemical admixtures became available and accepted, the use and development of silica fume in concrete became possible.

This chapter describes some of the effects of adding silica fume on fresh and hardened concrete including UHPC. The use of silica fume to enhance constructibility and sustainability is also discussed.

3.1 SILICA FUME AND FRESH CONCRETE

Figure 3.1 shows the effects of silica fume in fresh concrete. There are two distinct effects: the concrete is more cohesive and the concrete exhibits little or no bleeding. Although some finishers may look at these effects as making the concrete more difficult to place and finish, these are actually advantages to the fresh and hardened concrete.

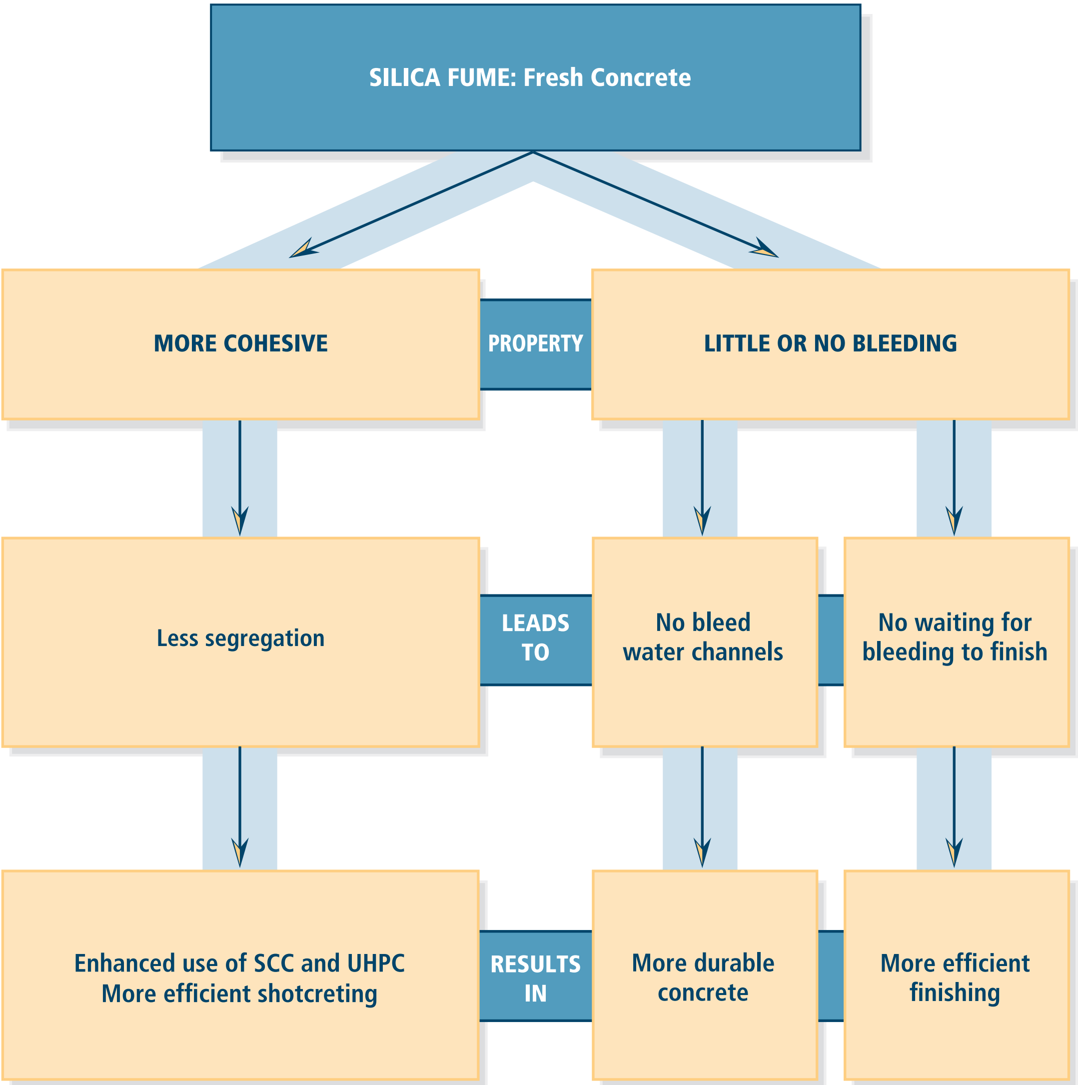

FIGURE 3.1. The viscosity-modifying effects of silica fume on fresh concrete and their influence on constructability.

3.1 SILICA FUME AND FRESH CONCRETE

3.1.1 Increased Cohesion

Fresh concrete made with silica fume is more cohesive and therefore less prone to segregation than concrete without silica fume. The increased cohesion allows silica-fume concrete to be used in very high fluidity applications such as self-consolidating concrete (SCC) or ultra-high-performance concrete (UHPC). (These materials are discussed later in this chapter.) If slump flow (ASTM C1611, *Standard Test Method for Slump Flow of Self-Consolidating Concrete,*) is used to characterize the concrete, values of 600 to 750 mm can be obtained without segregation. If fluidity is measured by slump, silica-fume concrete is typically placed at least 50 mm greater slump than concrete without silica fume in the same placement.

One additional benefit from increased cohesion can be seen in shotcrete, whether it is for new construction, repair of existing structures, or ground support in tunneling operations. Use of silica fume in shotcrete is discussed in Section 3.3.

3.1.2 Reduced Bleeding

Because of the high surface area of the silica fume and the usually low water content of silica-fume concrete, there will be very little, if any bleeding. Once a silica fume content of about five percent is reached, there will be no bleeding in most concretes mixtures.

Concrete bleeds as the heavier components settle under the influence of gravity before the concrete stiffens. As the heavier components settle, the lighter water is forced upward. Some of the water is trapped under aggregate particles or reinforcing steel and some of it reaches the surface of the concrete. This movement of water takes place in what are called capillary channels as is shown in Figure 3.2. Once the water evaporates, these channels serve as shortcuts for aggressive agents such as chloride ions from deicing salts or sea water to get back into the concrete. Therefore, the reduction or elimination of these channels improves the durability of the concrete.

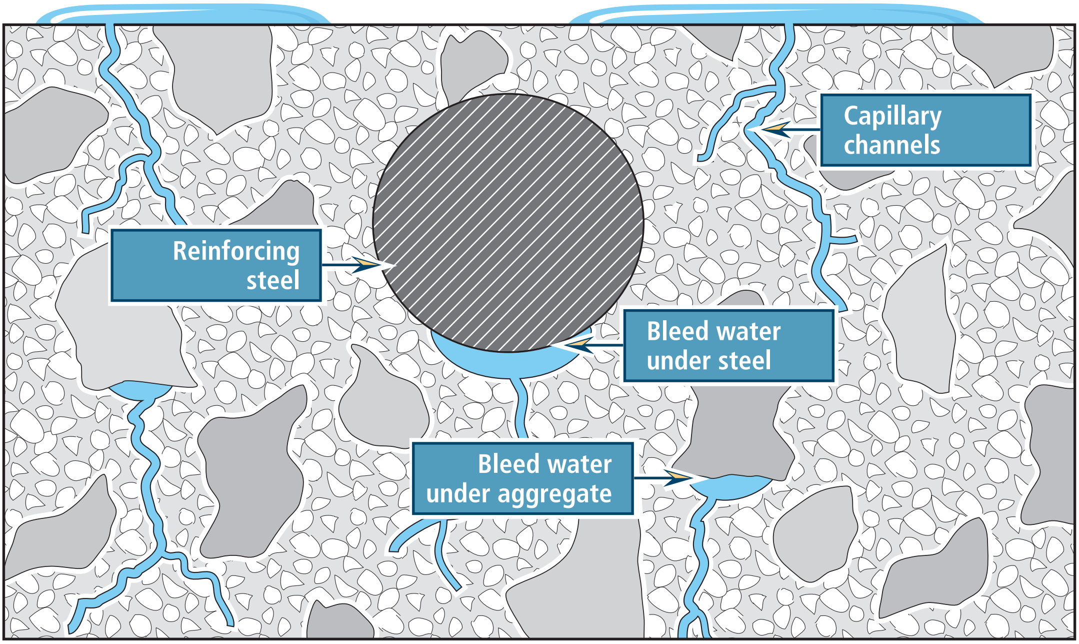

FIGURE 3.2. Schematic of bleeding and capillary channels. Reduction or elimination of bleeding is a benefit of adding silica fume to a concrete mixture.

In addition to the improvements in durability, the lack of bleeding allows a more efficient finishing process to be used with silica-fume concrete flatwork. For conventional concrete, it is critical not to conduct finishing operations until all bleeding has stopped and all bleed water has evaporated from the surface. Thus, there is usually a several-hour waiting period after the initial placing and finishing operations. Once bleed water has disappeared and the concrete has gained sufficient strength, final finishing is started.

3.1 SILICA FUME AND FRESH CONCRETE

With silica-fume concrete showing no bleeding, the finishing operation can be continuous from placement to texturing and curing. This approach is called "one-pass" or "fast-track" finishing and is particularly advantageous in structures where silica fume is likely to be specified for durability such as bridge decks or parking structures. Figure 3.3 shows one-pass finishing of silica-fume concrete in a parking structure. Unless a special finish is required, it is not unusual for finishing of silica-fume concrete to be completed within a half hour of the concrete arriving on the deck. Finishing is discussed in detail in Chapter 7.

FIGURE 3.3. One-pass finishing of silica-fume concrete in a parking structure. Placing, finishing, texturing, and curing are done as a continuous process.

3.2 SILICA FUME AND HARDENED CONCRETE

Figure 3.4 shows the effects of silica fume in hardened concrete. There are two distinct effects: enhanced mechanical properties such as strength and modulus of elasticity, and enhanced durability, which is largely achieved by reduced permeability. Both of these effects are discussed in the following sections.

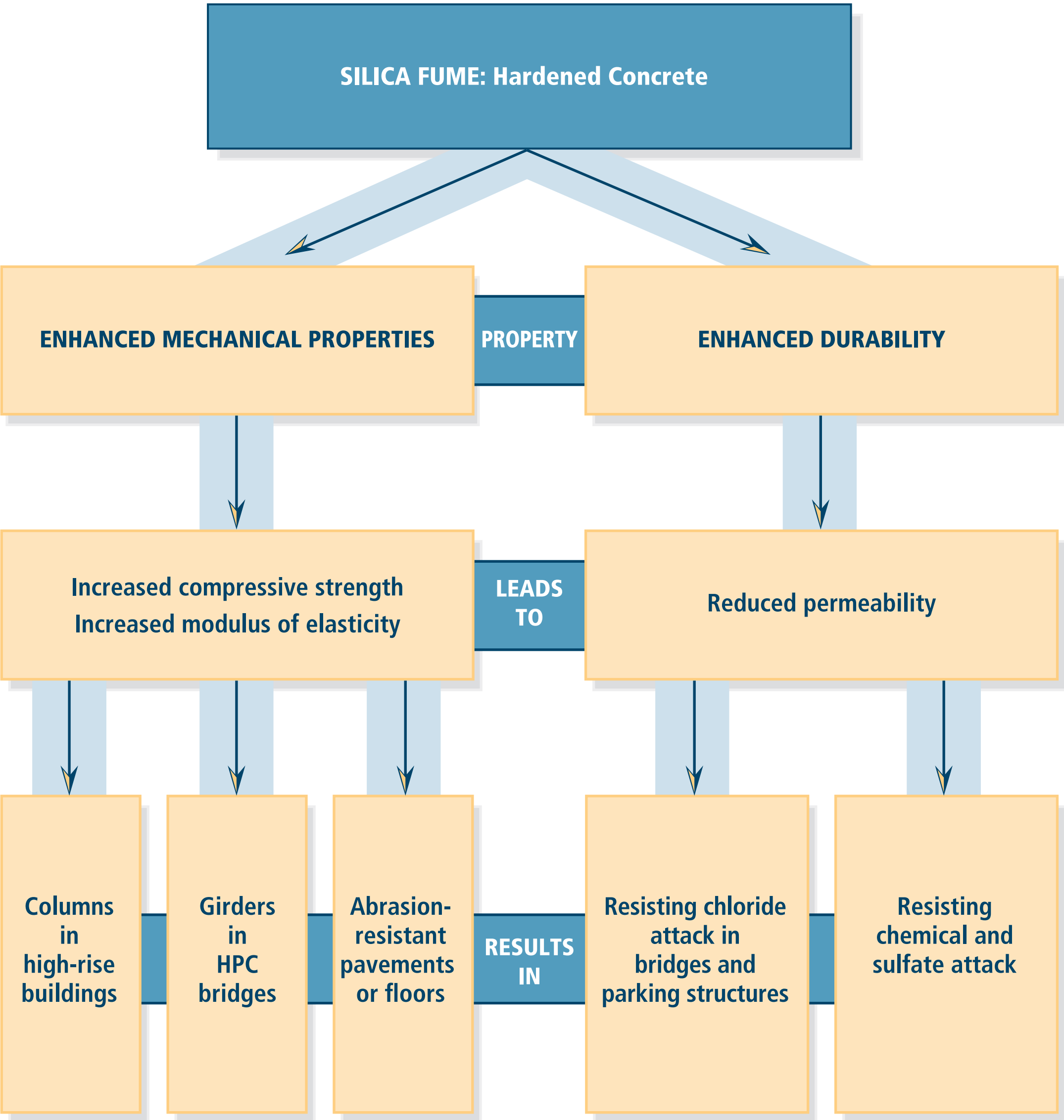

FIGURE 3.4. Effects of silica fume on hardened concrete and how those effects are used in concrete applications.

3.2 SILICA FUME AND HARDENED CONCRETE

3.2.1 Enhanced Mechanical Properties

Silica fume gained initial attention in the concrete market because of its ability to produce concrete with very high compressive strength. Improvements in other mechanical properties such as modulus of elasticity or flexural strength are also seen. Although concrete has been specified to take advantage of improvements in these other properties, the mechanical property of most interest is certainly compressive strength.

3.2.1.1 – Increased Compressive Strength

Figure 3.5 shows the effects on compressive strength of using different amounts of cement, fly ash, silica fume, and water in concrete. Basic mixture information is provided in Table 3.1. The curves that are shown are typical of what may be expected. There are several important points in this figure:

1. The increase in strength is proportional at all ages. Thus, the ratio of 3-day or 7-day strength to 28-day strength is reasonably consistent, regardless of the 28-day strength achieved. This ratio will be about the same for concrete with or without silica fume — the 3-day strength will be about 50 percent and the 7-day strength will be about 70 percent of the 28-day strength.

2. Adding more silica fume will usually increase strength. However, the effects of water content, fly ash content and type, if used, and silica fume all interact to determine the compressive strength and the rate of compressive strength development.

3. Silica fume has most of its impact on compressive strength by about 28 days. While the concrete will usually continue to gain strength after 28 days, the rate of strength gain will be much slower. This strength gain curve is very different from an ASTM C618 Class F fly ash, which is also a purely pozzolanic material.

4. The results presented are from different projects using different materials. **You must test any proposed mixture proportions using your project-specific materials.**

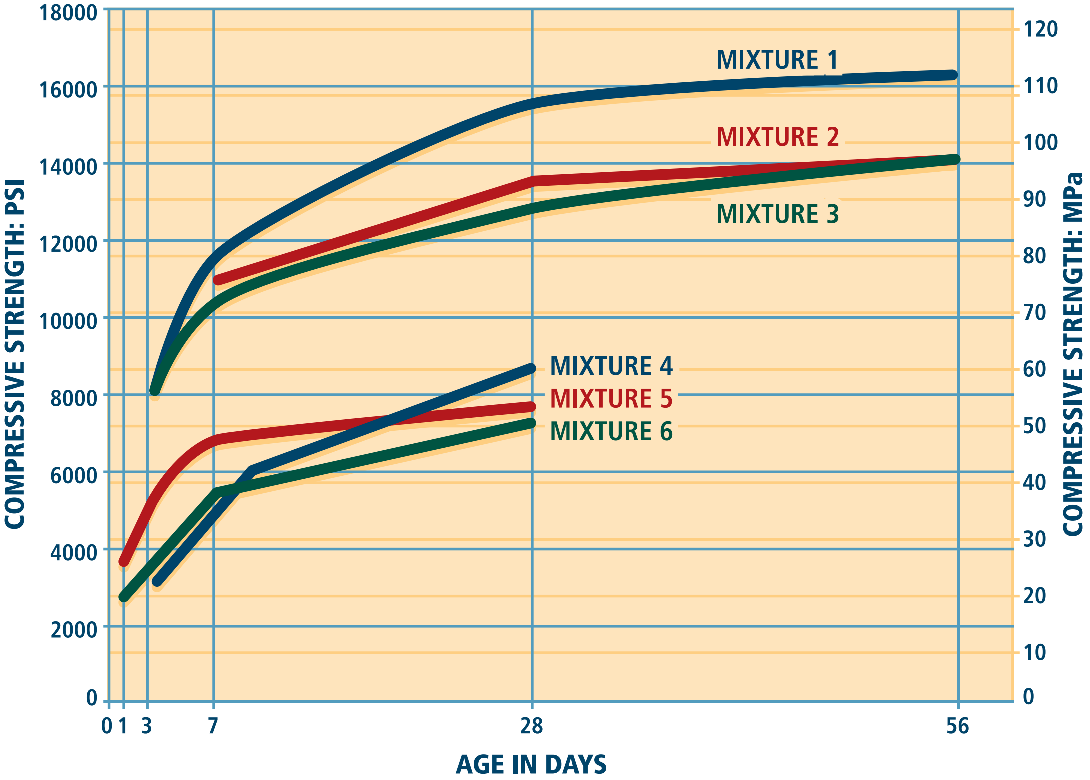

FIGURE 3.5. Strength development of several concrete mixtures containing silica fume. Details for the mixtures are provided in the table below.

TABLE 3.1

CONCRETE MIXTURES USED FOR STRENGTH DEVELOPMENT DATA SHOWN IN FIGURE 3.5

MIXTURES	CEMENT kg/m³	FLY ASH kg/m³	SF kg/m³	SF percent *(Note 1)*	W/CM
1 *(Note 3)*	475	104	74	11	0.23
2 *(Note 2)*	390	71	48	9	0.37
3 *(Note 3)*	475	59	24	4	0.29
4 *(Note 2)*	390	—	27	6	0.35
5 *(Note 2)*	362	—	30	8	0.39
6 *(Note 2)*	390	—	30	7	0.37

Note 1. Silica fume as a percentage of total cementitious materials, by mass.
Note 2. Data provided by Elkem.
Note 3. Data from Burg and Ost (1994). These are mixtures 8 and 9 in Table 5.3 of this manual.

3.2 SILICA FUME AND HARDENED CONCRETE

Several examples of how high-strength concrete is used in construction are described below.

The earliest applications for high-strength silica-fume concrete were in columns for high-rise structures as shown in Figure 3.6. When analyzing how building loads are carried to a foundation, it turns out that using high-strength concrete is very efficient. As concrete strength is increased, column size can be reduced. In addition to reducing the size of the columns, using this concrete can reduce and simplify the reinforcing steel used in the columns. Overall, more floor space is available to the owner of the structure, which can be a significant cost advantage in urban areas. The reduction in column size and reinforcement for a typical loading is shown in Table 3.2. Additional information on using high-strength concrete to reduce column size and reinforcement may be found in the paper by Smith and Rad (1989). By reducing the amount of concrete and reinforcing steel required, high-strength concrete columns also contribute to the sustainability of the structure.

FIGURE 3.6. High-strength silica-fume concrete column in a high-rise structure.

TABLE 3.2

REDUCTION OF COLUMN SIZE AND REINFORCEMENT BASED ON INCREASING CONCRETE COMPRESSIVE STRENGTH Load on column is 50 MN. (Data from SFA.)

CONCRETE STRENGTH, MPa	COLUMN SIZE, meters	REINFORCEMENT REQUIRED	COMMENTS
40	1.2 x 1.2	56 No. 36	Base case
55	1.2 x 1.2	24 No. 29	Save steel
85	1.2 x. 0.75	24 No. 22	Save steel and reduce size
85	0.95 x 0.95	24 No. 22	Save steel and reduce size

3.2.1.2 – Increased Compressive Strength in Bridges

High-strength concrete or ultra-high-performance concretes have been used in bridges constructed by various state DOTs. In general, these DOTs have used these concretes to achieve one or more of these four objectives:

- **To increase the span of a bridge.** Figure 3.7 shows a bridge constructed by Ohio DOT in which a single span replaced three spans in the previous bridge at this site.

FIGURE 3.7. High-performance concrete bridge. In this bridge in Ohio, high-strength concrete was used to increase span length and eliminate a pier in the river. For more information on this bridge, see the article by Miller (1999).

- **To reduce the number of girders for a given span.** Figure 3.8 shows a bridge constructed by New Hampshire DOT where the number of girders was reduced from seven to five.

FIGURE 3.8. High-performance concrete bridge. In this bridge in New Hampshire, high-strength concrete was used to reduce the number of girders required for the structure. For more information on this bridge, see the article by Wasczik (1999).

- **To reduce the section height for a given span.** Colorado DOT used high-strength silica-fume concrete for the bridge in Figure 3.9. Here, a two-span bridge replaced an earlier four-span bridge. The new girders were shallower than the earlier ones, giving an increase in clearance of about 450 mm.

FIGURE 3.9. High-performance concrete bridge. In this bridge in Colorado, high-strength concrete was used to increase span length to eliminate two piers and to increase clearance under the bridge. For more information on this bridge, see the article by Leonard (1999).

- **To increase bridge performance.** Ultra-high-performance concrete (UHPC) has been used in a variety of bridge applications to increase performance. UHPC properties allow designers to incorporate shallower cross-sections, thinner members, and longer spans. In repair and rehabilitation applications, lower weight loads and high durability levels are readily achievable. See Section 3.4 for additional discussion of using UHPC.

3.2.2 Enhanced Durability

Using silica fume in concrete enhances durability through three mechanisms: reducing permeability, pozzolanic activity, and increasing compressive strength. These mechanisms are described in the following sections.

3.2.2.1 – Reduced Permeability

In many situations, the durability of concrete is directly related to its permeability. One means of reducing permeability is to reduce the w/cm of the concrete. However, using silica fume can significantly further reduce the permeability of concrete. (This additional reduction is discussed in more detail below.) Figure 3.10 explains permeability and why it is important in concrete. By reducing the permeability, the time is extended for any aggressive chemical to get into the concrete and cause damage. Following are a few examples of how reducing permeability is used in actual structures.

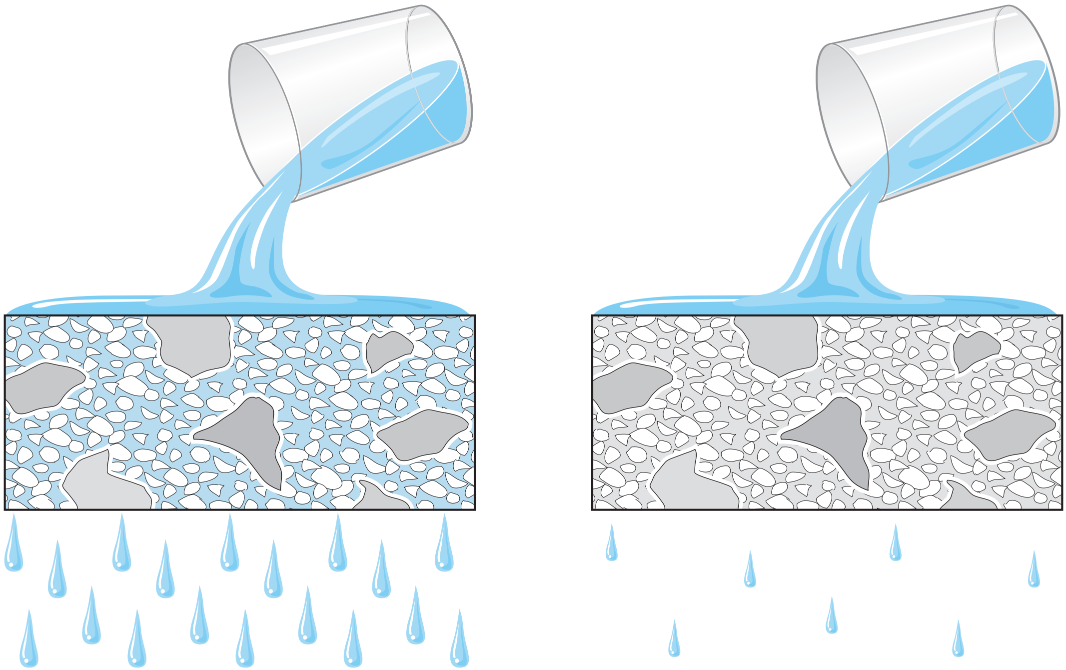

FIGURE 3.10. Schematic of concrete permeability. A high permeability concrete (left) allows water to move into and through the concrete readily. Lowering the w/cm and adding silica fume can reduce permeability to essentially zero (right). Such a reduction makes it very difficult for water and aggressive chemicals such as chlorides or sulfates to enter the concrete.

- **Chloride damage to reinforcing steel.** Corrosion of reinforcing steel is the most significant and costly cause of concrete deterioration. Figure 3.11 shows how corrosion occurs in concrete. It doesn't matter whether the chloride comes from the ocean or from deicing salts, the results are the same. Silica-fume concrete is used widely in applications where the concrete is exposed to salt from any source. The reduced permeability of this concrete can result in many years of extended life for a structure.

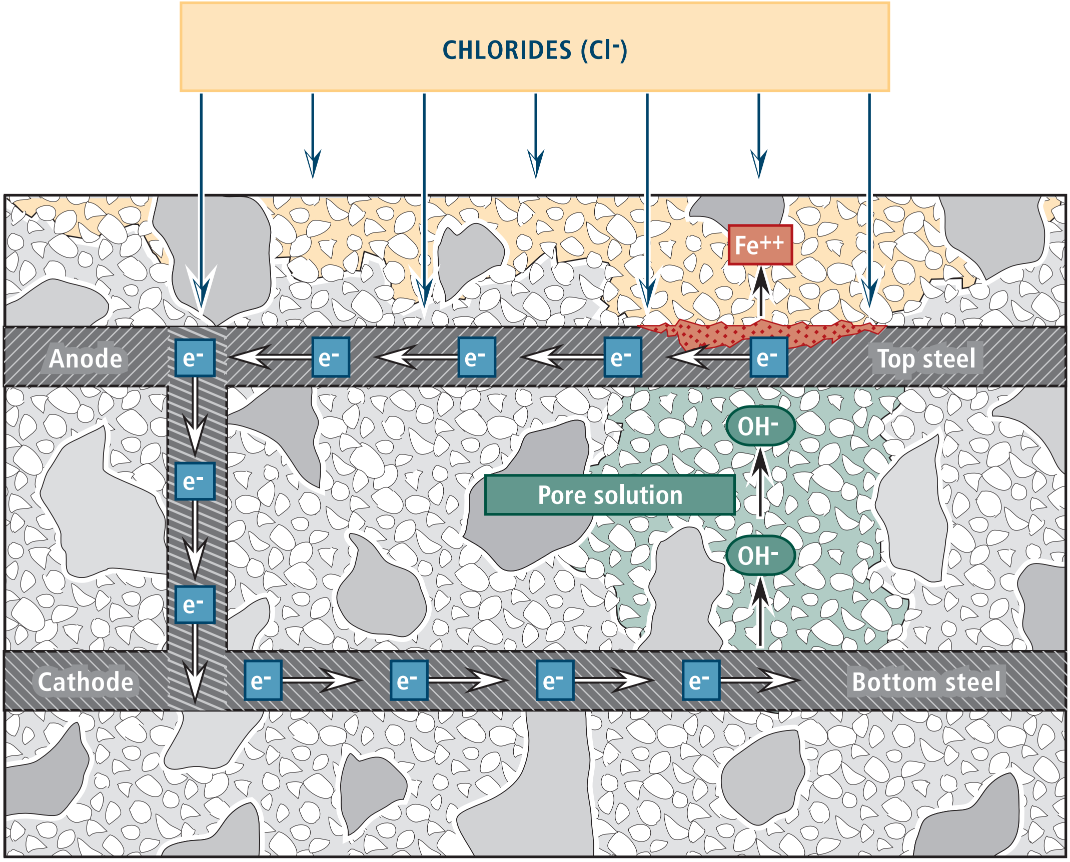

FIGURE 3.11. Schematic of corrosion in reinforced concrete. At the anode, chloride ions interact with iron to produce Fe^{++} ions. The electrons released flow through the reinforcing steel to the cathode. The electrical path is completed by OH^- ions flowing through the pore solution (electrolyte). In some cases, the anode and cathode may both be on the same bar. By reducing the permeability of the concrete, silica fume delays the chlorides reaching the steel.

3.2 SILICA FUME AND HARDENED CONCRETE

Figures 3.12 and 3.13 show concrete with damage caused by corrosion. Note that corrosion damage in concrete is a multi-step process as follows:

1. The chloride ions slowly work into the concrete to reach the level of the reinforcing steel. Once a certain amount of chlorides, called the threshold amount, reach the steel, corrosion begins. The chloride ions are not consumed in the process — they will continue to cause additional corrosion.
2. As the iron ions are removed from the reinforcing steel, they go through several stages of oxidation or rusting. The volume of the rust increases with each stage.
3. As the amount of rust increases, rust stains will be seen on the surface of the concrete. Next, cracking will be seen. Finally, the cracking will result in delaminations and spalling of concrete over the reinforcing steel.

Because silica fume is a pozzolanic material that reacts with calcium hydroxide, concerns have been raised over a possible reduction of concrete pH so that the reinforcing steel is no longer passivated. Any reduction in concrete pH from using silica fume is small and does not impact the passivity of the reinforcing steel.

FIGURE 3.12. Corrosion damage to a marine structure.

FIGURE 3.13. Corrosion damage to a highway overpass. Note that chlorides have apparently run off of the deck and onto this pier. Structural elements, as well as decks, should be protected.

- **To increase the life expectancy of bridges exposed to chlorides.** With decades of data on concrete bridge construction and associated repairs or replacements, extending the service life of concrete bridges, particularly those exposed to harsh chloride environments, can significantly reduce life-cycle costs. To maximize longevity in infrastructure, chloride permeability ratings as determined by ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, typically referred to as the Rapid Chloride Permeability Test (RCPT,) are often specified, sometimes in conjunction with a specified service life. Figure 3.14 shows how changing w/cm and adding silica fume can change the chloride permeability of concrete. Reducing w/cm shows some benefit, but the addition of silica fume is much more effective as measured by both tests shown.

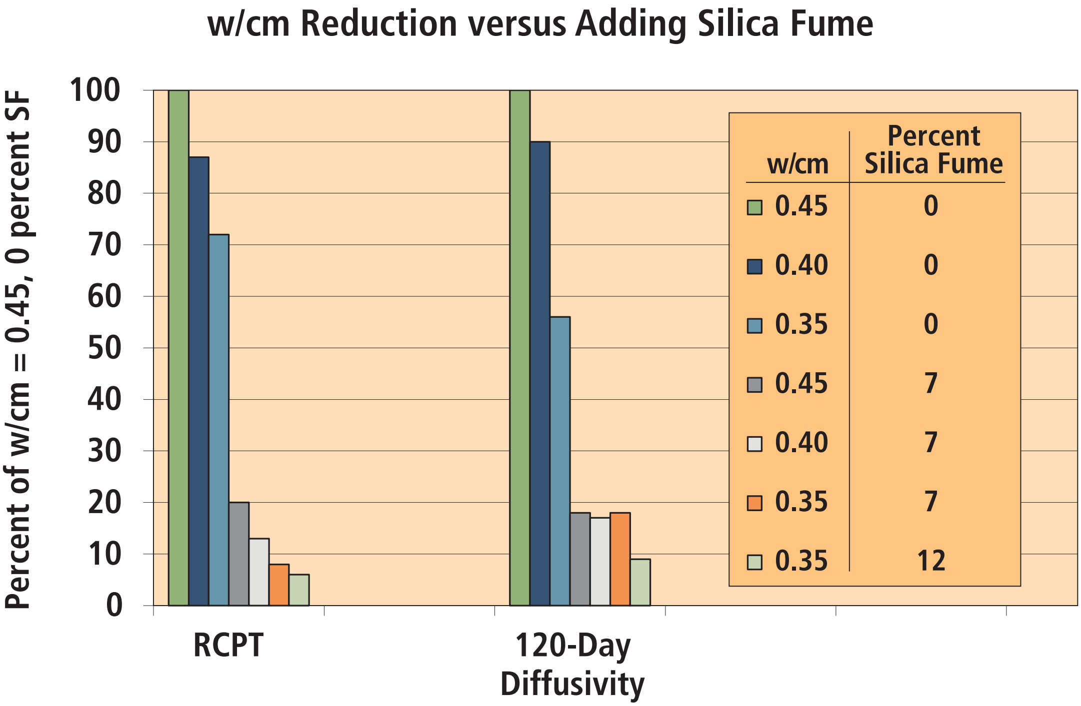

FIGURE 3.14. Comparison of w/cm reduction and adding silica fume on the chloride permeability of concrete. The base case (w/cm of 0.45 and no silica fume) had a RCPT value of approximately 3500 coulombs. This concrete also had a 120-day diffusivity of 10.5 x 10^{-12} m2/sec. (Hooton, et.al 1997.)

Additionally, software, Life-365,™* is available that allows predictions of service life in a variety of chloride exposures. Data from several silica-fume concrete mixtures showing chloride ratings and predicted service life are presented in Chapter 5. Figure 3.15 shows a bridge in a marine environment where silica-fume concrete was used to reduce chloride permeability and increase expected service life. Figure 3.16 shows a 32.5 km long bridge with a specified service life of 100 years.

FIGURE 3.15. After Hurricane Katrina damaged the I-10 Highway into New Orleans, the Louisiana Department of Transportation designed its replacement for longer service life with increased concrete durability, specifying a very low rapid chloride permeability rating on its new concrete structure.

**Life-365™ may be obtained free of charge from the SFA website. The trademark for Life-365 is owned by the SFA. The trademark superscript will not be shown in the remainder of the manual.*

FIGURE 3.16. Specifications of the 32.5 km long East Sea Bridge between Shanghai Harbor and Little Yangshan Island required a 100-year service life. Quaternary high-performance concrete including portland cement, silica fume, fly ash and slag cement was utilized for the 35 MPa and 50 MPa structural designs, yielding a chloride diffusion coefficient reduction up to 75 percent over conventional concrete and very low rapid chloride permeability below 750 coulombs.

- **Sulfate attack.** While the chemistry of the portland cement used plays an important role in sulfate attack, it has been shown that the water-cementitious materials ratio (w/cm) is also a critical factor. Reducing the w/cm effectively reduces the permeability of the concrete. Adding silica fume will further reduce the permeability resulting in further delays of any adverse reactions.

3.2.2.2 Pozzolanic Activity

In some situations where enhanced durability is required, silica fume can provide protection by its pozzolanic reaction. Usually, this reaction works in conjunction with reducing permeability to increase durability. Examples are:

- **Chemical attack.** Depending on the nature of the aggressive chemical, and the concrete mixture used, silica-fume concrete can be more resistant to this form of attack than an ordinary portland cement concrete. This improved resistance is due to the consumption of some calcium hydroxide by the pozzolanic reaction and the greatly reduced permeability. Such resistance to aggressive chemicals can extend the service life of a structure, or the intervals between maintenance operations. When designing a silica-fume concrete mixture for resistance to any specific chemical attack, it is essential to carry out exposure tests to establish the optimum dosage of silica fume for the application.

- **Alkali-silica reaction.** There is ample evidence that silica fume, when used alone or in conjunction with a suitable fly ash, can reduce or eliminate the potential for alkali-silica reaction when reactive aggregates are used. Testing will be required to determine the appropriate amount and types of cementitious materials to be used for each particular application. See ASTM C1778, *Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete*, for guidance on testing and selecting the appropriate amounts of silica fume to be used.

3.2.2.3 Increased Compressive Strength

Increased compressive strength can play a direct role in increasing the resistance of concrete to abrasion.

- **Abrasion resistance.** For concrete made with a particular aggregate, the higher the compressive strength, the higher the abrasion resistance. Additionally, silica-fume concrete develops greater bond to aggregates particles, which increases abrasion resistance. High-strength silica-fume concrete has been used in applications such as waste transfer stations and stilling basins in major dams. See Figure 3.17.

In 2014 the SFA sponsored a research program for the Federal Railroad Administration (FRA) to address rail-seat abrasion of concrete rail crossties. Concrete mixtures tested and performance data are presented in Chapter 5.

FIGURE 3.17. Abrasion-erosion damaged concrete. This structure was repaired using high-strength silica-fume concrete with a specified compressive strength of 86 MPa. For more information on this project, see the article by Holland et al. (1986).

3.3 SILICA FUME AND CONSTRUCTABILITY

Another way to look at the use of silica fume is from the viewpoint of constructability. Here, we are stepping across the boundary between effects on fresh and hardened concrete to take advantage of all aspects of the performance of silica-fume concrete to make construction easier or, in some cases, even possible. Here are a few examples:

- **One-pass finishing.** The lack of bleeding in silica-fume concrete offers the advantage of completing finishing in a single, continuous operation. The owner will get a better surface and the contractor will be able to complete the finishing in a shorter time using fewer finishers. One-pass finishing is discussed in detail in Chapter 7.

- **Reduced heat of hydration.** Although silica fume contributes about the same amount of heat of hydration as an equal mass of portland cement, its strength contribution is much greater on the same basis. Therefore, by balancing portland cement and silica fume in a mixture, the heat of hydration can be reduced while strength is maintained.

More and more state DOTs are using combinations of silica fume and fly ash to reduce the heat of hydration for concrete used in bridge decks. A typical such concrete from Colorado DOT is shown as Mixture 11 in Table 5.2. The total amount of cementitious material in this concrete is about the same as the amount of portland cement alone in many previous mixtures. Reducing the total amount of portland cement will reduce heat and help prevent early-age cracking.

- **Use of multiple cementitious materials.** There is an ever-increasing emphasis on using more recovered materials such as fly ash and slag cement in concrete. However, the early-age strength of concrete may suffer as a result. Adding small amounts of silica fume can offset this reduction in early strength. Mixtures containing three cementitious materials are referred to as “ternary mixtures.” Usually, using combinations of three cementitious materials will reduce the cost of concrete. Figure 3.18 shows a structure where silica fume was added to gain both a reduction in heat and to offset the loss of early-age strength resulting from using a large volume of fly ash.

3.3 SILICA FUME AND CONSTRUCTABILITY

FIGURE 3.18. Concrete containing portland cement, fly ash, and silica fume being placed. The fly ash was used to control heat of hydration, while the silica fume provided early strength required for stripping forms. For more information on this project, see the article by Holland (1998).

3.3 SILICA FUME AND CONSTRUCTABILITY

In a few cases, four cementitious materials have been used resulting in a "quaternary mixture" containing portland cement, silica fume, fly ash, and slag cement. The East Sea Bridge (shown earlier in Figure 3.16) used four cementitious materials. The World Trade Center, shown in Figure 3.19, also used a quaternary mixture for a highly pumpable and self-consolidating concrete. One of the concrete mixtures used on this structure is shown in Chapter 5.

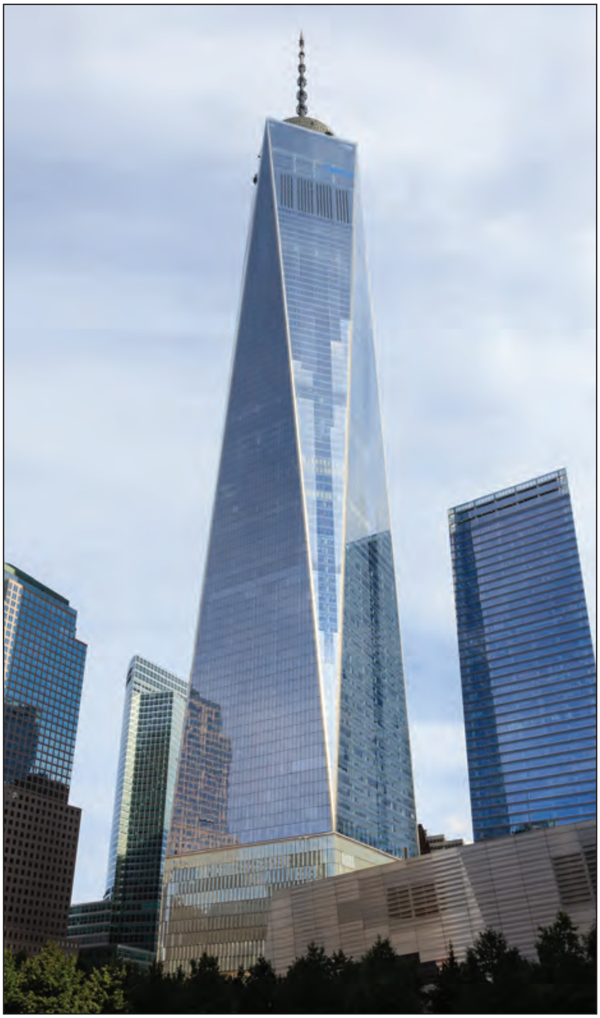

FIGURE 3.19. For the World Trade Center, high strength was initially the foremost goal for hardened concrete properties. The ability to achieve long-distance, vertical, single-stage pumpability of SCC coupled with consolidation around congested reinforcement was ultimately a more important goal in the fresh state of this concrete. This concrete mixture also was noted for its low-carbon footprint.

3.3 SILICA FUME AND CONSTRUCTABILITY

- **Shotcrete.** Silica-fume shotcrete is widely used, in both the wet and dry processes, with and without steel fibers (Figure 3.20A and B). The cohesive nature of this shotcrete allows for many applications that would have been difficult, uneconomical, or impossible to accomplish without the silica fume. Using silica fume in shotcrete allows for greater thickness of shotcrete layers, particularly when shooting overhead, and a significant reduction in rebound. Silica-fume shotcrete frequently includes steel fibers to provide increased flexural strength. Silica fume is compatible with all of the accelerators that are commonly used in shotcrete. Once the shotcrete is in place, all of the expected benefits of silica fume in hardened concrete come into play. An additional benefit is the increased bond strength of the silica-fume shotcrete to the underlying material and between lifts or layers in multi-pass applications.

FIGURE 3.20A. Overhead application of silica-fume shotcrete. Because of its increased cohesion, silica-fume shotcrete has much less rebound and allows for greater lift thickness when shooting overhead than shotcrete without silica fume.

FIGURE 3.20B. Robotic application of silica-fume shotcrete for ground support. This process is used with and without steel fibers for additional flexural performance.

- **Self-consolidating concrete (SCC).** SCC takes the workability of plastic concrete to a level beyond measurable slump, yet without segregation. Slump Flow (ASTM C1611) is measured instead of conventional slump. SCC minimizes or eliminates the necessity to consolidate concrete by mechanical means, making it ideal for difficult placement situations. The high workability affords a variety of placement advantages from expedited discharge from concrete-trucks to long distance continuous pumping. SCC can fill entire wall or column formwork quickly. This practice reduces the potential for cold joints, especially in larger volume placements. (When filling vertical forms, attention must be paid to designing formwork to withstand full hydraulic head.) Silica fume use in an SCC mix design improves cohesiveness to prevent segregation between paste and coarse aggregate and can be used as a tool to modify SCC viscosity. Because SCC is typically used in high-performance concrete applications, silica fume addition leads to higher strengths and other improved hardened concrete properties. An SCC mixture using silica fume is shown in Chapter 5.

3.4 SILICA FUME AND ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

UHPC is a relatively new concrete material that encompasses improvements in concrete strength and durability. As is discussed in Section 3.5, these increases also lead to increases in sustainability. This material is being used in new construction and repair of existing structures.

ASTM C1856, *Standard Practice for Fabricating and Testing Specimens of Ultra-High-Performance Concrete*, defines UHPC as concrete producing a compressive strength in excess of 120 MPa with other properties that comply with specified durability, ductility, and toughness requirements. A high cementitious materials content, often including large proportions of silica fume, in conjunction with a very low w/cm (typically ≤ 0.22) is frequently used to achieve compressive strength values of up to 200 MPa at 28 days of age. Use of 1 to 3 percent fiber content (both steel and polymer) may allow UHPC to be used without conventional steel reinforcement. Maximum aggregate sizing of less than 5 mm and very high dosages of HRWRA provide adequate workability to produce a highly cohesive yet self-consolidating composite that can be used in large volume specialty applications.

El-Tawil and associates (El-Tawil, et al. 2020) point out that many UHPC projects have been accomplished to date using proprietary mixtures. They advocate for open mixtures that can be produced by precast concrete producers or ready-mixed concrete suppliers. One of their generic mixtures for UHPC is shown in Table 3.3.

TABLE 3.3

GENERIC MIXTURE PROPORTIONS FOR UHPC.

MATERIAL	MASS, kg/m^3
Portland cement	387
Slag cement	387
Silica fume	194
Fine sand, 80-200 µm	236
Coarse sand, 400 to 800 µm	943
Water (w/cm = 0.17)	164
High-range water-reducing admixture *(Note 1)*	—
Steel fibers (2 percent by volume)	157

(El-Tawil, et al. 2020)

Note 1. 1.5 to 3.0 percent by weight of cementitious materials. Adjust to get adequate workability.

3.4 SILICA FUME AND ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

In the US one of the primary proponents for use of UHPC is the Federal Highway Administration (FHWA.) This agency has been researching and promoting the use of UHPC since the early 2000s. In 2022 FHWA published a summary of recommendations for using UHPC for bridge preservation and repair (FHWA 2022.) This document provides design and construction details and examples of projects including:

- Bridge deck overlays
- Link slabs to replace joints in simply supported spans Figures 3.21 A, B, C
- Steel beam end repair Figure 3.22
- Seismic retrofit
- Repair of corrosion damaged columns and wall panels

This report discusses proprietary and open source UHPC mixtures. Guidance for specifying concrete performance is also included.

A B C

FIGURE 3.21A, B, and C. Repair of a damaged bridge using a UHPC link slab. From left to right: A. Removal of deteriorated concrete; B. Link slab prepared for placement; and C. Completed repair. (FHWA 2022) (Photos copyright 2020 NYSDOT. Used with permission.)

3.4 SILICA FUME AND ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

FIGURE 3.22. End of steel bridge beam after repair using UHPC. (FHWA 2022)

3.4 SILICA FUME AND ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

Another area of interest for the FHWA has been the use of UHPC for field-cast connections between a variety of prefabricated bridge elements. These applications include connections between precast deck panels (Figure 3.23), deck panels and girders, precast abutments and adjacent box beams (FHWA 2019.) This publication states: “Between 2009 and 2018, nearly 200 bridge projects using field-cast UHPC connections between prefabricated elements have been completed in the United States.

FIGURE 3.23. UHPC placement between adjacent precast deck panels. (FHWA 2019)

Outside of the US, similar projects have been completed. The Chillon Viaduct, part of the Swiss A 9 highway, originally built in 1960, is comprised of two parallel 2.25 km long and 12 m wide prestressed concrete box girders. After half a century in service and use by six times the traffic it was designed to sustain, inspections revealed the bridge to be structurally deficient with mechanical properties compromised. In 2015, to meet the complex needs of this rehabilitation project, a 45 mm thick UHPC overlay was chosen as the most cost-effective and fast-track solution to increase the shear, bending, and fatigue resistance of the 53,000 m^2 of the bridge deck slab. Figures 3.24A and B show work on this bridge.

FIGURE 3.24A. Chillon Viaduct deck prepared for overlay with UHPC concrete.

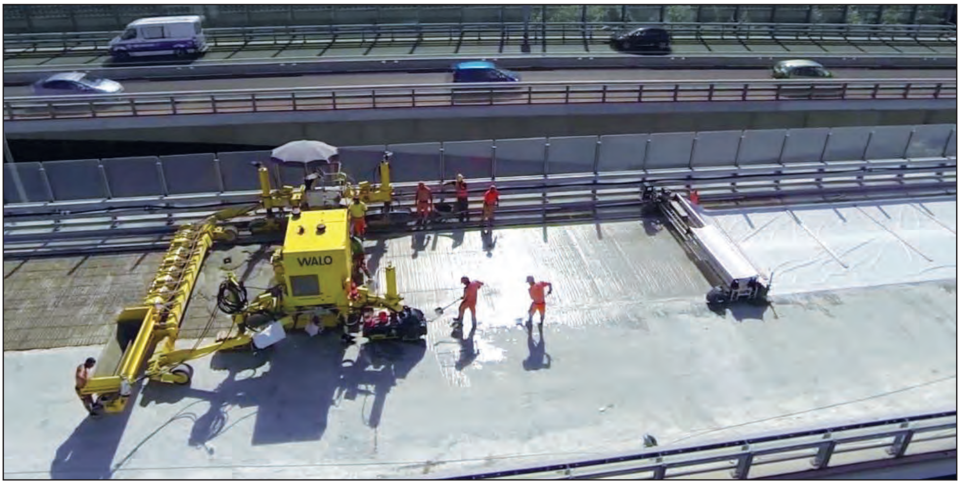

FIGURE 3.24B. UHPC being placed. Note curing process immedicately following placement.

3.4 SILICA FUME AND ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

In addition to repair and rehabilitation work, UHPC is being used in precast prestressed beams. Advantages include reduced cross sections, reduced concrete volume, and longer service life. Figures 3.25A and B show UHPC in this application.

FIGURE 3.25A. Cross-section of a beam ready to receive UHPC. Note the minimized concrete volume and absence of secondary reinforcing steel.

FIGURE 3.25B. The same beam being "topped-out." Placed from a single point, UHPC's high flow characteristics allow lateral void-less filling in a monolithic manner.

3.5 SILICA FUME AND SUSTAINABILITY

Because of the release of CO_2 associated with the production of portland cement clinker, the concrete industry has become a focal point in the global efforts to reduce CO_2. Using silica fume can lead to a significant reduction in CO_2 associated with concrete construction as shown below. More information on sustainability is presented in Chapter 8. Examples of the applications presented in the following paragraphs are in Chapter 3.

- Using silica fume to produce high-strength columns will reduce the volume of both concrete and reinforcement required to carry a given load. This benefit is most frequently seen in high-rise structures.
- Using silica-fume concrete can greatly increase the service life of a concrete structure exposed to chlorides and other chemicals. Additionally, high-strength concrete will be more abrasion resistant. As the service life is increased, fewer repairs or replacements will be required, saving concrete and reducing CO_2.
- Using silica fume in conjunction with higher amounts of other SCMs can reduce the quantity of portland cement required. This practice will reduce the heat generated and the silica fume will provide required early compressive strength. Concrete mixtures shown in Table 5.4 show the benefits of combining silica fume with other SCMs to obtain extended service life while greatly reducing CO_2.
- Combining the above practices can lead to the development of "Low-Carbon Concrete." This term encompasses CO_2 reduction, extended service life, and use of high-strength concrete. The benefits of low-carbon concrete are explained in Chapter 8.

4 ACI GUIDANCE, STANDARD SPECIFICATIONS, AND SPECIFYING SILICA-FUME CONCRETE

ACI provides a detailed discussion of silica fume in a committee guide. ASTM, AASHTO, and CEN all have specifications for silica fume to be used in concrete.

This chapter reviews the ACI, ASTM, AASHTO, and CEN documents. Guidance for specifying silica fume and silica-fume concrete is provided. A recently developed reference silica fume, which can be used to calibrate testing to the standards, is also presented.

4.1 ACI GUIDANCE

4.1.1 ACI Building Code for Structural Concrete

Silica fume is approved for use in structural concrete by ACI 318, *Building Code Requirements for Structural Concrete*. This approval is done by referencing silica fume meeting ASTM C1240, as an approved cementitious material.

4.1.2 Committee Guidance

Silica fume is covered within ACI by Committee 234. This committee has published a document titled “Guide for the Use of Silica Fume in Concrete,” (ACI 234R-06, Reapproved 2012). (Note that this document is currently being updated. The revised document is expected to be available from ACI after publication of this manual. Check with ACI for availablity.) The title page and table of contents of the current document are shown in Figure 4.1. As can be seen, this document covers all aspects of using silica fume. Readers of the User’s Manual are encouraged to review the ACI document for additional, extended information, particularly on the effects of adding silica fume on the properties of fresh and hardened concrete.

ACI 234R-06
(Reapproved 2012)

Guide for the Use of Silica Fume in Concrete

Reported by ACI Committee 234

Per Fidjestøl
Chair

Anthony N. Kojundic
Secretary

James M. Aldred, Mark A. Bury, Rachel J. Detwiler, Fouad H. Fouad, William Halczak, Terence C. Holland, R. Doug Hooton, Tarif M. Jaber, Kamal H. Khayat, V. M. Malhotra, Dudley R. Morgan, Jan Olek, H. Celik Ozyildirim, Michael F. Pistilli, Jean-Claude Roumain, Della M. Roy, Marco J. Scali, Michael D. A. Thomas, John T. Wolsiefer, Min-Hong Zhang

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.

CONTENTS

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

1

FIGURE 4.1. Cover page and table of contents of the ACI Committee 234 document on silica fume. Used with permission of the American Concrete Institute, P.O. Box 9094, Farmington Hills, MI 48333. A copy of the complete document may be purchased from ACI: www.concrete.org.

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

FIGURE 4.1. Continued

4.2 STANDARD SPECIFICATIONS FOR SILICA FUME

The first standard for silica fume was issued in Canada in 1987 and has been a template for the ones that followed: Norway in 1992 and the United States (ASTM) in 1993. The European standard was published much later, in 2005, due to the process of 'harmonizing' the numerous national standards within the European community.

When silica fume was first introduced in the United States, specifications for the material were written for each project. Since then, standardized specifications have been developed. In the United States, there are two major standard specifications of interest: ASTM C1240 and AASHTO M 307, *Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout*. In Europe, and in those areas that previously used British Standards, the standard is prepared by CEN (European Committee for Standardization) and is titled: EN 13263 *Silica Fume for Concrete*.

EN 13263 and ASTM C1240 are regarded as the two primary international standards for specifying silica fume for use in concrete.

All of these specifications are discussed in this chapter. The intent here is to review the parameters that are included in the specifications and the significance of each. ASTM C1240 and AASHTO M 307 contain mandatory and optional elements. EN 13263 contains only mandatory requirements. Both categories are discussed.

Keep in mind that all three of these specifications were derived from specifications for other pozzolans such as ASTM C618. Because of this origin, some of the requirements for silica fume are actually more appropriate for other pozzolanic materials. Over time these elements of the specifications are being revised or removed.

All of these standards presume that testing will be performed on the as-collected or undensified silica fume (defined as 'raw' in ASTM C1240.) Use of the undensified material makes it easier to perform the required tests. Testing is often performed for projects, and it must be noted that testing densified silica fume will not give the same results as the tests performed on the undensified material.

Because these standard specifications are frequently modified by the sponsoring organizations, readers are urged to check with ASTM, AASHTO, or CEN to determine the most current version.

4.2 STANDARD SPECIFICATIONS FOR SILICA FUME

4.2.1 ASTM C1240

The version discussed here is the 2020 edition of the specification. A copy of the cover page is presented in Figure 4.2. Each of the mandatory, optional, and report-only items is described below.

INTERNATIONAL

Designation: C1240 – 20

Standard Specification for Silica Fume Used in Cementitious Mixtures[1]

This standard is issued under the fixed designation C1240; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This specification covers silica fume for use in concrete and other systems containing hydraulic cement.

1.2 In the cases of slurried or densified silica fume, perform the tests on the raw silica fume from which these products have been made.

1.3 The units stated in SI are to be regarded as the standard. No other units of measurement are included in this standard.

1.4 The following safety hazards caveat pertains only to the test methods portions, Sections 10 – 19, of this specification: *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.* Read the material safety data sheets for materials used.

1.5 The text of this standard references notes and footnotes that provide explanatory information. These notes and footnotes (excluding those in tables) shall not be considered as requirements of this standard.

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C109/C109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
C114 Test Methods for Chemical Analysis of Hydraulic Cement
C125 Terminology Relating to Concrete and Concrete Aggregates
C135 Test Method for True Specific Gravity of Refractory Materials by Water Immersion
C183/C183M Practice for Sampling and the Amount of Testing of Hydraulic Cement
C185 Test Method for Air Content of Hydraulic Cement Mortar
C219 Terminology Relating to Hydraulic and Other Inorganic Cements
C311/C311M Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete
C430 Test Method for Fineness of Hydraulic Cement by the 45-µm (No. 325) Sieve
C441/C441M Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction
C494/C494M Specification for Chemical Admixtures for Concrete
C604 Test Method for True Specific Gravity of Refractory Materials by Gas-Comparison Pycnometer
C670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials
C1005 Specification for Reference Masses and Devices for Determining Mass and Volume for Use in the Physical Testing of Hydraulic Cements
C1012/C1012M Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution
C1069 Test Method for Specific Surface Area of Alumina or Quartz by Nitrogen Adsorption
C1157/C1157M Performance Specification for Hydraulic Cement
C1437 Test Method for Flow of Hydraulic Cement Mortar

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this specification, refer to Terminology C125 and Terminology C219.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *silica fume, densified, n*—silica fume processed to increase bulk density to facilitate handling and shipping.

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[1] This specification is under the jurisdiction of ASTM Committee C09 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.24 on Supplementary Cementitious Materials.

Current edition approved Jan. 15, 2020. Published March 2020. Originally approved in 1993. Last previous edition approved in 2015 as C1240 – 15. DOI: 10.1520/C1240-20.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

1

FIGURE 4.2. Cover page of the ASTM specification for silica fume. Extracted with permission from C1240-20, *Standard Specification for Silica Fume Used in Cementitious Mixtures,* © ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428. A copy of the complete standard may be obtained from ASTM: www.astm.org.

- **Silicon dioxide (SiO_2) content (mandatory).** This requirement calls for a minimum SiO_2 content of 85 percent. Because SiO_2 is the reactive ingredient of silica fume, a limit on the content is deemed appropriate. Other standard specifications (for example, Canada) allow the use of silica fume with a SiO_2 content less than 85 percent after appropriate testing in concrete.

- **Moisture content (mandatory).** This requirement limits maximum moisture content to 3 percent. The intent here is to minimize the amount of moisture that is brought along with the silica fume.

- **Loss on ignition (mandatory).** This requirement limits maximum loss on ignition to 6 percent. Fly ashes have had this requirement for many years because of the potential for partially combusted coal particles being included in the fly ash. This coal can be of a form with a very high surface area, which significantly increases the demand for air entraining admixture in air-entrained concrete. It is not clear whether any coal of this same nature is present in silica fume, so the LOI requirement is more of a control on any unburned coal or other material from the electric-arc furnace.

- **Oversize material (mandatory).** This requirement limits the amount of oversize material retained on a 45-µm (No. 325) sieve to a maximum of 10 percent. There is a further requirement that the maximum variation from average be no more than 5 percentage points. As noted in Chapter 2, silica fume is an extremely fine material and a sieve analysis will not provide any significant information on particle size or surface area. This requirement is aimed at minimizing the amount of foreign material in the silica fume. Such material could include uncombusted materials from the furnace or rust particles from the silica fume collection system.

- **Accelerated pozzolanic activity (mandatory).** This requirement states that the accelerated pozzolanic activity of a silica fume at seven days to be at least 105 percent of the control made without silica fume. This requirement is also a carry-over from the fly ash specification. This test is carried out at a constant water-cementitious materials ratio for both the cement only and the cement plus silica fume mixtures. The silica-fume mixtures use a dry superplasticizer to achieve a flow value equal to the cement-only mixtures.

- **Specific surface (mandatory).** This requirement calls for a minimum specific surface (surface area) of 15 m^2/g. As noted in Chapter 2, determining specific surface for silica fume requires a very sophisticated technique known as nitrogen adsorption or the "BET" method. Values obtained from this type of testing are not directly comparable with air-permeability test methods such as Blaine. Specific surface is an important parameter for silica fume because the higher the surface area, the smaller the particles.

- **Uniformity requirements (optional).** This requirement limits the variation in air-entraining admixture demand for mortar containing silica fume to a maximum of 20 percent over the ten preceding tests. This testing is infrequently done and is not of much significance to the user of the silica fume. What is more important is the actual demand for air-entraining admixture in concrete made with project materials. Adding silica fume should be expected to increase the requirement for AEA by about 50-100 percent, depending upon the nature and the amount of the silica fume being added and the actual AEA being used. Increases in AEA usage outside this range or decreases (very rare) should be investigated to ensure that a suitable air-void system is being developed.

- **Reactivity with cement alkalies (optional).** This requirement calls for a reduction in expansion of mortar bars of 80 percent when tested at 14 days. As noted earlier, because silica fume, used in the appropriate amount, is known to be very effective in controlling ASR, this limit is not of much value. If preventing ASR is important in a particular application, appropriate testing with the actual project concrete materials will provide much more meaningful information.

- **Sulfate resistance expansion (optional).** This requirement establishes permissible expansion limits for silica fume used in sulfate resistance applications. Limits are presented for moderate, high, and very high resistance. The same philosophy applies here as was true for ASR prevention: if sulfate resistance is of importance, the only meaningful data will come from testing with project-specific materials.

- **Bulk density (report only).** Bulk density is the loose unit weight of the silica fume. Testing is accomplished using a vibrating table to compact the silica fume. There is no limit established — the value is reported for use by the purchaser of the silica fume.

- **Density (report only).** Density is the term used by ASTM for the specific gravity of the silica fume. There is no limit established — the value is reported for use by the purchaser of the silica fume.

- **Total alkalies (report only).** There is no limit established for total alkalies — the value is reported for use by the purchaser of the silica fume. Reporting the total alkalies was originally a mandatory requirement that was derived from the fly ash specification. Given the low alkali content and relatively small amount of silica fume in a cubic meter of concrete, any alkalis contributed by silica fume are not usually included in the total alkali content of concrete. ASTM C1778 does not require inclusion of any alkalis other than those contributed by the portland cement in the total alkali calculation. If preventing ASR is important in a particular application, appropriate testing with the actual project concrete materials will provide much more meaningful information than knowing the alkali content of the silica fume.

4.2.2 AASHTO M 307

AASHTO developed a standard specification for silica fume before ASTM. The current AASHTO version is M 307, 2013. A copy of the cover page of this document is in Figure 4.3.

AASHTO has revised its specification to contain essentially the same requirements as the ASTM specification. The revised document has a dual designation of AASHTO M 307 and ASTM C1240. Because the AASHTO requirements will be generally the same as ASTM, they are not described in detail in this document.

Because of differences in the timing of ballots between ASTM and AASHTO, differences between the two standards may be expected to exist in future editions. Be sure that you are referring to the correct standard from the appropriate organization for your project.

Standard Specification for

Silica Fume Used in Cementitious Mixtures

AASHTO Designation: M 307-13 (2021)

Technically Revised: 2020 **Reviewed but Not Updated: 2021**

Technical Subcommittee: 3b, Fresh Concrete

ASTM Designation: C1240-15

1. SCOPE

1.1. This specification covers silica fume for use in concrete and other systems containing hydraulic cement.

1.2. In the cases of slurried or densified silica fume, perform the tests on the raw silica fume from which these products have been made.

1.3. The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.4. The following safety hazards caveat pertains only to the test methods portions, Section 10, of this specification: *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.* Read the material safety data sheets for materials used.

1.5. The text of this standard references notes and footnotes that provide explanatory information. These notes and footnotes (excluding those in tables) shall not be considered as requirements of this standard.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:
- M 194M/M 194, Chemical Admixtures for Concrete
- R 71, Sampling and Amount of Testing of Hydraulic Cement
- T 105, Chemical Analysis of Hydraulic Cement
- T 106M/T 106, Compressive Strength of Hydraulic Cement Mortar (Using 50-mm or 2-in. Cube Specimens)
- T 137, Air Content of Hydraulic Cement Mortar
- T 192, Fineness of Hydraulic Cement by the 45-µm (No. 325) Sieve

2.2. *ASTM Standards*:
- C125, Standard Terminology Relating to Concrete and Concrete Aggregates
- C135, Standard Test Method for True Specific Gravity of Refractory Materials by Water Immersion
- C219, Standard Terminology Relating to Hydraulic and Other Inorganic Cements

TS-3b M 307-1 AASHTO

FIGURE 4.3. Cover page of the AASHTO specification for silica fume. From *Standard Specification for Transportation Materials and Methods of Testing,* © 2004, by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by permission. Documents may be purchased from the bookstore at 1-800-231-3475 or online at http://bookstore.transportation.org.

4.2.3 EN 13263

This standard is the responsibility of the European Committee for Standardization (CEN.) The European standard consists of two parts: Part 1: Definitions, requirements and conformity criteria; and Part 2: Conformity evaluation. Criteria for both part 1 and part 2 must be met for the silica fume to conform to the standard. This standard was developed, in similar fashion to ASTM, from the standard for fly ash. An addendum was added in 2009 allowing for a second class of silica fume with a lower silicon dioxide content than the original Standard material. This was for product already in use in some minor applications.

It is reviewed on a 5-year rolling basis and in 2020 was passed for continued use without any revisions. EN 13263 will continue to be used in the UK after the separation from the European Union. European Standards are 'harmonized' across the countries that are part of the greater European Economic Community, hence EN 13263 will remain as a European and International Standard for silica fume. Unlike the two American standards, EN 13263 contains only mandatory test criteria. The ASTM and EN standards are compared in Table 4.1. A copy of the cover page of this document is in Figure 4.4.

4.2 STANDARD SPECIFICATIONS FOR SILICA FUME

TABLE 4.1

COMPARISON OF ASTM C1240 AND EN 13263				
COMPONENT/ CRITERION	**American ASTM C1240-20**	**European EN 13263.05 +A1.09**	**TESTING FREQUENCY**	**ADDITIONAL INFORMATION**
SiO_2 (percent)	> 85	> 85 / 80	Weekly	In the EN version the Class b) product at >80 percent is very low usage in specific applications.
SO_3 (percent)	—	< 2.0	Weekly	To address the potential for sulfate expansion.
Cl (percent)	—	< 0.3	Monthly	To reduce the potential for steel corrosion caused by chlorides within the concrete.
Free CaO (percent)	—	< 1.0	Weekly	To control the potential for conversion to calcium carbonate (carbonation)
Free Si (percent)	—	< 0.4	Monthly	—
Available Alkalis: NaO_2 eq. (percent)	Report	Report	Weekly	—
Moisture (percent)	< 3.0	—	Weekly	—
Loss on Ignition (percent)	< 6.0	< 4.0	—	—
Specific Surface (m^2/g)	> 15	15 - 35	Monthly	—
Bulk Density u/dens (kg/m^3)	Report	—	Daily	—
Pozzolanic Activity Index (percent)	> 105 at 7d acc. curing	> 100 at 28d std. curing	Monthly	—
45-micron sieve residue (percent)	< 10	—	Weekly	—

Only the mandatory tests for compliance to the standards are shown. The SFA does not believe that the differences in properties tested or differences in limits established by the two standards are significant. Such differences will not reflect how the silica fume performs in concrete. Note that frequency of testing applies only to EN13263.

4.2 STANDARD SPECIFICATIONS FOR SILICA FUME

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 13263-1

June 2005

ICS 91.100.30

English version

Silica fume for concrete - Part 1: Definitions, requirements and conformity criteria

Fumée de silice pour béton - Partie 1: Définitions, exigences et critères de conformité

Silikastaub für Beton - Teil 1: Definitionen, Anforderungen und Konformitätskriterien

This European Standard was approved by CEN on 19 May 2005.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 13263-1:2005: E

FIGURE 4.4. Cover page of EN 13263. Used with permission of European Committee for Standardization (CEN.) Each European country that is using the CEN Standards can publish their own version – hence NS EN 13263 for Norway; BS EN 13263 for the UK, etc. CEN is the singular place to go for the generic specification. The CEN website may be accessed at: https://standards.cen.eu.

4.3 SPECIFYING SILICA FUME AND SILICA-FUME CONCRETE

To specify silica fume, it is best to refer to one of the standard specifications that were described previously in this chapter. Do not invoke any of the optional requirements in these specifications unless there is a specific need to do so. If there are specific project requirements for the silica fume, include those requirements in addition to the requirements from the standard specification. For example, if you want a specific quantity of silica fume in a big bag to facilitate batching, include that requirement along with the overall requirements of ASTM C1240.

There are three major options when it comes to specifying silica-fume concrete:

1. Develop a specification following the format used by AASHTO;
2. Develop a specification using a format along the lines of the three-part specification as developed by the Construction Specifications Institute (CSI) and as used by the American Concrete Institute;
3. Develop a specification using the format developed by a specific organization.

AASHTO addresses concrete construction for bridges in the AASHTO LFRD (Load and Resistance Factor Design) Bridge Construction Specifications, Fourth Edition, (AASHTO 2019). and in the AASHTO LRFD Bridge Design Specifications, Ninth Edition, (AASHTO 2020). The use of silica-fume concrete is included in these documents. If you are developing specifications for a transportation project, review the AASHTO requirements for your particular project.

Under the CSI format, concrete work is included in Division 3 of the overall project specification. In this format, cast-in-place concrete is usually designated as Section 033000. Usually, specifiers will create a separate section for silica-fume concrete that will include all of the specific requirements for the silica-fume concrete.

Many organizations have developed their own format for specifications. There is a very wide range of specification formats that have been used.

Regardless of the format selected, the SFA strongly urges that the specifications be based upon required concrete performance needs rather than prescriptive mixture parameters. Let the concrete producer develop a mixture that best meets the requirements placed on the concrete.

4.4 SILICA FUME REFERENCE MATERIAL

Different laboratories have encountered difficulties when testing silica fume for compliance with either ASTM C1240 or AASHTO M 307. In order to reduce these difficulties, a silica fume reference material has been prepared by the SFA in cooperation with the United States National Institute of Standards and Technology (NIST). This material is a silica fume of known characteristics, which may be used by laboratories for calibrating their internal testing. The reference silica fume has been tested by multiple laboratories and values have been determined for a number of parameters. These parameters include SiO_2 content, specific surface area by BET, moisture content, loss on ignition, and the amount of several trace elements that may be present. Apparently, there is no other standard reference material available internationally.

Figure 4.5 shows a package of the reference silica fume. This reference material is designated SRM 2696, and it is available from the National Institute of Standards and Technology (NIST) at a nominal cost. Please check either the SFA website (www.silicafume.org) or the NIST website (https://srmors.nist.gov/index.cfm) for instructions on how to obtain this material.

FIGURE 4.5. Silica fume Standard Reference Material (SRM 2696) available from the National Institute for Standards and Technology. Check either the SFA or NIST websites, as listed in the text, for instructions on how to order this material.

5 PROPORTIONING SILICA-FUME CONCRETE

Proportioning silica-fume concrete is very similar to proportioning any other concrete mixture. However, there are a few differences, particularly how water is controlled and how slump is achieved. The best approach is to start with a mixture of known performance. Once the performance of that mixture is established using project materials, then the mixture can be adjusted as necessary.

This chapter looks at proportioning in general and then presents a step-by-step procedure for proportioning silica-fume concrete. Several examples of proportioning silica-fume mixtures for specific applications are presented. The chapter concludes with a discussion of advanced concepts that may be appropriate for proportioning mixtures with complex requirements.

5.1 BASIC CONSIDERATIONS

Following are several basic considerations to keep in mind when proportioning silica-fume concrete:

In most cases, silica-fume is not purchased directly. When silica fume is specified it will simply come as an ingredient in the concrete. Producers of silica fume have entered into marketing agreements with major admixture suppliers. These arrangements allow the concrete producer to purchase silica fume and chemical admixtures from the same supplier. It is the concrete supplier's responsibility to obtain silica fume meeting the project specification and to proportion the concrete to meet specified concrete requirements.

The basics of good concrete practice apply to silica-fume concrete just as they do to any other concrete. If anything, violating good practice will show up more readily in silica-fume concrete simply because of the high performance typically specified. Some of the areas of good practice are:

- Control the weights of all ingredients
- Monitor the moisture contents of aggregates
- Control air content
- Do not use chloride or chloride-bearing ingredients as an accelerator
- Pay attention to hot- and cold-weather considerations

Use common sense regarding concrete performance - don't expect the silica-fume concrete to behave all that differently from conventional concrete. If what is happening does not make sense, get help from someone experienced with the material.

Work to a fixed cementitious materials content and a fixed water-to-cementitious material ratio (w/cm.) In many cases with conventional concrete with a low specified w/cm, the cement content is raised to bring in additional water to provide slump. This practice is usually not the case for silica-fume concrete because it will result in very high contents of cementitious materials. Both the total amount of cementitious materials and the maximum water content will frequently be specified.

Will there be enough water to hydrate the cement? This question is frequently asked. Don't worry about whether there is enough water. Concrete mixtures with w/cm of less than 0.25 have achieved over 120 MPa compressive strength. If the cement is not hydrated, it will serve as filler material to fill in void spaces in the mixture.

5.1 BASIC CONSIDERATIONS

Some specifiers are uncomfortable about using a superplasticizer without first verifying a water slump of 50 to 75 mm. This requirement is outdated but still seen in many specifications. For many high-performance concrete applications, the w/cm will be so low that there is not enough water to get a measurable slump and still develop a concrete with the desired performance characteristics. Additionally, the superplasticizers that are now available are intended to be added with the batch water for maximum efficiency. Specifiers are encouraged to work with concrete producers and admixture suppliers to achieve the required concrete properties rather than being concerned with a slump limit.

Use chemical admixtures to achieve adequate slump for placement. Usually, both a water-reducer (normal setting or retarding) and a superplasticizer will be used. If multiple admixtures are used, follow the instructions of the admixture supplier for sequence and timing of addition.

In some cases, it may be necessary to go above manufacturers' recommended limits for chemical admixture dosages, particularly for superplasticizers. For high-strength concrete with a very low w/cm, the necessary dose may be as much as twice the recommended dosage and in UHPC may be multiple times that recommended. Testing at the proposed dosages of admixture is recommended to ensure that other properties such as time of setting, air content, and rate of strength development are not being affected.

Entrained air is required with silica-fume concrete if it will be exposed to freezing and thawing during construction or service. Use the amount of air recommended in standard documents for conventional concrete, such as ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*, or ACI 318, (see Table 5.1.) ACI 318 and most specifications allow a one percent reduction in air content if the compressive strength is above 35 MPa; this will almost always be the case for silica-fume concrete.

TABLE 5.1

RECOMMENDED TOTAL AIR CONTENT FOR CONCRETE EXPOSED TO FREEZING AND THAWING (From ACI 318)			
NOMINAL MAXIMUM AGGREGATE SIZE		AIR CONTENT PERCENT	
mm	in.	SEVERE EXPOSURE	MODERATE EXPOSURE
9.5	3/8	7.5	6
12.5	1/2	7	5.5
19	3/4	6	5
25	1	6	4.5
37.5	1 1/2	5.5	4.5
50	2	5	4
75	3	4.5	3.5

Expect to use a little more air-entraining admixture (AEA) than usual for silica-fume concrete. Once the proper amount of AEA is established, there will be no more or no fewer problems controlling air for this concrete than for concrete without silica fume.

Use the largest aggregate allowable for the application and the strength that is specified. In most cases, a 19 mm aggregate will be appropriate. Just because a high-strength concrete is required does not necessarily mean that a smaller aggregate must be used. Also, try to use as much coarse aggregate as possible to reduce the drying shrinkage of these concretes. Many silica-fume concretes are slightly under sanded when compared to concretes without silica fume.

5.2 PROJECT REQUIREMENTS

It is essential to understand the requirements for a particular project. While this may seem to be an obvious statement, it needs to be said. Usually, all of the project requirements will be spelled out in the specifications. Take the time to read the entire concrete specification to be sure that all of the requirements are found. It is not unusual to find requirements on shrinkage, hardened air void parameters, and chloride permeability in addition to compressive strength. There may also be unusual requirements for the information that is to be submitted at the time of concrete mixture approval.

If there are any questions regarding the project requirements, particularly if some of the requirements seem to contradict one another, be sure to seek clarification from the specifier. It is always easier, and less expensive, to get questions answered before rather than after the concrete mixture is developed.

5.3 CONSTRUCTION CONSIDERATIONS

Once the project requirements are identified, it is critical to determine the requirements of the contractor who will be placing the concrete. Here are a few topics to consider:

Slump: Fresh silica-fume concrete is very cohesive and behaves somewhat differently than conventional concrete. A given slump will not be indicative of the same workability for concrete with and without silica fume. A good rule of thumb for silica-fume concrete is to place at as high a slump as possible for the placement. Usually, the slump for the silica-fume concrete should be increased by about 50 mm over concrete without silica fume to achieve the same workability.

For concrete containing over 6 percent silica fume, a minimum slump of 200 mm is recommended.

Using a higher slump will make closing the surface and achieving the desired finish much easier. Frequently, for bridge decks or parking structure flatwork, the slump will be determined by the grade of the placement. Because of its increased cohesiveness, silica-fume concrete will hold on slopes much better than concrete without silica fume, even when vibrated. Always place at the highest slump that will hold on the slope.

Figure 5.1 shows silica-fume concrete being placed on a dome of a waste-water tank in Jacksonville, Florida. The concrete had a slump of approximately 200 mm (Figure 5.2) and held the slump during vibration on a significantly sloped surface. This project did not have silica fume in the concrete initially. The contractor elected to use silica fume to take advantage of the increased ability to hold the slope. As a side benefit, because of the high reactivity of the silica-fume concrete, a membrane coating was applied to the inside of the tank concrete at 7 days rather than waiting for 28 days.

5.3 CONSTRUCTION CONSIDERATIONS

FIGURE 5.1. Silica-fume concrete being placed on the sloping dome of a waste-water treatment tank. Note the cohesive concrete holding the slope during vibration.

FIGURE 5.2. Slump of concrete placed on the tank dome was approximately 200 mm.

Other issues: Determine any other specific placing or finishing requirements that the contractor may have. The more information available before proportioning the concrete, the faster and easier it will be to develop a suitable mixture.

Frequently, the requirements of the specifier and the requirements of the contractor may seem to be at odds with one another. For example, a requirement for a very low water content does not lend itself to high slump concrete. Differences such as this can frequently be resolved by using suitable types and amounts of chemical admixtures.

5.4 PROPORTIONING PROCEDURE

Proportions for silica-fume concrete are typically developed to meet specific project requirements. These requirements may be prescriptive in nature, giving details about the mixture proportions or they may be purely performance giving only the requirements that must be met. In either case, it is best to follow a step-by-step procedure to develop the mixture proportions for a specific project.

5.4.1 General Rules

There is no "scientific" method for proportioning. This means that there is no chart 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. However, there are decades of project applications providing a good summary of various silica-fume percentages used and resulting hardened concrete properties. Table 5.2 shows a summary of silica-fume contents and properties that are typically obtained. The following sections provide general rules for proportioning.

TABLE 5.2

TYPICAL SILICA-FUME CONTENTS VERSUS CONCRETE PROPERTIES

SILICA FUME CONTENT (By mass of cement)	CONCRETE MIXTURE, Total Cementitious material and w/cm	RAPID CHLORIDE RESULTS ASTM C1202	COMPRESSIVE STRENGTH, 28 days
0 percent	386 kg/m^3 w/cm < 0.40	> 3000 coulombs	35 MPa
5-10 percent	386 kg/m^3 w/cm < 0.40	< 1000 coulombs	> 50 MPa
> 10 percent	386 kg/m^3 w/cm < 0.40	< 500 coulombs	> 65 MPa
> 15 percent	475 kg/m^3 w/cm < 0.35	< 300 coulombs	> 85 MPa

5.4 PROPORTIONING PROCEDURE

Prescriptive specifications: Many DOTs specify concrete mixture proportions to be used for all similar projects. This procedure may cause differences in performance from project to project because the performance of silica-fume concrete depends upon the interaction of the specific materials used. In this case, follow the prescriptive proportions and test to verify that acceptable hardened concrete properties are achieved.

Performance specifications: If the specification is performance based, remember that local materials will determine the final mixture performance. Don't assume that a mixture developed and used elsewhere will provide the same results when local materials are used. Mixtures used elsewhere are excellent starting points, but the influence of project materials on the results obtained must be determined. For a performance specification, the SFA recommends developing a mixture after the project materials have been identified.

Test at both the laboratory and production scale during mixture development. The process is too complex to predict what the outcome will be without appropriate testing. Allow plenty of time for the necessary testing.

Finally, follow the procedure described in the following section. This procedure has evolved over many years and is the best recommendation currently available.

5.4.2 Step-By-Step Procedure

This section presents a seven-step procedure. Examples are given for each step. See Figure 5.3 for a summary of this procedure.

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 requirements at various stages of construction
- 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 cement, and silica fume
- Slump

STEP 2

Coordinate with contractor who will be placing the concrete. Save time and expense by getting input from the contractor early in the process. Knowing what the contractor needs to get the concrete into place will also help a producer price the concrete correctly. Items to consider here include:

- Special constructability requirements
- Placing and finishing methods
- Nominal maximum allowable aggregate size
- Slump requirements — don't forget to increase the slump for silica-fume concrete
- Responsibility for adding admixtures on the site, if necessary

STEP 3

Select starting mixture. Table 5.3 contains a number of silica-fume concrete mixtures that have been developed for a variety of applications. If the project specifications don't include specifics on the mixture, use this table to find a concrete mixture that meets requirements that are similar to those on the current project.

5.4 PROPORTIONING PROCEDURE

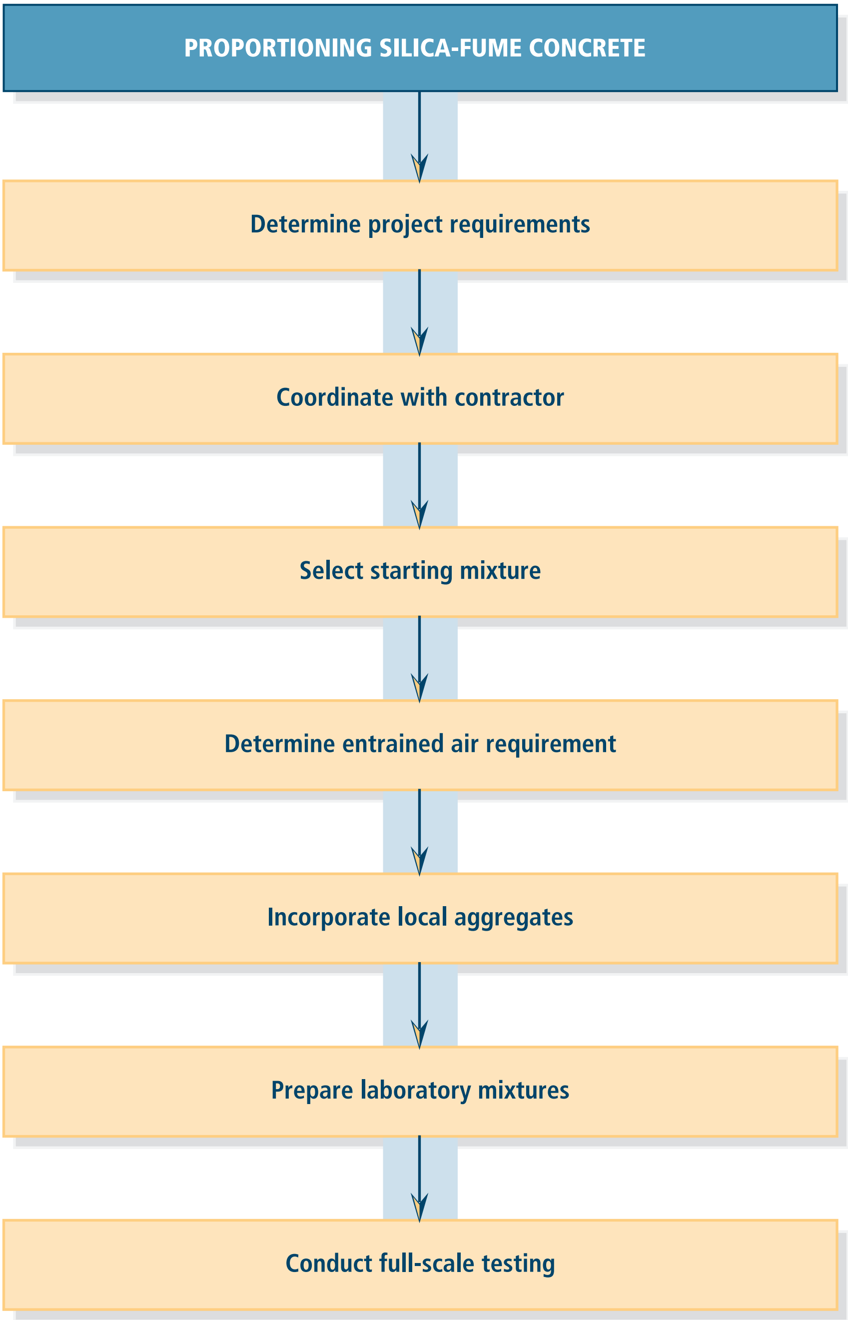

FIGURE 5.3. Steps in proportioning silica-fume concrete. Each of these steps is discussed in detail in the text.

TABLE 5.3

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS

	HIGH-STRENGTH CONCRETE Key Tower, Cleveland	HIGH-STRENGTH CONCRETE Scotia Plaza, Toronto	BRIDGE DECK, WITH FLY ASH New York State DOT HP Mix	WET SHOTCRETE REPAIR	TEMPERATURE CONTROLLED CONCRETE Hanford Storage Facility
	MIXTURE 1	MIXTURE 2	MIXTURE 3	MIXTURE 4	MIXTURE 5
References	None	Bickley, et al, 1991	Alcompalle and Owens, 2000	Forrest, et al, 1995	Holland, 1998
Compressive strength (Note 1)	83 MPa at 28 days	69 MPa at 28 days	> 37 MPa at 28 days	42 MPa at 28 days	35 MPa at 28 days 42 MPa at 90 days
Rapid chloride test, coulombs	—	303 at 1 year 258 at 2 years	< 1,600	—	—
Other requirements	Pumpable, 57 stories	—	Minimize plastic and drying shrinkage cracking	59 kg/m³ of steel fibers to increase toughness	Max delivered < 21°C, Max at 48 hr < 38°C, Pumpable, early strength for form removal
Entrained air (Note 2)	—	—	6.50 percent	8 to 10 percent as delivered 4 to 6 pecent in place	2 to 6 percent
Slump	> 250 mm	100 mm	Unknown	50 to 100 mm	Unknown
Maximum aggregate size	13 mm	39 mm	39 mm	9.5 mm	25 mm
Cement, kg/m³	406	316	297	405	232
Fly ash, kg/m³	0	0	80, Class F	0	89, Class F
Slag cement, kg/m³	169	117	0	0	0
Silica fume kg/m³	47	37	24	42	35
Maximum w/cm	0.24	0.31	0.40	0.45	0.37
Water, kg/m³ (Note 3)	149	145	160	200	99

Note 1. Strength shown is f′c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 35 MPa has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

TABLE 5.3 (continued)

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS

	HIGH-PERFORMANCE BRIDGE GIRDERS Colorado DOT	PARKING STRUCTURE Milwaukee Airport	TEST HIGH-STRENGTH MIX	TEST HIGH-STRENGTH MIX	BRIDGE DECK Colorado DOT
	MIXTURE 6	MIXTURE 7	MIXTURE 8	MIXTURE 9	MIXTURE 10
References	Leonard, 1999	Data from SFA Member	Burg & Ost, 1994	Burg & Ost, 1994	Xi, et al, 2003
Compressive strength (Note 1)	45 MPa at release 69 MPa ultimate	14 MPa at 36 hrs 39 MPa at 56 days	89 MPa at 28 days 115 MPa at 3 yrs	107 MPa at 28 days 126 MPa at 3 yrs	32 MPa at 28 days
Rapid chloride test, coulombs	—	< 1,000 from cores at 2-10 months	—	—	1,400–1,600 at 56 days
Other requirements	—	—	—	—	—
Entrained air (Note 2)	Unknown	Unknown	—	—	8.5 percent
Slump	Unknown	160 to 190 mm	250 mm	240 mm	140 mm
Maximum aggregate size	Unknown	Unknown	13 mm	13 mm	Unknown
Cement, kg/m^3	433	335	475	475	288
Fly ash, kg/m^3	0	59, Class C	59, Class C	104, Class C	58, Class F
Slag cement, kg/m^3	0	0	0	0	0
Silica fume kg/m^3	21	23	24	74	12
Maximum w/cm	0.28	0.35	0.29	0.23	0.41
Water, kg/m^3 *(Note 3)*	127	146	160	151	147

Note 1. Strength shown is f'c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 35 MPa has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

TABLE 5.3 (continued)

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS	WORLD TRADE CENTER 1 New York City	EAST SEA BRIDGE China
	MIXTURE 11	**MIXTURE 12**
References	SCC mix data from Norchem (2012)	Data from Elkem (2002)
Compressive strength (Note 1)	83 MPa at 28 days	50 MPa at 28 days
Rapid chloride test, coulombs	—	< 750
Other requirements	—	—
Entrained air (Note 2)	—	—
Slump	610-710 mm (slump flow)	250 mm
Maximum aggregate size	16 mm	Unknown
Cement, kg/m³	173	188
Fly ash, kg/m³	51, Class F	28, Class F
Slag cement, kg/m³	279	239
Silica fume kg/m³	30	15
Maximum w/cm	0.29	0.32
Water, kg/m³ *(Note 3)*	155	150

Note 1. Strength shown is f'c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 35 MPa has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

5.4 PROPORTIONING PROCEDURE

In 2014 the SFA sponsored a research program for the Federal Railroad Administration (FRA) to address seat abrasion of concrete rail crossties. The technology is already well developed using high coarse aggregate content with excellent hardness characteristics combined with a low w/cm to maximize abrasion resistance. Increasing silica fume percentages, alternating supplementary cementitious materials, and decreasing w/cm were investigated to maximize compressive strength performance. Other properties looked at were to increase concrete workability to improve consolidation properties, prolong service life, and reduce the carbon footprint of the concrete.

Select concrete mix designs, FRA 2-6 in Table 5.4, were evaluated to improve abrasion resistance beyond the state-of-the-art standard specified concrete (FRA-1) for concrete rail crosstie manufacture. The coarse aggregate content was kept constant and cementitious material volume increase was balanced by lowering fine aggregate and water contents. HRWR was used to maximize workability. The data presented also includes service life predictions made using Life-365.

TABLE 5.4

CONCRETE MIXTURES EVALUATED DURING THE SILICA FUME ASSOCIATION/ FEDERAL RAILROAD ADMINISTRATION TEST PROGRAM

	FRA - 1	FRA - 2	FRA - 3	FRA - 4	FRA - 5	FRA - 6
Total Cementitious Materials Content (kg/m^3)	445	475	489	510	534	578
Slag Cement, Grade 100	—	—	—	34.9 percent	40.0 percent	46.2 percent
Fly Ash, Class F	6.7 percent	6.3 percent	6.1 percent	—	—	—
Silica Fume	—	6.3 percent	9.1 percent	11.6 percent	12.2 percent	12.3 percent
Water-Cementitious Materials Ratio	0.35	0.30	0.28	0.26	0.24	0.22
Slump or Slump Flow (mm)	45	225	225	230	580 Slump Flow	560 Slump Flow
Compressive Strength, MPa at 28 Days	80	108	113	121	124	128
Increase	**control**	**35 percent**	**41 percent**	**51 percent**	**55 percent**	**60 percent**
Abrasion, ASTM C779, depth of wear, mm *(Note 1)*	1.65	1.42	1.25	1.17	1.27	1.14
Reduction	**control**	**14 percent**	**24 percent**	**29 percent**	**23 percent**	**31 percent**
Abrasion, ASTM C1138, volume loss, cm^3 *(Note 2)*	1.65	1.42	1.25	1.17	1.27	1.14
Reduction	**control**	**67 percent**	**75 percent**	**83 percent**	**83 percent**	**75 percent**
Service Life prediction, years before repairs are required *(Note 3)*	16	28	40	104	136	156
Carbon Footprint CO_2 estimate, kg/m^3 *(Note 4)*	401	401	402	290	278	272
Material Costs, estimate per cubic meter	**control**	**128 percent**	**136 percent**	**150 percent**	**164 percent**	**179 percent**

Note 1. ASTM C779, Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces.
Note 2. ASTM C1138, Standard Test Method for Abrasion Resistance of Concrete (Underwater Method).
Note 3. Service life estimates are for chloride-induced corrosion of reinforcing steel. Estimates were derived using Life-365 assuming a coastal exposure with 38 mm concrete cover.
Note 4. CO_2 reduction estimates were based on the quantity of portland cement and supplementary cementitious materials in the mixtures.

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 is air entrained. Use an industry-standard table such as found in ASTM or ACI to determine the volume of air required. Table 5.1 shows one such table from ACI 318. It is usually allowed to reduce air content by one percent for compressive strength above 35 MPa.

STEP 5

Incorporate local aggregates into the starting mixture. There are two considerations here:

- Calculate a total aggregate volume that will yield one cubic meter of concrete.* (Note: some concrete producers proportion their concrete mixtures to yield slightly more than one cubic meter. It is best to first proportion the concrete to develop the necessary fresh and hardened properties and then adjust the proportions for yield as appropriate.)

- Use a ratio of fine to coarse aggregate that works well for project materials. This ratio can always be adjusted while making trial mixtures. Although the ratio of fine to coarse aggregate will have an influence on the workability, small changes will not seriously affect hardened concrete properties. Because of the very fine nature of silica fume, it may be appropriate to start with a concrete mixture that is slightly “under sanded” compared to similar mixtures without silica fume. If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.

- Control of aggregate moisture is critical for both laboratory and full-scale testing. Controlling aggregate moisture is more critical for silica-fume concrete than for concrete without silica fume. When working with concretes with very low w/cm, minor changes in water content can result in significant changes in performance.

**Proportioning examples are given in the text in SI units. The same examples are shown in Appendix 1 using inch-pound units.*

STEP 6

Prepare laboratory trial mixtures. This step is not all that different from what is normally done. However, the SFA is aware of instances in which silica-fume concrete prepared in a laboratory has failed to produce the expected hardened concrete properties, whether the property is compressive strength or low permeability. This problem is particularly common in laboratories having small, and often less efficient, concrete mixers. Figure 5.4 shows steps to be taken when making silica-fume concrete in the laboratory. Following these recommendations will help ensure that the results in the laboratory will closely resemble the results to be expected in actual silica-fume concrete production.

- Silica fume is a very fine powder — the particles are approximately 1/100 the diameter of portland cement grains. When used to produce high-performance concrete, silica fume is typically 4-15 percent of the cement weight. The exact addition rate depends upon the specific performance characteristics to be achieved. Compared to the other ingredients in concrete, the amount of silica fume used is small. For the silica fume to be effective, it must be dispersed uniformly throughout the concrete.

- When making concrete in the laboratory, the key to success is batching the silica fume at the appropriate time and then mixing the concrete adequately. ASTM C192, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, paragraph 7.1.2 recommends: "Mix the concrete, after all ingredients are in the mixer, for 3 min. followed by a 3-min. rest, followed by a 2-min final mixing." Unfortunately, these recommended mixing times are simply not long enough to ensure that the silica fume is well dispersed.

- The SFA strongly recommends that undensified silica fume be used in laboratory mixers. If densified silica fume is used, additional mixing time will be required.

- In the laboratory, batch the concrete at the maximum allowed water content. Remember that even with the maximum allowed water there may not be any measurable slump. Use chemical admixtures to achieve the necessary workability.

- Follow the admixture supplier's recommendations for when and how to add all chemical admixtures. Do not mix any admixtures together before batching them into the concrete mixture.

MAKING SILICA-FUME CONCRETE IN THE LABORATORY

↓

1. Place 75% of water in mixer*
2. Add coarse aggregate
3. Add silica fume slowly into the revolving mixer
4. Mix 1-1/2 minutes

*Follow ASTM C192 for addition of admixtures. Consult admixture manufacturers' recommendations for proper dosage and addition sequence.

↓

5. Add cement and fly ash or slag cement, if being used, slowly into the revolving mixer
6. Mix 1-1/2 minutes

↓

7. Add fine aggregate
8. Wash-in all ingredients using the remaining 25% of water

↓

Finish by mixing as follows:

9. Mix 5 minutes**
10. Rest 3 minutes
11. Mix 5 minutes**

** Time may be extended by user based on equipment and performance results.

FIGURE 5.4. Recommendations for making silica-fume concrete in a laboratory mixer.

5.4 PROPORTIONING PROCEDURE

- Silica fume must always be added with the coarse aggregate and some of the water. Batching silica fume alone or first can result in head packing or balling in the mixer. Mix silica fume, coarse aggregates, and water for 1½ minutes.

- Add the portland cement and any other cementitious material such as fly ash or slag cement. Mix for an additional 1½ minutes.

- Add the fine aggregate and use the remaining water to wash in any chemical admixtures added at the end of the batching sequence. Mix for 5 minutes, rest for 3 minutes, and mix for 5 minutes. Actual mixing time may vary, depending upon the characteristics of a specific mixer. If there are any doubts that full dispersion and efficient mixing has been accomplished, mix longer.

- 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 upon the results of testing the hardened concrete, adjust the mixture proportions as necessary. At this point it may be necessary to make additional laboratory mixtures, or it may be time to go to production-scale testing.

STEP 7

Conduct production-scale testing. There can always be minor differences between proportions developed in the laboratory and those used for concrete production, particularly in chemical admixture dosages. Making production batches of the concrete is the best way to work out the bugs. Keep in mind:

- The SFA's experience is that truck mixers, and especially central plant mixers, are much more efficient in breaking down the agglomerations and dispersing silica fume. However, remember to limit batch sizes to the rated mixing capacity of the equipment.

- Conducting full-scale testing 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 used, a significant amount of paste can be lost to the drum. When conducting production trials, make at least 3 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 seen in the lab, examine the process carefully — there is no reason to expect major differences.

- Make more than one batch. It is always good to confirm the performance of a particular concrete mixture.

5.5 ADJUSTING THE MIXTURE

There are two areas that frequently require adjustments during either the laboratory or the production-scale testing. These are compressive strength and the viscosity of the fresh concrete.

Compressive strength. Failure to achieve a required compressive strength is most frequently the result of having too much water in the concrete. For very high-strength concrete, don't be afraid to drop the w/cm well below customary levels. Look again at the starting mixtures in Table 5.3. To get into the very high strength range, there must be a very low water content.

Concrete viscosity. In some applications, such as flatwork with higher amounts of silica fume, finishers may complain that the concrete is sticky. This stickiness is actually increased cohesion, which is a result of the high fines content and the high superplasticizer content. If stickiness is a problem, here are some suggestions:

- Silica fume from a particular source can behave differently when used with different superplasticizers. Simply try a different superplasticizer from your admixture supplier and see if that switch makes a difference in stickiness.

- The use of one of the mid-range water-reducing admixtures may also help reduce stickiness. Many of these products are usually based upon a lignin ingredient, which seems to help reduce stickiness. Try replacing about one-third of the superplasticizer with the mid-range product. Since these mid-range products are priced about the same as superplasticizers, there should be little impact on the cost of the concrete.

- Look at the grading of the fine aggregate. If there are a lot of fines in the aggregate, replacing some or all of the fine aggregate with a coarser material may help reduce stickiness.

5.6 MIXTURE PROPORTIONING EXAMPLES

Following are three examples of the step-by-step mixture proportioning procedure. The same examples are given in inch-pound units in Appendix 1 of this manual.

5.6.1 EXAMPLE 1. Bridge Deck, Figure 5.5.

FIGURE 5.5. Bridge deck project. Mixture proportions for a concrete that could be used on this project are developed in Example 1.

STEP 1

Determine project requirements. A review of the specifications develops the following requirements:

- Low chloride permeability, approximately 1,500 Coulombs at 56 days
- Compressive strength of 31 MPa at 28 days
- Reduced heat and shrinkage
- Reduced rate of strength gain to minimize cracking
- Protection against freezing and thawing in a severe environment

STEP 2

Coordinate with contractor. Discussions with the contractor develop the following additional requirements:

- Maximum size of coarse aggregate is 25 mm
- Desired slump is 100 to 150 mm
- Concrete will primarily be placed by pump

STEP 3

Select starting mixture. From Table 5.3 select the Colorado DOT mixture as being a good starting mixture. This mixture has the following characteristics:

Cement	288 kg/m^3
Fly ash	58 kg/m^3
Silica fume	12 kg/m^3
Maximum w/cm	0.41

STEP 4

Determine volume of air required. From Table 5.1 for 25 mm aggregate, the volume of air required for a severe environment is 6 percent. Because this concrete will not have a compressive strength of over 35 MPa, do not reduce the air content by 1 percent.

STEP 5

Incorporate local aggregates.

First, determine the volume the paste will occupy, as shown in the following table:

MATERIAL	MASS, kg	SPECIFIC GRAVITY	VOLUME, m^3
Cement	288	3.15	0.091
Fly ash	58	2.50	0.023
Silica fume	12	2.20	0.005
Water (w/cm = 0.41)	147	1.00	0.147
Air, 6 percent	—	—	0.060

Total paste volume = 0.326 m^3

Second, calculate aggregate volumes and masses:

Coarse aggregate specific gravity: 2.68
Fine aggregate specific gravity: 2.64
Fine aggregate: 40 percent of total aggregate volume *(Note: If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.)*
Aggregate volume = 1.000 m^3 – 0.326 m^3 = 0.674 m^3
Fine aggregate volume = 0.40 × 0.674 m^3 = 0.270 m^3
Fine aggregate mass = 0.270 m^3 × 2.64 Mg/m^3 = 0.713 Mg = 713 kg
Coarse aggregate volume = 0.674 m^3 – 0.270 m^3 = 0.404 m^3
Coarse aggregate mass = 0.404 m^3 × 2.68 Mg/m^3 = 1.083 Mg = 1,083 kg

STEP 6

Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 5.4 for recommendations
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

STEP 7

Conduct production-scale testing. Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

5.6.2 EXAMPLE 2. Cast-in-Place Parking Structure, Figure 5.6.

FIGURE 5.6. Parking structure project. Mixture proportions for a concrete that could be used on this project are developed in Example 2.

STEP 1

Determine project requirements. A review of the specifications develops the following requirements:

- Low chloride permeability, less than 1,500 Coulombs at 42 days
- Early strength of 28 MPa to allow for stressing of tendons
- Compressive strength of 42 MPa at 28 days
- Reduced heat and shrinkage
- Protection against freezing and thawing in a severe environment

STEP 2

Coordinate with contractor. Discussions with the contractor develop the following additional requirements:

- Maximum size of coarse aggregate is 25 mm
- Desired slump is 125 to 175 mm
- Concrete will primarily be placed by pump

STEP 3

Select starting mixture. From Table 5.3 select the Milwaukee Airport Parking Structure mixture as being a good starting mixture. This mixture has the following characteristics:

Cement	335 kg/m^3
Fly ash (Class C)	60 kg/m^3
Silica fume	24 kg/m^3
Maximum w/cm	0.35

STEP 4

Determine volume of air required. From Table 5.1 for 25 mm aggregate, the volume of air required for a severe environment is 6 percent. Because this concrete will have a compressive strength of over 35 MPa, reduce the air content by 1 percent and proportion for 5 percent.

STEP 5

Incorporate local aggregates.

First, determine the volume the paste will occupy, as shown in the following table:

MATERIAL	MASS, kg	SPECIFIC GRAVITY	VOLUME, m^3
Cement	335	3.15	0.106
Fly ash	60	2.50	0.024
Silica fume	24	2.20	0.011
Water (w/cm = 0.35)	142	1.00	0.142
Air, 5 percent	—	—	0.050

Total paste volume = 0.338 m^3

Second, calculate aggregate volumes and masses:

Coarse aggregate specific gravity: 2.72
Fine aggregate specific gravity: 2.68
Fine aggregate: 40 percent of total aggregate volume *(Note: If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.)*
Aggregate volume = 1.000 m^3 – 0.338 m^3 = 0.662 m^3
Fine aggregate volume = 0.40 × 0.662 m^3 = 0.265 m^3
Fine aggregate mass = 0.265 m^3 × 2.68 Mg/m^3 = 0.710 Mg = 710 kg
Coarse aggregate volume = 0.662 m^3 – 0.265 m^3 = 0.397 m^3
Coarse aggregate mass = 0.397 m^3 × 2.72 Mg/m^3 = 1.080 Mg = 1,080 kg

STEP 6

Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 5.4 for recommendations
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

STEP 7

Conduct production-scale testing. Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

5.6.3 EXAMPLE 3. High-Strength Concrete Columns, Figure 5.7.

FIGURE 5.7. High-strength columns project. Mixture proportions for a concrete that could be used on this project are developed in Example 3.

STEP 1

Determine project requirements. A review of the specifications develops the following requirements:

- Design compressive strength of 96 MPa at 28 days
- No exposure to freezing and thawing

5.6 MIXTURE PROPORTIONING EXAMPLES

STEP 2

Coordinate with contractor. Discussions with the contractor develop the following additional requirements:

- Maximum size of coarse aggregate is 13 mm
- Desired slump is 200 to 250 mm
- Concrete will primarily be placed by pump

STEP 3

Select starting mixture. From Table 5.3 select the high-strength mixture (Mixture 9) as being a good starting mixture. This mixture has the following characteristics:

Cement	475 kg/m^3
Fly ash	105 kg/m^3
Silica fume	75 kg/m^3
Maximum w/cm	0.23

STEP 4

Determine volume of air required. None. Assume that 1.5 percent will be entrapped in this mixture.

STEP 5

Incorporate local aggregates.

First, determine the volume the paste will occupy, as shown in the following table:

MATERIAL	MASS, kg	SPECIFIC GRAVITY	VOLUME, m^3
Cement	475	3.15	0.151
Fly ash	105	2.50	0.042
Silica fume	75	2.20	0.034
Water (w/cm = 0.35)	151	1.00	0.151
Air, 1.5 percent	—	—	0.015

Total paste volume = 0.393 m^3

Second, calculate aggregate volumes and masses:

Coarse aggregate specific gravity: 2.68
Fine aggregate specific gravity: 2.60
Fine aggregate: 38 percent of total aggregate volume *(Note: If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.)*
Aggregate volume = 1.000 m^3 – 0.393 m^3 = 0.607 m^3
Fine aggregate volume = 0.38 × 0.607 m^3 = 0.231 m^3
Fine aggregate mass = 0.231 m^3 × 2.60 Mg/m^3 = 0.601 Mg = 601 kg
Coarse aggregate volume = 0.607 m^3 – 0.231 m^3 = 0.376 m^3
Coarse aggregate mass = 0.376 m^3 × 2.68 Mg/m^3 = 1.088 Mg = 1,088 kg

STEP 6

Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 5.4 for recommendations
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

STEP 7

Conduct production-scale testing. Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

5.7 ADDITIONAL CONSIDERATIONS FOR MIXTURE PROPORTIONING

The mixture proportioning examples given in this chapter are, of course, based on standard procedures. Interesting new systems are being developed that can augment these standard practices. Two such advanced procedures are discussed in the following sections. The SFA recommends that users of either of these approaches have a strong understanding of concrete mixture proportioning to ensure that mixtures are suitable for production and use.

5.7.1 Particle Packing

Particle packing is an umbrella term for various procedures that can enhance mixture development. As the name suggests, these procedures take the physical characteristics of the materials, gradings and specific gravities, and the mixture design weights and calculate how the particles pack into a cubic meter space. The tighter the packing – the better grading from large to small particle size – the denser the concrete will be. This can give a concrete mixture that is more durable and stronger, simply by getting the correct "blend" of the components. Adjustments of the design to achieve the best particle packing can give designs with lower cementitious materials contents and often higher coarse-to-fine aggregate ratios. Particle packing can be advantageous in achieving the best balance of fine materials for highly fluid concrete mixtures and is regularly used to proportion SCC and UHPC concretes.

Several programs have been developed to conduct the particle packing analysis. This software can calculate the changes in material content to achieve optimum particle packing, when presented with the "original" mix design. Such software will only use the materials given in the design and will not suggest the use of alternate materials. This software does not preclude a need for knowledge of standard mixture design procedures, which is essential for understanding the performance requirements of the mixture in both the fresh and hardened states.

Two examples of such software are:

- EMMA – Elkem Materials Mixture Analyser. This can be requested (free download) at the website: https://www.elkem.com/silicon-products/construction/concrete/
- KU MIX– University of Kansas– Concrete Proportioning Aggregate Optimization. This software can be accessed via: https://www.silicafume.org/ku-mix.html

5.7.2 Modifying Viscosity

In addition to the software approaches described above, ACI 211.6T, *Aggregate Suspension Mixture Proportioning Method*, provides a manual approach to developing concrete mixtures with optimized particle packing.

5.7.3 Statistical Approach for Complex Mixtures

For projects with complex requirements and where portland cement and silica fume may be used in conjunction with either fly ash or slag cement, development of mixture proportions in the laboratory may entail making a very large number of trial mixtures. Even with a large number of batches, the optimum mixture, in terms of best performance at the least cost, may not be found.

In such a case, it may be better to use a statistical approach to mixture development. In essence, this approach consists of six steps:

1. Determine the range of variables to be tested. For example, a set of variables could include a range of w/cm, a range of portland cement contents, a range of portland cement substitution by fly ash, and a range of silica fume contents.
2. Develop a suitable set of mixtures to be prepared to evaluate the various ranges defined above.
3. Make the concrete mixtures in the laboratory and determine the fresh and hardened concrete properties of interest.
4. Review the test data to determine the concrete mixture that will best meet the requirements of the project at the least cost. This can be considered the optimum concrete mixture.
5. Confirm the performance of the optimum mixture in the laboratory. In all likelihood, you will not have made this exact mixture during the testing phase.
6. Move on to production-scale testing.

Most concrete producers don't have access to a statistician to help with the process described above. This type of service may be provided by the supplier of chemical admixtures. Additional information may be found in one of the following references: Luciano et al. (1991) or Luciano and Bobrowski (1990).

Another option for optimizing a concrete mixture is to use online software available from the National Institute of Standards and Technology (NIST). This program is called "COST" (Concrete Optimization Software Tool), and it was developed by the Federal Highway Administration. NIST describes the two likely uses for this tool as:

- The first (and probably most common) use would be to proportion a concrete mixture to meet a set of performance criteria while minimizing the cost of the mixture.
- The second use would be to maximize or minimize one or more concrete properties (for instance, to achieve the highest possible strength or to achieve the lowest permeability).

COST may be found at the following location: https://www.nist.gov/services-resources/software/concrete-optimization-software-tool.

6 PRODUCING SILICA-FUME CONCRETE: HANDLING, BATCHING, AND MIXING

Producing concrete containing silica fume is not significantly different from producing concrete without silica fume. How the silica fume is supplied—bulk or bags — will be a major factor in determining exactly how the concrete is produced.

This chapter addresses making concrete containing silica fume. Topics covered are storage of the material, batching into concrete during production, and concrete mixing. Additionally, precautions are presented for the problems that can arise during concrete production.

6.1 GENERAL CONSIDERATIONS

The aim during production of silica-fume concrete is to introduce as few differences into the concrete production process as possible while turning out a high-quality, high-performance concrete. The key element to keep in mind is that silica-fume concrete includes a relatively small amount of silica fume, typically 30-45 kg/m^3, in a relatively large amount of concrete, 2,400 kg/m^3 for normal-weight concrete. For the silica fume to be effective, it must be accurately batched and thoroughly dispersed.

This chapter first presents general recommendations that apply to production of silica-fume concrete. The remainder of the chapter is organized by the product type of silica fume that is being used — bulk densified or bagged densified. Available product types are discussed in Chapter 2. Figure 6.1 shows which section of the chapter covers each product form.

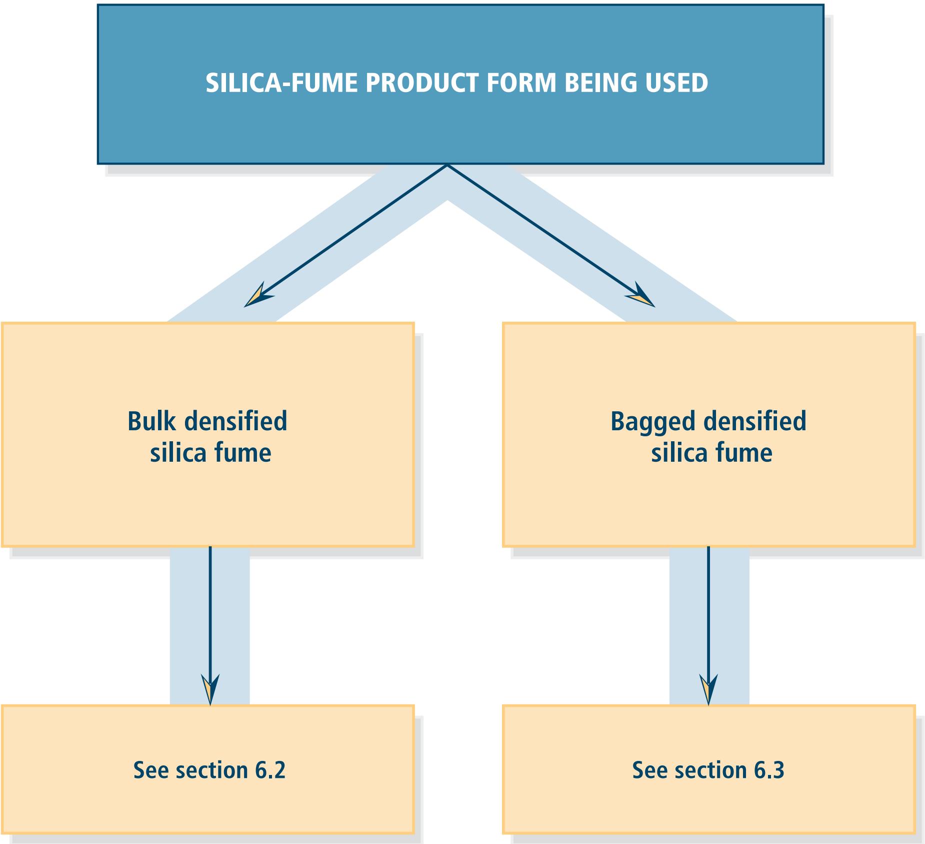

FIGURE 6.1. Organization of Chapter 6. Select the section of the chapter that discusses making concrete with the product form of silica fume that has been selected.

6.1 GENERAL CONSIDERATIONS

As appropriate, the following topics are covered for each product:

- Shipping
- Storage requirements
- Unloading
- Batching
- Mixing
- Other concerns

The most basic recommendation is to be overly cautious at the beginning of a project if you have not worked with silica-fume concrete previously. Your admixture supplier or the SFA can provide guidance on getting started using silica fume. Over time, as experience is gained, it may be appropriate to relax procedures as long as the quality of the concrete is maintained. It is much easier to relax over time than it is to attempt to tighten procedures if problems develop.

Following are several general recommendations that apply to all silica-fume product forms:

- **Air entraining.** It will usually be necessary to increase the dosage of air-entraining admixture (AEA) to develop and maintain the specified air content for the concrete. The required amount of AEA will usually be 150 to 200 percent of the dosage without silica fume. Once the required volume of air is developed, there is no evidence that indicates that silica-fume concrete behaves any differently from concrete without silica fume as far as maintaining air is concerned.

- **Mixer uniformity.** There are frequently recommendations that mixer uniformity testing as described in ASTM C94, *Standard Specification for Ready-Mixed Concrete,* be performed to qualify truck mixers for silica-fume concrete projects. Such testing is not necessary unless there is a specific concern over the uniformity of silica-fume concrete from truck to truck. This testing involves comparing concrete from different parts of a load using air content, slump, unit weight, aggregate proportions, and compressive strength. While these are important parameters for the concrete, they may not be indicative of whether the silica fume is being well dispersed. If the project specifications are built around performance on a specific test such as the rapid chloride test, then that test should be added to any uniformity testing that is performed. Look at the results of all testing performed to determine whether there is adequate mixing throughout the load.

6.1 GENERAL CONSIDERATIONS

- **Concrete temperature.** In concrete with a high portland cement content and a low water content, there may be an increase in temperature caused by hydration of the portland cement. Depending upon the application, this temperature increase may have to be considered. The first step to control temperature is to replace some of the portland cement with a suitable fly ash or slag cement. Silica fume can be used to offset early age strength loss that may result from the replacement. If a project has stringent concrete temperature controls, measures for controlling concrete temperature as described in ACI 305R, *Guide to Hot Weather Concreting*, should be considered.

- **Batching.** Never place silica fume in any form into an empty mixer before any other ingredients. Contact between the silica fume and any wash water or mortar on the drum can result in development of silica fume balls that will not dissipate during mixing. Specific batching recommendations for bulk and bagged silica fume are given later in this chapter.

- **Mixing.** High-performance concrete containing silica fume will usually require additional mixing beyond what is typically done on day-to-day concrete. Don't take shortcuts with mixing — this is a very poor place to attempt to economize.

- **Remixing.** Always remix the concrete upon arrival at the project site. Usually, thirty revolutions at mixing speed will be sufficient.

- **Mixer wash-out procedures.** Concrete mixtures with a high cementitious materials content, including silica-fume concrete, may be more difficult to wash out of a mixer. If a concrete mixture is difficult to wash from a drum, recommendations on washing out from the National Ready Mixed Concrete Association are given in Figure 6.2.

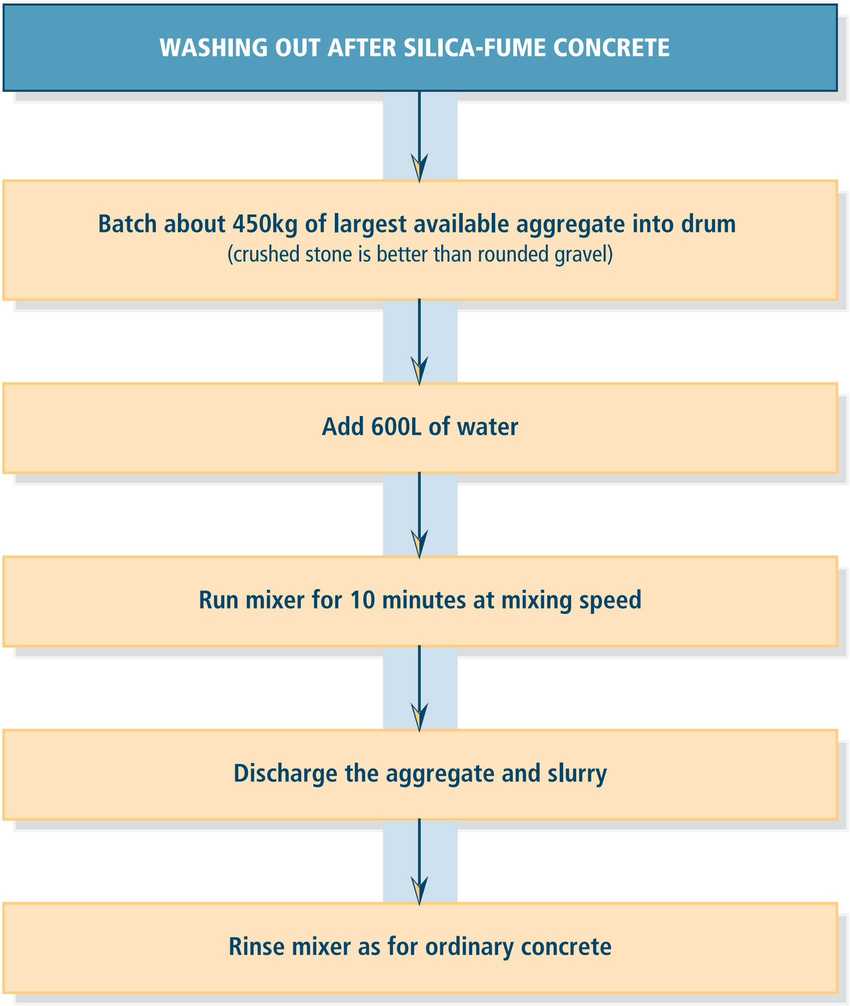

FIGURE 6.2. Recommendations for washing out truck mixers after silica-fume concrete based upon the NRMCA *Truck Mixer Driver's Manual* (2015).

6.2 BULK DENSIFIED SILICA FUME

Bulk densified silica fume is well suited for large projects where silo storage space is available. This product offers the same performance characteristics in concrete as undensified silica fume while being much more economical and user-friendly to work with. Keep in mind that this material will have a bulk density between 450 to 700 kg/m^3 while portland cement as delivered will be about 1,500 kg/m^3. This difference will require some adjustments in storing and handling the material.

6.2.1 Shipping

Bulk densified silica fume is typically shipped in the same types of bulk tankers used to ship cement or other pozzolans. Figure 6.3 shows a typical tanker unloading at a concrete plant. These tankers will have the following characteristics:

- Volume: 40 m^3
- Capacity of material: Approximately 20 metric tons

These tankers will have aeration pads to help move the material during unloading.

The major silica fume suppliers in the United States use trucking firms that deliver only silica fume in their tankers and who are very experienced in handling the material. Use of tanker operators without training or specific experience delivering silica fume is not recommended.

FIGURE 6.3. Unloading bulk densified silica fume into a silo. Note rubber hose and large-radius turn at top of the silo.

6.2.2 Storage Requirements

Bulk densified silica fume can be stored in any silo designed to hold cementitious materials. For major projects where multiple loads of silica fume will be used, minimum silo capacity should be 80 m^3 to allow for adequate material to be on hand between deliveries and to allow for complete discharge of tankers.

Other considerations for silos to store silica fume include:

- Silos should be free from leaks and should be in good overall condition.
- Silos with shared compartments and a single divider wall should be inspected to ensure that no material can leak from one compartment to the other. (Single-wall silos are not allowed by most concrete specifications.)
- Silos for silica fume should be clearly marked at the fill pipe location.
- Silos must be vented with a working dust collection system sized for the capacity of the silo. A dust collection system with a minimum surface area of 14 m^2 is recommended. The dust collection system must be clean at the time of delivery to eliminate back-pressure during unloading.

The most significant difference between silos used to store cement and those used to store silica fume is the fill pipe itself. It is highly recommended that any silo used for silica fume be equipped with a rubber fill hose rather than a steel pipe. Figures 6.4A, 6.4B, and 6.4C summarize recommendations for a silica-fume silo. Characteristics of such a system are:

- Use a minimum 150 mm diameter smooth wall rubber hose.
- Attach the hose to the silo approximately every 3 to 4.5 m. Attachments should be such that the hose is free to vibrate, which will help to prevent blockages.
- Eliminate steel pipes in the system wherever possible.
- Eliminate 90-degree bends. All bends in the hose should have at least a 1.5 m radius.
- Minimize, or eliminate if possible, horizontal runs of the hose.
- Direct the entry into the silo vertically in the center of the silo. Do not use any sort of deflector box or plate. Figure 6.4B shows two options for connecting the rubber fill hose to the top of a silo. Both options have been successfully used. Running the rubber hose directly into the silo (Option B) may cause difficulties in the connection.

Another recommendation for the silica fume silo is to provide a grounding connection between the silo and the tanker to prevent the buildup of static charges.

Following these recommendations for the silo will greatly reduce unloading times. Pump-off times of 90 to 120 minutes can be expected. Additionally, the potential for lumps forming in the silica fume during unloading will be minimized.

6.2 BULK DENSIFIED SILICA FUME

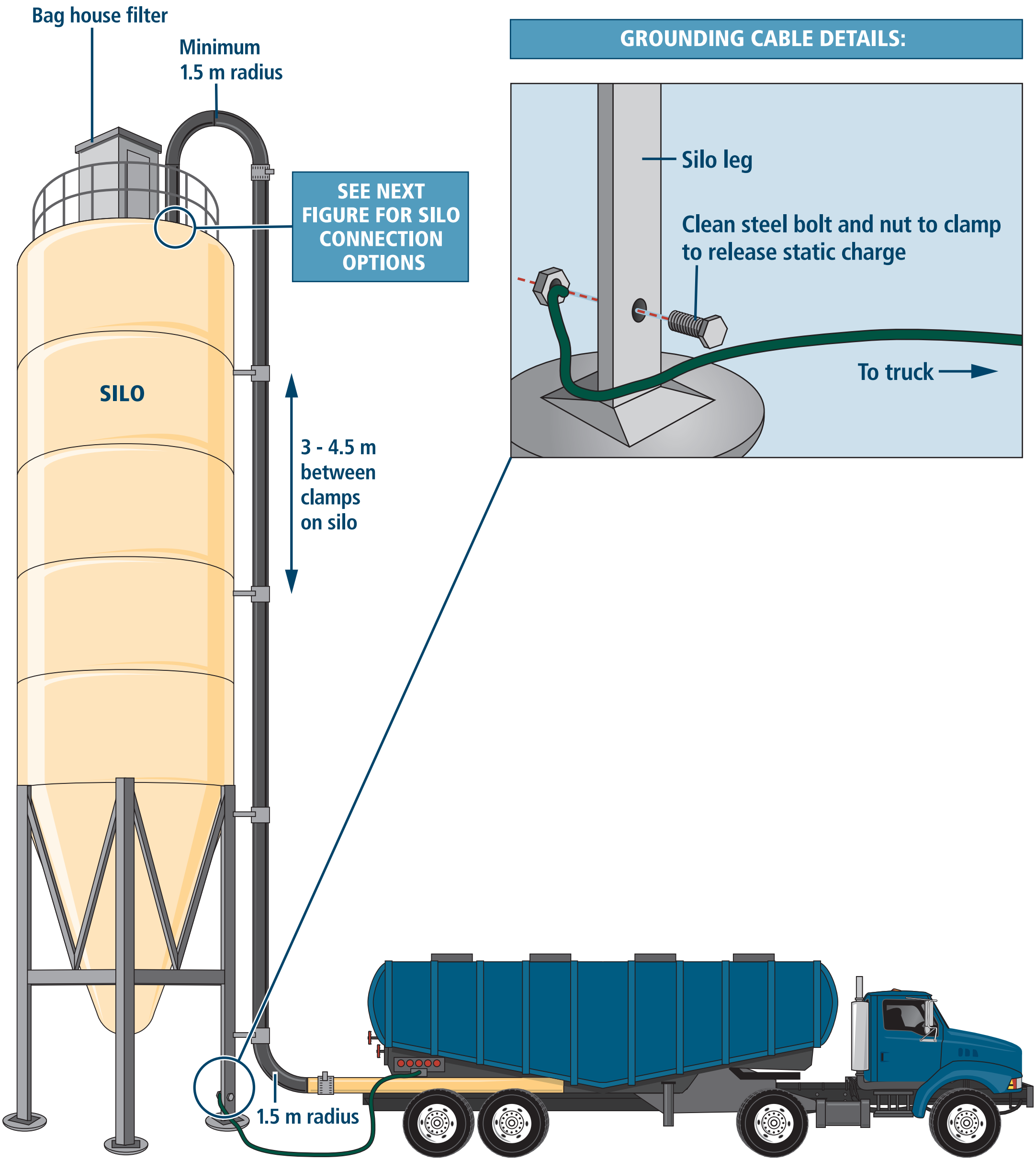

FIGURE 6.4A. Recommendations for silo for storage of bulk densified silica fume. Also, note grounding recommendations for unloading. See Figure 6.4B for options for connecting the rubber hose to the top of the silo.

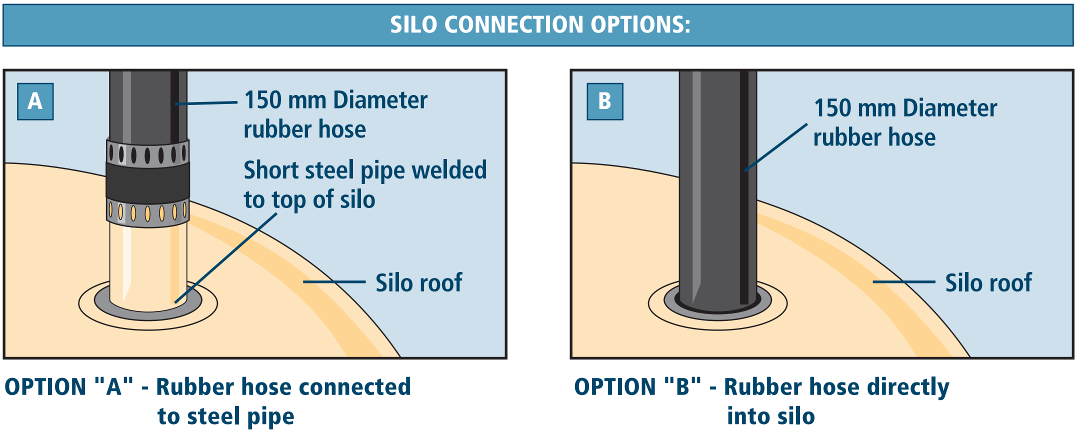

FIGURE 6.4B. Options for connecting the rubber silica-fume fill hose to the top of the storage silo.

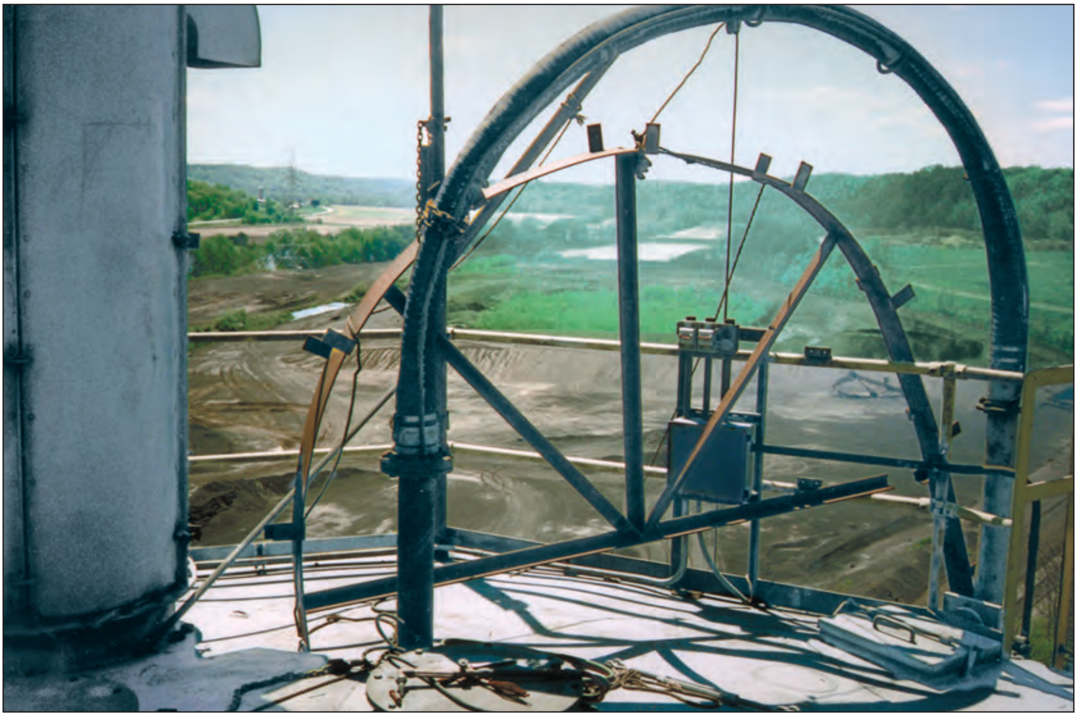

FIGURE 6.4C. Rubber fill hose connected to steel pipe on silo top. Note support frame for rubber hose being fabricated.

6.2.3 Unloading

Unloading a tanker of bulk silica fume can be a routine operation or a lengthy ordeal. This section looks at how to unload bulk silica fume into a storage silo.

The first step to successful unloading is to follow the instructions given in Section 6.2.2 regarding the fill pipe for the silo. Once the physical configuration is correct, here is a checklist to follow:

- Use only carriers with experience transporting and unloading silica fume.
- Ensure that the tanker is connected to the correct silo.
- Ensure that the silo baghouse filter is clean and operational. If the silo back-pressure exceeds 35 kPa, either the rubber hose or the baghouse filter may be clogged.
- Ground the tanker truck to prevent buildup of static electricity.
- Do not let the pump-off pressure exceed 70 kPa. Using higher pressure will clog either the tanker truck or the fill line to the silo.
- Do not attempt to rush the unloading process. Doing so will only increase chances of clogging the system.

Figures 6.5A and 6.5B show a tanker unloading at a concrete plant.

FIGURE 6.5A. Rubber hose used to transfer silica fume from tanker to producer's silo.

FIGURE 6.5B. Connecting rubber hose from tanker to rubber fill hose of silo.

6.2.4 Batching

Batching involves moving the silica fume from the storage silo, correctly weighing it, and then adding it to the mixer or truck.

Silica fume has been successfully transferred from storage silos using gravity feed, air slides, and horizontal screw conveyors. Remember that silica fume will usually flow out of a silo more readily than portland cement. This characteristic increases the possibility of clogging and packing when using an inclined screw feed device. Reduce the opening of feed gates or use a rotary valve to ensure not overwhelming the system.

When weighing silica fume, remember that relatively small amounts of material are being weighed compared to other concrete ingredients. Weighing errors can result in significant problems for a concrete producer:

- Using too much silica fume will cost more than estimated for the project.
- Using too little silica fume will result in the concrete not performing as intended.

Do not assume that a plant will automatically weigh the correct amount of silica fume. Even if a plant is operating within the tolerances established by ASTM C94, it is entirely possible to meet tolerances and not have the correct amount of silica fume in the concrete.

Many of the newer plants have tolerances much tighter than those called for in ASTM C94 and present no problems. If there are any questions regarding the accuracy of a plant, check with the plant manufacturer before beginning a silica fume project.

To minimize the potential for problems during weighing, some producers weigh the silica fume before the other cementitious materials. Review the plant to determine if such a practice would be appropriate.

Once questions regarding the weighing of the silica fume have been resolved, concrete production will be pretty much "business as usual." Add the silica fume slowly along with the other cementitious materials while mixing the other concrete ingredients. Do not add silica fume to a central mixer or a truck mixer without aggregates and water present. Follow the instructions in the next section about possibly holding back water or chemical admixtures to maintain an appropriate slump for mixing.

6.2.5 Mixing

The secret to achieving the benefits of using silica fume is to ensure that the silica fume is uniformly dispersed throughout the concrete. This dispersion can only be achieved if the concrete is adequately mixed.

Here are a few tips for mixing:

- Do not overload trucks. We recommend that loads be restricted to the rated mixing capacity of the trucks, which is defined by ASTM C 94 as 63 percent of the drum volume. This is important even for central mix plants because it may be necessary to perform additional mixing of the silica-fume concrete once it is in the truck.

- Once the concrete is in the truck, mix for at least 100 revolutions at mixing speed. Table 6.1 shows minimum recommended mixing times.

- Do not mix at too high a slump. The best dispersion will occur if mixing is done initially at 50 to 100 mm of slump. This lower slump will allow for the mixing action that helps eliminate any silica fume or cement balls. At higher slumps, the balls tend to float and do not get crushed. Once the concrete is adequately mixed, then adjust slump as necessary. Add an additional 30 revolutions after adding any additional chemical admixture.

- As the job progresses, it may be appropriate to increase load size or to reduce extra mixing. Make any such adjustments based on concrete test results obtained. As is discussed in Section 6.1, mixer uniformity testing may be of assistance, but don’t rely entirely on the results obtained from such testing.

TABLE 6.1

BASIC MIXING RELATIONSHIPS: TRUCK MIXERS AND CENTRAL MIXERS	
TRUCK MIXERS	
MIXER SPEED*	TIME TO GET 100 REVOLUTIONS
15	6 minutes 40 seconds
16	6 minutes 15 seconds
17	5 minutes 54 seconds
18	5 minutes 34 seconds
19	5 minutes 16 seconds
20	5 minutes 00 seconds

As recommended by manufacturer.

CENTRAL MIXERS	
BATCH SIZE	MINIMUM MIXING TIME PER ASTM C94
5 m^3	1 + (4 × 15) = 2 minutes 00 seconds
6 m^3	1 + (5 × 15) = 2 minutes 15 seconds
7 m^3	1 + (6 × 15) = 2 minutes 30 seconds
8 m^3	1 + (7 × 15) = 2 minutes 45 seconds
9 m^3	1 + (8 × 15) = 3 minutes 00 seconds
10 m^3	1 + (9 × 15) = 3 minutes 15 seconds

DON'T SHORTCUT MIXING TIME!

DON'T MIX MORE CONCRETE THAN RATED MIXING CAPACITY OF TRUCK OR CENTRAL MIXER!

6.2.6 Other Concerns

A very small number of producers have reported problems with lumps of silica fume showing up in concrete. If left in place in concrete in a climate subject to freezing and thawing, these lumps will absorb water, freeze, and expand. This expansion will result in popouts that look very similar to those caused by porous aggregate particles.

Some cases of such popouts can be traced to problems unloading the silica fume from a tanker into a silo. The silos have either had steel fill pipes that have clogged or some sort of deflector plate. Both of these situations have resulted in the build up of silica fume in the pipes or in the silo itself. The built-up silica fume falls from the silo wall or from the pipe and ends up in the concrete. An indication of possible problems is the need to “bang” on a steel fill pipe repeatedly with a hammer during unloading. This action can cause the silica fume that is building up on the walls of the pipe to break away as lumps and flow into the silo.

Other cases of these popouts have been traced to improper batching that has resulted in balling of the silica fume. These balls have not broken up in the truck and have been found in the hardened concrete.

6.3 BAGGED DENSIFIED SILICA FUME

Bagged densified silica fume is the same product that is sold and delivered in bulk. This product form is intended for use on smaller projects where a full tanker of silica fume may not be required. Additionally, bagged densified silica fume may be used on projects where there is no silo available to hold bulk deliveries of densified silica fume.

Bagged silica fume is available in 11.4 kg "repulpable" or "shreddable" bags. Since the introduction of these bags, millions of cubic meters of concrete have been produced using silica fume added as unopened bags.

These bags are intended to be added directly to a central or truck mixer without opening as shown in Figure 6.6. The bags are designed to disintegrate through a combination of wetting and grinding the paper during concrete mixing.

Since their introduction, these bags have gone through several modifications aimed at making them more readily repulpable. These modifications have included reducing the number of layers of paper and modifying the design of the corners and filling spouts to reduce the thickness of these areas. As might be expected, there is a trade-off between making the bags easier to disintegrate and strong enough to protect the silica fume during shipment and handling. The bags that are currently available are believed to be about as weak as is prudent.

FIGURE 6.6. Adding repulpable bags of densified silica fume directly to truck mixer. See Section 6.3 for precautions regarding unopened bags. Note the use of a dust mask and safety glasses. See Chapter 9 for personal safety recommendations.

6.3 BAGGED DENSIFIED SILICA FUME

6.3.1 Shipping

These bags are usually shrink wrapped on a pallet (Figure 6.7) and shipped by appropriate means depending upon the volume of material ordered.

FIGURE 6.7. Bagged silica fume.

6.3.2 Storage Requirements

Store this material as any other cementitious material in bags. This means keep the material dry and protected from physical damage to the bags.

There is no shelf life associated with silica fume in the densified form. If the material gets wet there will not be a hydration reaction in the bags like portland cement. However, the silica-fume agglomerates may become more difficult to disperse when added to concrete. If the bags are damaged, it will be difficult or impossible to verify that the correct amount of silica fume is being added per cubic meter of concrete.

6.3.3 Unloading

Use whatever means are typically used for handling palletized materials.

6.3.4 Batching

The repulpable bags are intended to be added directly to a central or truck mixer without opening. The bags are designed to disintegrate through a combination of wetting and grinding the paper during concrete mixing. As is discussed below in Section 6.3.6, in some instances it may be appropriate to open the bags and empty the silica fume into the concrete rather than add the bags unopened. Figure 6.8 shows bagged silica fume being emptied into a truck mixer. Recommendations for adding bags either unopened or opened are given in Table 6.2. The instructions vary slightly depending upon whether a central mix plant or a batch plant is being used.

FIGURE 6.8. Emptying a bag of densified silica fume into a truck mixer.

6.3 BAGGED DENSIFIED SILICA FUME

TABLE 6.2

RECOMMENDATIONS FOR BATCHING BAGGED SILICA FUME

USING REPULPABLE BAGS

CENTRAL MIX PLANT

Adding bags to central mixer with other ingredients

- Limit the load size — see note.
- Select the appropriate number of bags for the volume of concrete being produced. If necessary, round up to the nearest whole number of bags.
- Add unopened bags to central mixer simultaneously with other mix ingredients.
- Drop concrete into truck.
- Thoroughly mix concrete in truck, at least 100 revolutions at mixing speed.

CENTRAL MIX PLANT OR TRUCK MIXERS

Adding bags into truck after concrete is dropped into truck

- Limit the load size — see note.
- Select the appropriate number of bags for the volume of concrete being produced. If necessary, round up to the nearest whole number of bags.
- Central mix: Batch and mix in central mixer as you normally would. It may be necessary to hold back some HRWRA if the mixture is too wet without the silica fume. Drop concrete into truck.
- Truck mix: Batch as you normally would. Drop ingredients into truck.
- Add unopened bags of silica fume on top of concrete in truck.
- Thoroughly mix concrete in truck, at least 100 revolutions at mixing speed.
- Adjust slump as necessary to the level desired.

REMEMBER MIXING:
See recommendations in Section 6.3.5

LIMIT YOUR LOAD SIZE:
See recommendations in Section 6.3.5

USING OPENED BAGS

CENTRAL MIX PLANT OR TRUCK MIXERS

Adding silica fume through the plant

- Limit the load size — see note .
- Select the appropriate number of bags for the volume of concrete being produced. If necessary, round up to the nearest whole number of bags.
  - Empty bags of silica fume onto the coarse or fine aggregate. Adjust aggregate batch weights to account for the weight of the silica fume.
    OR
  - Empty bags of silica fume into the cement weigh hopper.
- Central mix: Batch and mix in central mixer as you normally would. It may be necessary to hold back some HRWRA if the mixture is too wet without the silica fume. Drop concrete into truck.
- Truck mix: Batch as you normally would. Drop ingredients into truck.
- Thoroughly mix concrete in truck, at least 100 revolutions at mixing speed.
- Adjust slump as necessary to the level desired.

CENTRAL MIX PLANT OR TRUCK MIXERS

Emptying bags into truck after concrete is dropped into truck

- Limit the load size — see note.
- Select the appropriate number of bags for the volume of concrete being produced. If necessary, round up to the nearest whole number of bags.
- Central mix: Batch and mix in central mixer as you normally would. It may be necessary to hold back some HRWRA if the mixture is too wet without the silica fume. Drop concrete into truck.
- Truck mix: Batch as you normally would. Drop ingredients into truck.
- Empty bags of silica fume on top of concrete in in truck.
- Thoroughly mix concrete in truck, at least 100 revolutions at mixing speed.
- Adjust slump as necessary to the level desired.

6.3.5 Mixing

The secret to achieving the benefits of using silica fume is to ensure that the silica fume is uniformly dispersed throughout the concrete. This dispersion can only be achieved if the concrete is adequately mixed.

When adding unopened bags of silica fume directly to concrete, thorough mixing is extremely critical to disperse the silica fume and to destroy the bags.

Here are a few tips for mixing:

- Do not overload trucks. We recommend that loads be restricted to the rated mixing capacity of the trucks, which is defined by ASTM C94 as 63 percent of the drum volume. This is important even for central mix plants because it may be necessary to perform additional mixing of the silica-fume concrete once it is in the truck.

- Once the concrete is in the truck, mix for at least 100 revolutions at mixing speed. Table 6.1 shows minimum recommended mixing times.

- Do not mix at too high a slump. The best dispersion will occur if mixing is done initially at 50 to 100 mm of slump. This lower slump will allow for the mixing action that helps eliminate any silica fume or cement balls. At higher slumps, the silica fume or cement balls tend to float and do not get crushed. Once the concrete is adequately mixed, then adjust slump as necessary. Mix an additional 30 revolutions after adding any additional chemical admixture.

- As the job progresses it may be appropriate to increase load size or to reduce extra mixing time. Make any such adjustments based on test results for the concrete. As is discussed in section 6.1, mixer uniformity testing may be of assistance, but don’t rely entirely on the results obtained from such testing.

6.3.6 Other Concerns

The SFA is aware of several instances in which the bags have failed to disintegrate as intended. The result is the appearance of fragments of paper in the surface of the concrete. This problem seems to be particularly persistent during construction of flatwork such as bridge decks.

We believe that the problem is caused by inadequate wetting and grinding of the paper during concrete mixing. The problem is particularly evident in concrete mixtures that have a very low w/cm, that contain a small maximum-sized coarse aggregate such as 13 mm, or that contain rounded aggregates. Pan-type concrete mixers are also very prone to problems with these bags.

The remedy for this situation is straight forward: if there are any doubts about the performance of the bags, conduct testing to determine whether the bags will deteriorate under the conditions and materials that will be used on a specific project. Testing should follow these steps:

- Make concrete using project materials and project mixers (for truck-mixed concrete, test all trucks to be used)
- Simulate haul time that will be expected
- Discharge the concrete and look for paper fragments

If fragments are seen or if there is any question of performance, **DO NOT** add the bags directly. Instead, simply empty the bags into the mixer, following the directions of Table 6.2.

7 PLACING, CONSOLIDATING, FINISHING, AND CURING SILICA-FUME CONCRETE

Placing and consolidating concrete containing silica fume is essentially the same as for concrete without silica fume. Finishing silica-fume concrete for both bridge decks and other flatwork is usually done without the waiting periods associated with traditional finishing practices. Curing must begin immediately to protect the concrete from drying.

This chapter looks at silica-fume concrete from the perspective of the contractor who is responsible for working with the material. The areas covered are those for which the contractor is typically responsible: placing, consolidating, finishing, and curing. The chapter begins with a look at drying of concrete, whether it contains silica fume or not.

The goal of the recommendations presented in this chapter is to achieve the hardened concrete properties that caused a specifier or owner to select silica-fume concrete for a structure. This goal can only be achieved by closely following the good practices that are presented here.

7 PLACING, CONSOLIDATING, FINISHING, AND CURING SILICA-FUME CONCRETE

(continued)

7.1 GENERAL CONSIDERATIONS

In most aspects, working with silica-fume concrete is not different from working with concrete without silica fume. The most notable exception to this statement is in finishing the concrete. However, if the finishing process is approached as is presented in this manual, the differences associated with silica-fume concrete can actually be turned into an advantage for the contractor. Here are a few general items to consider:

7.1.1 Coordination

It is critical that there be good coordination between the contractor working with the concrete and the concrete supplier. Relatively minor changes in the fresh properties of the concrete can make significant differences in the effort necessary to get the concrete placed and finished. Some of the items to consider:

- **Slump, No. 1.** A good rule of thumb is to start at a slump that is about 50 mm higher than what would be used for concrete without silica fume in the same placement. This increase in slump allows for the additional cohesiveness of the silica-fume concrete. Don't worry about segregation — it takes a very large increase in slump to produce segregation in silica-fume concrete.

- **Slump, No. 2.** It is usually best to place at the highest slump that is practical for actual project conditions. The higher the slump, the easier it is to close the surface of the concrete during screeding and bull floating. The limiting factor for bridge deck or flatwork placements will usually be any slopes involved in the placement. Use the highest slump that will hold on the slope that is being placed.

- **Viscosity.** Finishers frequently report that silica-fume concrete is "sticky" and difficult to work with. So-called "stickiness" is caused by increased concrete viscosity that is inherent with high cementitious materials content, low water content mixtures that utilize superplasticizers for a chemically-induced workable slump. Experience has shown that stickiness may result from the interaction of the silica fume and some chemical admixtures (water reducers and superplasticizers) that are in the concrete. One approach is simply to substitute one chemical admixture for another of a different chemistry. Polycarboxylate-based admixtures are usually very effective as substitutes. Another approach is to remove about one-third of the superplasticizer and replace it with an equal amount of a mid-range water reducer. Don't be afraid to try different combinations of admixtures to get the best concrete possible for the project. Another consideration in stickiness can be the grading and amount of the fine aggregate, as fine aggregate grading can also influence overall concrete viscosity. It may help to change the fine-to-coarse aggregate ratio to include more coarse aggregate. In some cases, changing the source of the fine aggregate may help reduce stickiness. A final suggestion is to use available particle packing software that looks at the grading of all concrete ingredients from coarse aggregates to cementitious materials. This approach can help eliminate excess fines that may be responsible for the stickiness. See additional discussion of stickiness in Section 5.5.

7.1.2 Preplacement Considerations

There are two topics that should be considered before any silica-fume concrete placement takes place. These are the preplacement conference and the test placement.

- **Preplacement conference.** A preplacement conference is important for any type of concrete work, but such a meeting is even more important for silica-fume concrete. This is the opportunity for the contractor to outline all plans for placing, protecting, finishing, and curing the concrete so everyone involved understands what will occur. It is also the time for the contractor to resolve any unanswered questions regarding the expectations of the owner and the engineer. Frequently, the preplacement conference is held in conjunction with a test placement.

  A key element to discuss at the preplacement conference is the rate of concrete delivery. A typical problem is getting too much concrete on site and having trucks back up. This is particularly true for bridge deck overlays or for silica-fume toppings over precast elements. In these types of placements, a small volume of concrete will cover a large surface area.

- **Test placement.** It is almost imperative that a test placement be conducted before concrete work actually starts on a project. This placement gives everyone the opportunity to get the "bugs" out of the system and to observe and approve all procedures. Representatives of all parties should be present: owner, engineer, concrete supplier, materials suppliers, and, of course, the contractor. If the test placement goes well, the next step is to begin actual placements in the structure. Some of the topics that ought to be discussed during the test placement include:

  1. **Concrete mixture.** This is usually the first chance for the contractor's finishers to see the concrete mixture. This is their chance to fine tune the concrete and placement procedure. The test placement is also a good time to determine whether any adjustments to the concrete based upon weather or placing conditions will be required. For example, it may be appropriate to request a retarder or a non-chloride accelerator, depending upon conditions.

  2. **Finishing approach.** This is the opportunity to try different approaches and different tools for finishing the concrete. Determine which tools work best to close and finish the surface to the degree required.

  3. **Acceptable finish.** Have the owner define the exact nature of the finish that will be acceptable for the actual concrete work. Don't leave the test placement without achieving this decision.

  4. **Protecting the concrete.** It is appropriate to leave a portion of the test concrete unprotected against drying to see how quickly it will dry out and what the consequences may be. This is also an opportunity to determine how well different protection schemes will work.

7.1.3 Formed Silica-Fume Concrete

For concrete that is formed and not finished, such as columns and walls, there will be no differences between normal practices and those required for silica-fume concrete. Place, consolidate, and protect the concrete as appropriate for the application and job conditions. A higher slump will help get concrete into congested forms with a lot of reinforcing steel. However, high-slump concrete will still require vibration to remove air voids. When using silica-fume concrete with a high dosage of superplasticizer, don't forget to consider the form pressures from the fluid concrete.

7.2 PLACING AND CONSOLIDATING

Silica-fume concrete has been successfully placed by all means of placing concrete. These include direct discharge from mixer trucks, crane and bucket, tremie under water, and pumping. Given the nature of the applications where silica-fume concrete tends to be used, the vast majority has been placed by pump. Overall, do not expect to see any significant differences when placing and consolidating silica-fume concrete.

As noted earlier in Section 7.1, it is always easier to work with as high a slump as practical for a given placement. Use a slump for silica-fume concrete based upon actual job conditions and not based upon arbitrary recommendations that were probably developed for concrete without silica fume and superplasticizer.

Because a lot of silica-fume concrete is placed by pump, there are the usual concerns over air loss. Silica-fume concrete is no more or no less susceptible to air loss than any concrete without silica fume placed under the same circumstances. Following good pumping practices, air loss of 1 to 2 percent going through the pump can be expected. If greater air loss is being seen, look at the procedures and configuration of the pump boom before blaming the concrete mixture. If higher air losses are being experienced, be very careful attempting to fix the problem by increasing the air content of the concrete going into the pump. What may work on one day may not work well the next day if the configuration of the boom is changed. See ACI 304.2R, *Placing Concrete by Pumping Methods*, for additional information on pumping and air loss.

Silica-fume concrete is a very fluid material, particularly if the recommendations regarding increasing slump are followed. However, don't be fooled by the apparent workability — this concrete still needs to be adequately vibrated during placement. Do not assume that a vibratory screed will vibrate concrete in deeper sections such as beams cast integrally with slabs. An internal vibrator must be used in accordance with recommendations from ACI. For more information, see ACI 309R, *Guide for Consolidation of Concrete*.

7.3 CONCRETE DRYING

Much has been written about the tendency of silica-fume concrete to dry out during placing and finishing. This section will explain what is really happening and how to adjust the work to accommodate the concrete. The descriptions and recommendations in this section apply to concrete with and without silica fume.

7.3.1 Bleeding

Because of the very high surface area of silica fume that tends to adsorb water and the typically very low water contents of silica-fume concrete mixtures, there is little, if any, bleed water. As the silica fume content increases or as the water content decreases, bleeding will be reduced or eliminated. There are good and bad aspects of this lack of bleeding. On the positive side, the lack of bleeding means that finishing can start earlier and be completed sooner. Additionally, bleed water will not accumulate under aggregate particles and under horizontal reinforcing bars. There will be no bleed water channels for chlorides or other intrusive materials to use as a "shortcut" to get into the concrete. On the negative side, the lack of bleeding means that silica-fume concrete flatwork, under the appropriate environmental conditions, will dry from the surface downward. This drying will make it more difficult to close the surface of the concrete during finishing. Drying can also lead to plastic crusting and, eventually, plastic shrinkage cracking.

7.3.2 Surface Drying

Let's first look at the environmental conditions that lead to drying of the concrete surface. There are four elements to be considered: air temperature, relative humidity, concrete surface temperature, and wind speed. Many years ago, a chart was developed to estimate how all of these factors interact to contribute to drying of concrete. This chart is shown in Figure 7.1. By entering the appropriate values in the chart, an estimate of moisture loss in units of kilograms of water per square meter per hour can be developed. The conventional wisdom presented by ACI is that if the predicted loss is less than 1.0 $kg/m^2/hr$, then there should not be a problem. Because this value was determined for concrete without silica fume, many recommendations for silica-fume concrete use a value that is one-half the original value: 0.5 $kg/m^2/hr$.

Many specifiers include a requirement to use this chart in their specifications for silica-fume concrete. If the estimated rate of moisture loss exceeds some specified value, these specifications require some form of protection for surface drying of the concrete.

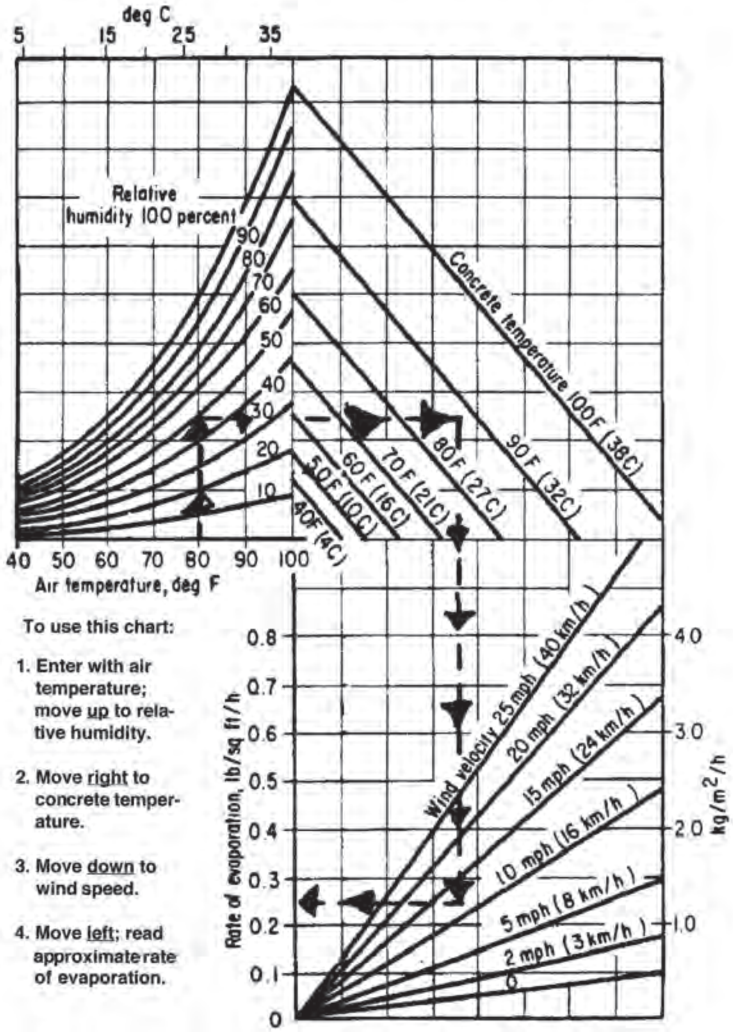

FIGURE 7.1. ACI evaporation estimation chart. Source: ACI 308R, *Guide to Curing Concrete.*

However, it is important to look at this approach to estimating evaporation a little more closely. Table 7.1 presents the recommendations for actually measuring the parameters involved. Usually, the measurements are not made as recommended; instead, weather data is obtained by calling the local weather office. The data are then plotted and decisions are made regarding whether to place or not place concrete and whether to protect or not protect the concrete. Everyone on the job is satisfied because the requirements of the specification are being met. However, the actual requirements of preventing drying of the concrete may not be met, and that is what gets contractors into trouble with crusting and plastic shrinkage cracking.

7.3 CONCRETE DRYING

TABLE 7.1

WHERE TO MEASURE INPUT FOR EVAPORATION CHART
■ Air temperature: 1.2 – 1.8 m above surface, in shade
■ Water temperature: Equals concrete temperature
■ RH: 1.2 – 1.8 m above surface, in shade, upwind
■ Wind speed: 0.5 m above surface

Source: ACI 308R, Guide to Curing Concrete.

The best approach is to combine the use of the chart with a little common sense. First, go ahead and obtain the values from the local weather source and use the chart to develop an estimate. But don't rely solely on the estimate from the chart, particularly if the estimated value is near the limit of 0.5 or 1.0 kg/m^2/hr.

Identify the particulars of the actual project site. Is the placement in direct sun, is the humidity low, and is the wind or temperature or both increasing? Regardless of what the chart may indicate, these are conditions that can result in rapid surface drying. If the temperature and humidity are high, workers may be uncomfortable. However, the high humidity will help keep the concrete from drying out. The more uncomfortable workers are personally from the temperature and humidity, the less likely that the concrete will dry out. **It's always best to err on the safe side when deciding whether to provide protection against concrete drying out.**

One additional thought on drying is appropriate. As the weather gets hotter every summer, many contractors or concrete suppliers add a retarder to increase the working time of their concrete. Under the appropriate circumstances, this approach may be correct. However, for concrete flatwork, the use of a retarder is usually not correct. The retarder will slow the initial hydration reactions, which will expose the concrete to the drying conditions for a longer time. The retarder, in some cases, can actually make the situation worse rather than better.

7.3.3 Results of Drying

There are two consequences of concrete drying - plastic crusting and plastic shrinkage cracking.

- **Plastic crusting —** Concrete finishers frequently say: "My concrete is setting from the top down." The surface concrete may actually be setting more quickly than the underlying concrete if it is a sunny day and the surface temperature is high. Or, the surface concrete may simply be drying out if the environmental conditions are conducive to drying and if there is little or no bleed water coming to the surface. In either case, a crust will form on the surface of the concrete as shown in Figure 7.2. If a finisher touches or steps on the concrete it will seem like it is setting and that it is time to begin floating and troweling. But actually, only the surface is getting stiffer and the center of the concrete may still be very soft. Finishing under these conditions will typically result in a very wavy surface that will not meet any smoothness or flatness requirements.

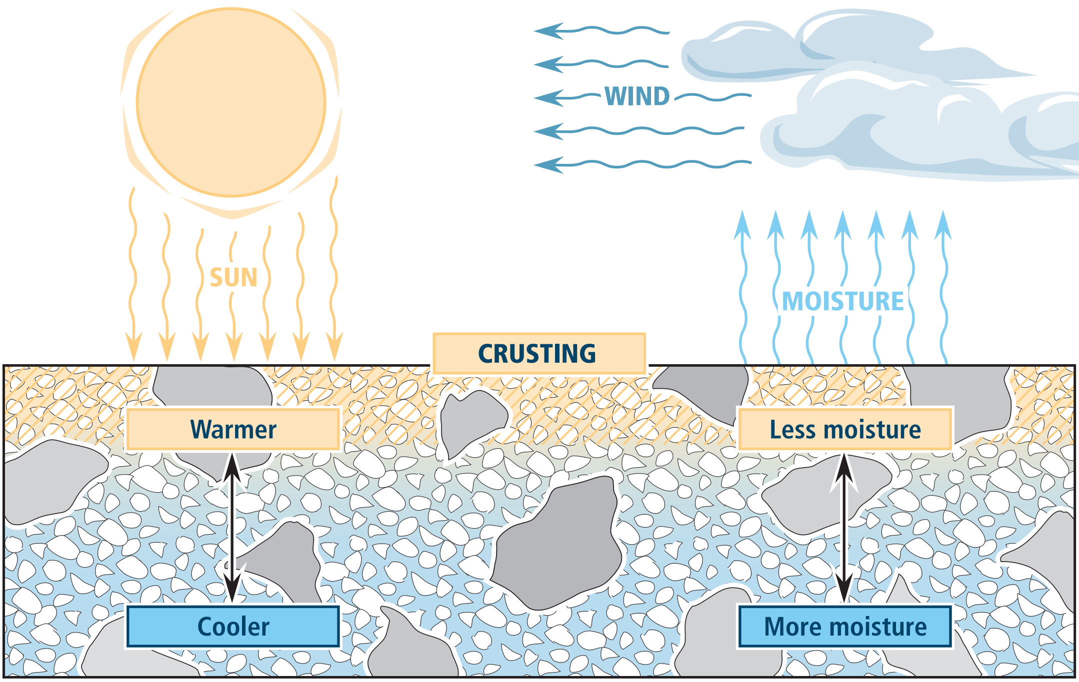

FIGURE 7.2. Crusting of concrete surface. Under some circumstances, crusting may lead to plastic cracking.

Once the surface begins to dry, it is very difficult to recover from the situation. The tendency is to get onto the concrete "before it gets away." Water or "finishing aid" is frequently applied to the surface, which may result in a concrete surface that is less durable than intended.

- **Plastic shrinkage cracking —** Under some circumstances, rather than crusting of the surface, cracking will appear. Usually, these cracks are oriented randomly and typically don't go to the edge of a slab. Also, they are usually not full depth. Figure 7.3 shows plastic shrinkage cracks in silica-fume concrete. Exactly why cracking will occur in some placements and crusting occurs in others is not clear.

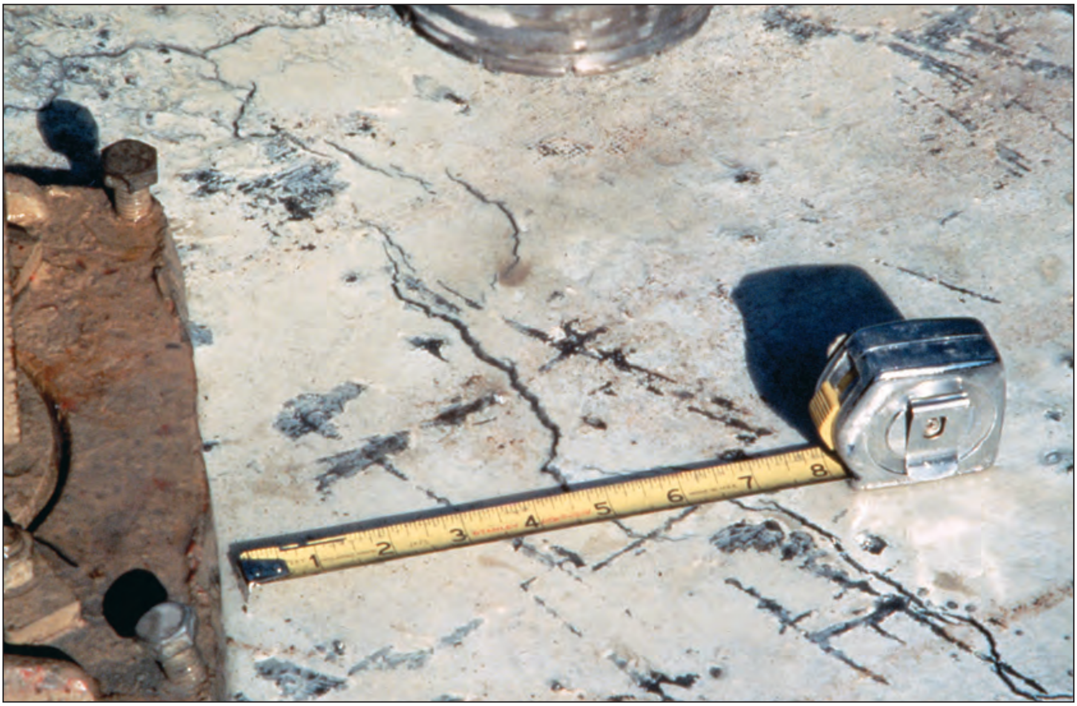

FIGURE 7.3. Plastic shrinkage cracks in silica-fume concrete.

7.3 CONCRETE DRYING

When does the drying leading to plastic crusting or plastic shrinkage cracking take place? Look at the typical finishing procedure presented in Table 7.2. The time when the concrete is most likely to dry and suffer problems is during the initial waiting period between the first pass of bull floating and the actual beginning of floating and troweling. This period is usually several hours while waiting for the concrete to begin to harden. The actual time will vary depending upon the type of placement, mixture proportions, cement and silica-fume content, presence of other pozzolans, concrete temperature, and use of accelerating or retarding admixtures. For bridge decks the waiting period may be significantly less than that for other types of flatwork. If estimates of moisture loss raise concern, it is during this initial waiting period that steps must be taken to protect the concrete from drying.

A second period of potential damage is between the final finishing pass and the beginning of curing. Usually, the concrete has gained enough strength by this time to resist plastic shrinkage cracking, but prolonged drying after finishing will result is a less durable surface.

TABLE 7.2

STEPS IN FINISHING CONCRETE FLATWORK
PLACE — SCREED — BULL FLOAT
WAIT — DANGER!
FLOAT — TROWEL
WAIT — LESS DANGER!
CURE
THE WAITING PERIODS ARE WHEN THE SILICA-FUME CONCRETE MUST BE PROTECTED FROM DRYING. USING THE ONE-PASS FINISHING PROCEDURE CAN ELIMINATE OR MINIMIZE THE WAITING PERIODS.

7.3.4 Protecting Against Drying

Table 7.3 presents some of the commonly recommended approaches for protection against drying. Of the approaches shown, the most commonly used with silica-fume concrete are fogging, using an evaporation retarder, and using the one-pass finishing technique. Each is discussed below.

TABLE 7.3

APPROACHES FOR PREVENTING PLASTIC CRUSTING AND PLASTIC SHRINKAGE CRACKING
Conduct one-pass finishing
Use evaporation retarder
Use fogging
Use cool concrete
Dampen subgrade
Erect windbreaks
Erect sunshades
Use synthetic fibers
Work at night
Cover concrete with plastic between finishing operations
See ACI 308R, *Guide to Curing Concrete*, for additional recommendations

- **One-pass finishing.** The first approach to preventing problems associated with drying of silica-fume concrete is to use the one-pass finishing approach. This procedure takes advantage of the lack of bleeding and eliminates the waiting period between placing and finishing. One-pass finishing is described in Section 7.5.

- **Evaporation retarders.** These products are widely available and are frequently used. For many years, the products were promoted and sold as "evaporation retarders and finishing aids" by the manufacturers. This practice has been reduced, and most data sheets now refer to the products as only evaporation retarders. Using too much of these products and finishing the product into the surface can result in damage to the concrete.

  How are they supposed to be used? Figure 7.4 shows an evaporation retarder being applied. These products form a very thin film on the surface of the concrete. This film is technically supposed to be only one molecule thick, so the products are frequently called "mono-molecular" materials. This thin film will keep moisture in the concrete, even under extreme drying conditions. Apply the evaporation retarder after the bull floating is completed and do not disturb the product until floating begins. If any type of finishing tool is run across the surface after the evaporation retarder is applied, then the film will be broken, and it will no longer keep in moisture.

FIGURE 7.4. Applying evaporation retarder to silica-fume concrete to prevent loss of moisture before curing begins.

- **Fogging.** The goal of fogging is to maintain a high humidity above the concrete surface during the time from placement to application of curing. If environmental conditions cause a concern over drying, fogging should begin immediately after the concrete is placed by a finishing machine or after bull floating. Depending upon the type of placement and the degree of finishing required, it may be necessary to fog between finishing passes.

  Fogging is best accomplished using a nozzle that combines compressed air and a very small amount of water. Figure 7.5A shows a hand-held fogging device being used on a parking structure and Figure 7.5B shows a fogging system mounted on a bridge-deck finishing machine. The equipment can be commercially purchased or it can be made on site. Misters like those used in a supermarket for produce or pressure washers with a fine nozzle have been used successfully. The key is to deliver a very small amount of water in a very fine mist.

  Inspectors frequently express concerns regarding the potential damage that fogging can do to the concrete surface. Just like almost any other construction practice, fogging can be abused, and if this happens, surface damage will result. Remember, the goal of fogging is to increase humidity and not to put water on the surface that gets finished into the concrete. However, if environmental conditions are such that rapid drying is a concern, a little water that does fall onto the concrete surface can be expected to evaporate quickly. Just as it is true for any other placement operation, do not finish bleed water or fog water into the surface.

FIGURE 7.5A. Proper fogging of silica-fume concrete in a parking structure to increase humidity and prevent drying of the concrete surface.

FIGURE 7.5B. Fogging equipment mounted on paving machine. The fog nozzles are pointed upward so moisture is not added to the concrete surface.

- **Control environmental conditions.** Taking steps to directly address environmental conditions that result in rapid drying can help reduce finishing problems and should be considered for all placements. These steps are shown in Table 7.3 starting with using cooler concrete. Cooling the subgrade or cooling metal pans for deck placements will significantly reduce the rate at which water leaves the concrete. Other steps such as working at night, or in the shade or controlling wind directly address specific issues. For interior slabs, consider placing after the structure is enclosed. Using synthetic fibers has been shown to reduce plastic shrinkage cracking.

7.4 FINISHING BRIDGE DECKS

Finishing silica-fume concrete bridge decks is very similar to finishing bridge decks without silica fume. The greatest differences are the requirement to move quickly from one step to the next and the requirement to begin curing immediately after the concrete is placed and finished. Actually, because of the equipment that is available, finishing bridge decks can be done under an even more compressed time scale than other flatwork. Finishing other types of silica-fume concrete flatwork is described in Section 7.5.

The procedures described below are the same for both full-depth placement and overlays. The only difference is the necessary surface preparation and the possible requirement for a bond coat for overlay placements.

Typical bridge deck finishing steps are shown in the flow chart in Figure 7.6. This flow chart covers silica-fume concrete used in both full-depth or overlay placements. The steps shown in the flow chart are discussed below:

7.4.1 Determine the Degree of Finishing Required

For bridge decks the degree of finishing required will usually be defined in the project specifications. Remember that the least amount of working of the concrete surface usually will result in the most durable concrete

7.4.2 Conduct a Preplacement Conference

As is discussed in Section 7.1.2, this meeting is the opportunity to discuss the contractor's plans for all aspects of the work. Don't leave the meeting with any unanswered questions.

7.4.3 Conduct a Trial Placement

Also, as is discussed in Section 7.1.2, a trial placement is an ideal time to finalize all decisions regarding finishing. The trial placement must be attended by the DOT representatives who have the authority to accept the mixture and procedures demonstrated. The contractor must commit to using the same finishing crew for the trial placement and the actual placements on the structure. The trial placement must be large enough to allow for realistic finishing techniques to be demonstrated. At the conclusion of the trial placement, one of two conclusions must be reached: an acceptable finishing approach has been demonstrated and accepted or the need for an additional trial placement has been established.

7.4 FINISHING BRIDGE DECKS

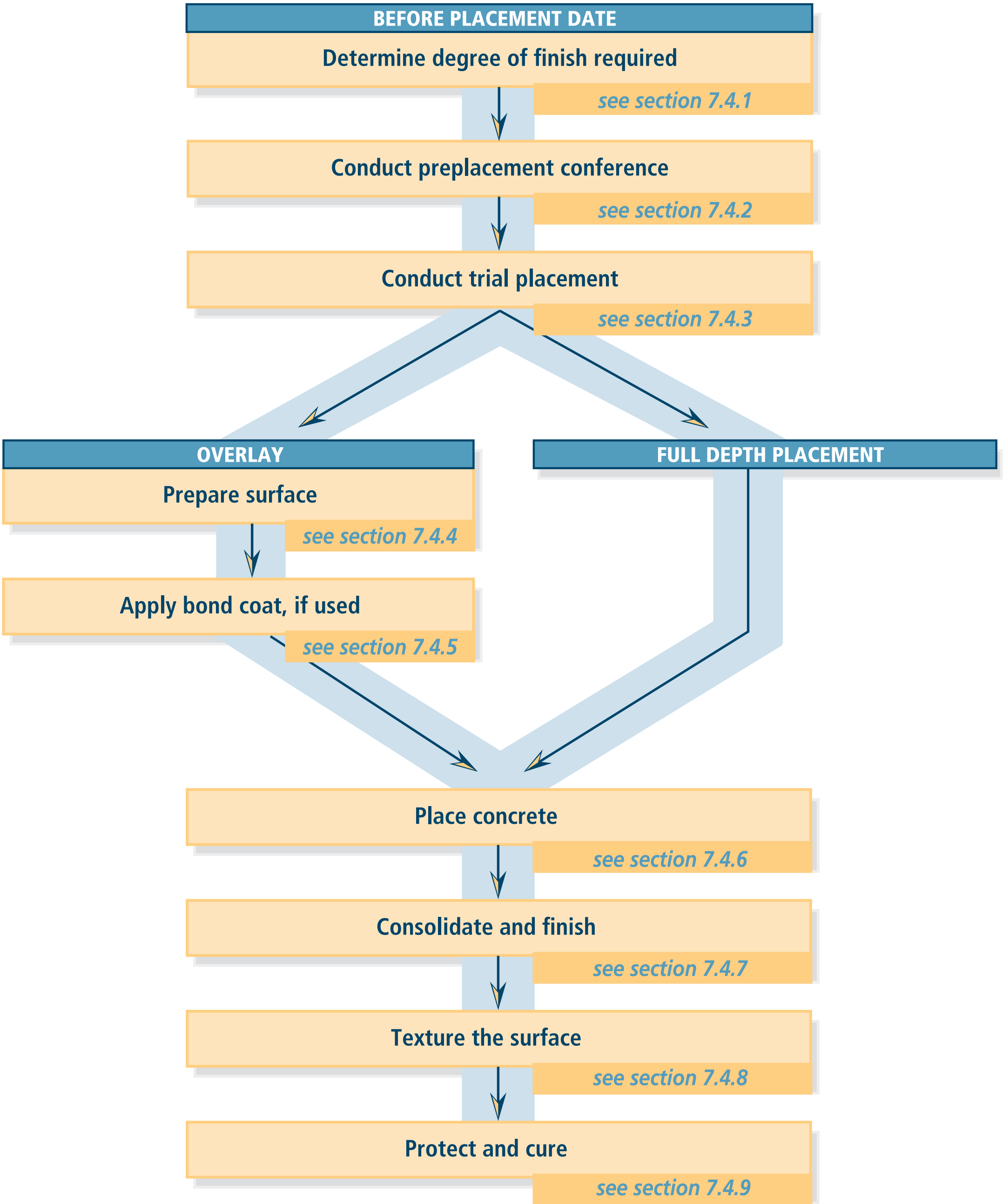

FIGURE 7.6. Finishing steps for concrete bridge decks. The steps are described in the text section noted.

7.4.4 Surface Preparation for Overlays

As is true for any overlay material, proper surface preparation is critical for successful placement of a silica-fume concrete overlay. All unsound concrete must be removed and corroded reinforcing replaced or repaired as required by specifications as shown in Figure 7.7. Extreme care must be taken to ensure that any concrete left in place, to which the overlay is expected to bond, is undamaged. Frequently, overlays fail just below the bond line because of damage to this concrete during removal operations. Generally, milling machines should not be used because of the potential for microcracking in the substrate. Shot blasting or hydro demolition techniques are preferred. See ACI 546.1R, *Guide for Repair of Concrete Bridge Superstructures*, for a discussion of appropriate concrete removal techniques for overlay placements.

FIGURE 7.7. Concrete bridge deck prepared for a silica-fume concrete overlay. Deteriorated concrete has been removed and the reinforcing steel has been cleaned to prepare for the placement of the overlay.

Another problem that has been seen on concrete overlays, with or without silica fume, is that the surface of the underlying concrete has been too smooth for good mechanical bond to take place. A rough surface with coarse aggregate particles exposed and a surface amplitude of approximately 5 mm is recommended by the SFA. An ASTM test, ASTM E 965, *Standard Test Method for Measuring Pavement Macrotexture Using Volumetric Techniques,* (sometimes referred to as the "sand patch test") can be used to evaluate surface preparation. Another approach is to use the surface roughness samples prepared by the International Concrete Repair Institute.

7.4.5 Apply Bond Coat

Different states specify different requirements for the use of a bond coat between an overlay and the underlying concrete. A typical bond coat is prepared as a cementitious grout. If a bond coat is specified, it should contain the same cementitious materials as the overlay concrete. There are two areas where the grout can become a problem: First, don't make a weak grout on site using a small mixer. Order the grout from the concrete supplier. Second, don't allow the grout to get too far ahead of the actual concrete placement. When this situation occurs, the grout will dry out and the bond enhancer actually becomes a bond reducer. Some states allow the grout from the concrete itself to be broomed into the deck ahead of the placement. If this practice is followed, be sure to remove the aggregate that is not broomed into the deck.

Whether or not a bond coat is used, be sure the surface of the concrete to receive the overlay is clean. This step includes removing any loose material and checking for any concrete that may have been damaged but not removed during the removal of the existing deck.

7.4.6 Place the Concrete

For almost all bridge decks, concrete placement will be directly from a delivery vehicle or by a pump (Figure 7.8). If pumping, particularly if the pump is located beneath the bridge deck, don't forget the considerations mentioned in Section 7.2 regarding pump boom configuration and air loss.

FIGURE 7.8. Silica-fume concrete being placed on the deck. Note the use of the vibrator to provide additional consolidation to that provided by the finishing machine.

7.4.7 Consolidate and Finish the Concrete

Most bridge deck placements use a heavy-duty bridge machine to strike off, consolidate, bull float, and pan float the concrete (Figure 7.9). When these machines are set up properly, there is essentially no requirement for any additional hand finishing of the concrete. The only concern with these machines is that the concrete should not be placed on the deck too far ahead of the machine. New York State DOT recommends a maximum of 1.5 to 2.5 m ahead of the machine. These limits are appropriate; however, under severe drying conditions the lower limit ought to be used.

FIGURE 7.9. Bridge deck machine being used to place silica-fume concrete overlay.

7.4.8 Texture the Surface

The requirements for surface texture vary from state to state. Figures 7.10A and 7.10B show a deck being broomed or tined immediately behind the finishing machine. Some states incorporate a drag behind the finishing machine while others require the drag and later saw cutting. If a texture is to be applied at the time of concrete placement, be sure not to let the concrete dry out during the process.

FIGURE 7.10A. Applying a broomed finish. After the finishing machine passes over the surface, some additional floating and finishing by hand may be required, particularly along the edges of the placement. Texturing using a broom can also be seen in this photo.

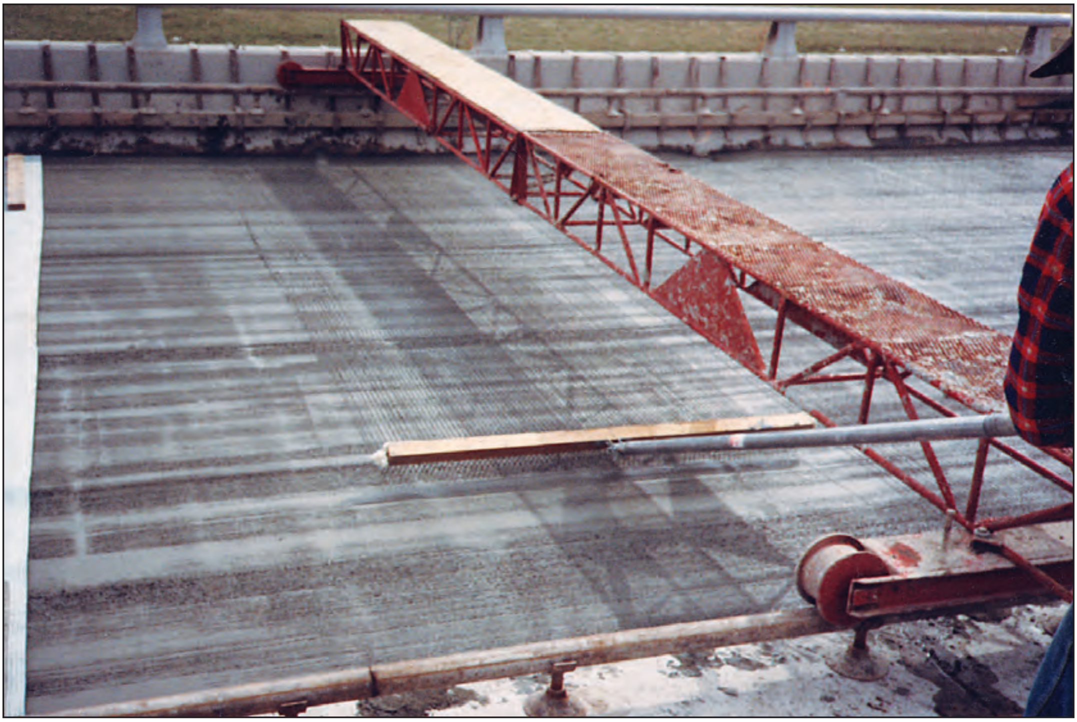

FIGURE 7.10B. Applying a tined finish. Some DOTs prefer to have the grooves ground in after the concrete has hardened.

7.4.9 Protect and Cure the Surface

This is one of the most critical steps for successful placement of bridge decks. If there are delays in the placing-finishing-texturing process, protect the concrete using an evaporation retarder, fogging, or plastic sheeting as appropriate. Immediately after the final finishing step, whether this is the pass of the finishing machine or the texturing, begin curing. The term "immediately" can be open to interpretation. **The SFA recommends that curing be started within 10 to 15 minutes after concrete placement.** Figures 7.11A and 7.11B show curing being applied immediately after the finishing machine. For additional information on the importance of immediate curing, see the article by Praul (2001).

When bridge decks are placed in a single lane, it is usually possible to apply wet burlap and plastic immediately without waiting for the concrete to harden to allow workers to walk on it. This type of curing is shown in Figure 7.11C.

FIGURE 7.11A. Curing silica fume bridge deck. Curing is following placement and finishing without any delay.

FIGURE 7.11B. Curing silica-fume concrete bridge deck. Applying wet burlap while the concrete is still too soft to walk on.

FIGURE 7.11C. Wet curing using burlap and plastic sheeting applied to a silica-fume concrete bridge deck during a single lane placement.

7.4 FINISHING BRIDGE DECKS

Two frequently asked questions are:

- What type of curing is necessary?
- How long must the silica-fume concrete be cured?

The SFA strongly recommends that all silica-fume concrete bridge decks be wet cured. We also recommend a minimum of 7 days of uninterrupted wet curing.

Any other means of curing or curing for a shorter duration can compromise the quality of the concrete. See Section 7.6 for additional discussion on the importance of curing silica-fume concrete.

7.5 FINISHING PARKING STRUCTURES AND OTHER FLATWORK

This section discusses finishing silica-fume concrete used in flatwork such as parking structures. Finishing bridge decks is covered in Section 7.4.

Finishing silica-fume concrete flatwork will be the one area in which some differences from regular practices will be seen. These differences are the result of the fact that silica-fume concrete does not bleed. Understanding this section will help minimize any problems that may result from the lack of bleeding.

The flatwork finishing process that the SFA recommends is usually called “one-pass finishing.” It is also sometimes referred to as “fast-track finishing” or “assembly line finishing.” The overall process is based on two simple concepts — protect the concrete at all times and don’t wait for the concrete to stiffen before applying the final texture and cure. The one-pass finishing process is shown in Figure 7.12. Note that this approach to finishing is actually very similar to that used in bridge decks.

FIGURE 7.12. One-pass finishing. Concrete is being placed, screeded, floated, textured, and cured without any waiting between operations.

At first glance the additional precautions necessary to prevent drying may seem like a lot of trouble. But review of the following paragraphs will show that finishing silica-fume concrete, using the one-pass procedures, can actually be much less labor-intensive and can be done much more quickly than finishing conventional concrete.

Typical flatwork finishing steps are shown in the flow chart of Figure 7.13, which describes both conventional and one-pass finishing procedures. Each of the steps in the flow chart is described below:

7.5 FINISHING PARKING STRUCTURES AND OTHER FLATWORK

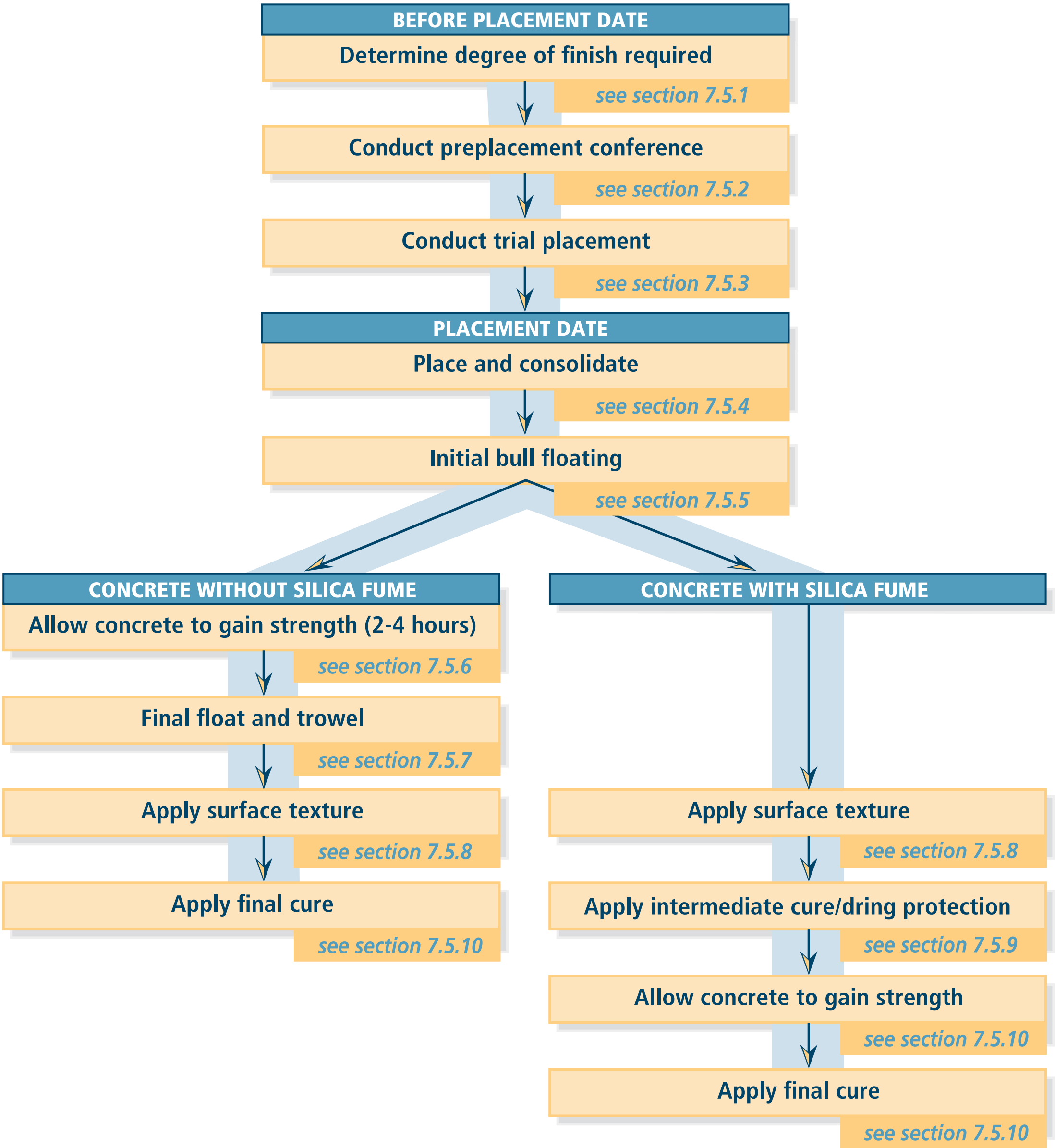

FIGURE 7.13. Finishing steps for concrete flatwork with and without silica fume. The steps are described in the text section noted.

7.5 FINISHING PARKING STRUCTURES AND OTHER FLATWORK

7.5.1 Determine the Degree of Finishing Required

Much concrete flatwork tends to be over finished because many owners have come to believe that concrete is not suitably finished unless a power trowel has been used to produce a hardened surface. This is not necessary for many structures, particularly for parking structures, where silica-fume concrete is frequently used. The degree of finishing necessary for a particular structure must be determined in consultation with the project specifiers and owner. This information ought to be included in the project specifications. The Silica Fume Association strongly recommends that a medium broomed finish without power troweling is the most suitable surface for almost all silica-fume concrete flatwork. This surface will provide excellent traction for pedestrians as well as high durability for longer service.

7.5.2 Conduct a Preplacement Conference

As is discussed in Section 7.1.2, this meeting is the opportunity to discuss the contractor's plans for all aspects of the work. Don't leave the meeting with any unanswered questions.

7.5.3 Conduct a Trial Placement

Also, as is discussed in Section 7.1.2, a trial placement is an ideal time to finalize all decisions regarding finishing. The trial placement must be attended by the owner or the owner's representatives who have the authority to decide what degree of finish is acceptable. The contractor must commit to using the same finishing crew for the trial placement and the actual placements on the structure. The trial placement must be large enough to allow for realistic finishing techniques to be demonstrated as shown in Figure 7.14. At the conclusion of the trial placement, one of two conclusions must be reached: an acceptable finishing approach has been demonstrated and accepted or the need for an additional trial placement has been established.

FIGURE 7.14. Conducting a trial placement using the one-step finishing process using a slab on ground in the actual structure. Note that placing the wire mesh on the bottom of the slab is not recommended practice.

7.5.4 Place and Consolidate the Concrete

As discussed earlier in this Chapter, these steps are not significantly different from the procedures used for any concrete not containing silica fume. Figure 7.15A shows concrete being leveled using a hand screed. By far, the most effective method of consolidating silica-fume concrete flatwork is to use a vibrating screed as shown in Figure 7.15B. This approach will leave a flat surface that requires very little additional finishing work. Don't forget, however, that thicker sections and beams will have to be consolidated using standard internal vibrators.

FIGURE 7.15A. Consolidating silica-fume concrete using a hand screed.

FIGURE 7.15B. Consolidating silica-fume concrete using a vibrating truss screed.

7.5.5 Perform Initial Bull Floating

This step is also not different from what is done for concrete without silica fume. The purposes of bull floating are to embed any aggregate particles on the surface and to smooth out any imperfections resulting from the screeding process. See Figure 7.16. Some contractors feel that wooden floats tend to tear the surface of silica-fume concrete. They prefer the smoother magnesium or steel floats for this concrete.

FIGURE 7.16. After screeding, the next finishing step is to bull float the concrete. Bull floating levels the surface and prepares the concrete to receive the texture desired.

7.5.6 Allow Concrete to Finish Bleeding and Gain Strength

This step is a traditional part of finishing flatwork, but it is not usually necessary for silica-fume concrete. Bleeding must be allowed to finish before the surface is closed to prevent accumulation of air and water, which can lead to delaminations. Additionally, the concrete must develop enough strength to support the weight of the finishers and equipment involved in the next finishing steps.

It is during this waiting period that all concrete, whether it contains silica fume or not, is susceptible to plastic shrinkage cracking and crusting. If the environmental conditions are found to be conducive to drying, protective steps must be taken during this period (see Section 7.3.)

Because silica-fume concrete does not bleed, there is no reason to wait to complete the finishing process, if the owner will accept that additional floating and troweling are not required. Taking advantage of this opportunity for immediate final finishing can result in significant labor and dollar savings.

7.5.7 Perform Final Floating and Troweling

This step consists of at least one pass over the concrete with a float and perhaps several passes with a trowel. For some applications where a tightly closed and hardened surface is required, these steps are essential. For most silica-fume concrete flatwork applications, the Silica Fume Association does not believe that these steps are necessary. (There may be silica-fume concrete floors where conventional procedures of floating and troweling are required. This process is described in Section 7.8.)

7.5.8 Apply Surface Texture

For concrete without silica fume in an application such as a parking structure, the finishers would apply a medium broom finish after troweling the concrete. The success of this practice is somewhat open to question because troweling will usually tighten the surface such that brooming will be difficult.

For silica-fume concrete, brooming should be done as soon after the bull floating as the concrete will allow. Usually this means waiting a few minutes while the concrete stiffens slightly so that it will hold the broom marks to the degree determined satisfactory. Usually brooming will be completed not more than 15 to 30 minutes after the concrete is placed. See Figures 7.17A, 7.17B, and 7.17C.

FIGURE 7.17A. Depending upon the nature of the surface finish selected, it may be necessary to perform one additional pass with a float before the surface texture is applied.

FIGURE 7.17B. This photo shows a finishing tool that is a combination of a float and a broom. In one direction, it serves as a float. In the other direction, it serves as a broom.

FIGURE 7.17C. Brooming of a silica-fume concrete surface. In this case, the broom has a wire attached to it to lift it off the surface for travel from right to left in the photo. The texture is applied by pulling the broom from left to right.

7.5.9 Apply Intermediate Cure/Drying Protection

Once the surface texture is completed, the still-soft concrete must be protected from drying until it gains enough strength to resist plastic shrinkage cracking or to allow for the application of final curing. This protection may be done by using evaporation retarder, fogging, or applying curing compound. (Figure 7.18A.) If curing compound is to be used as the final curing step, it can be applied at this time. Don't forget to consider what will happen in future construction steps when selecting the protection method. For example, if curing compound is used, it may be necessary to remove the compound before painting parking stripes.

7.5.10 Apply Final Cure

There is a great deal of evidence available supporting wet curing for silica-fume concrete. The SFA strongly recommends that silica-fume concrete be wet cured. Any approach that keeps the surface continually wet for at least 7 days is suitable. Most applications use wet burlap covered with plastic sheeting or a proprietary all-in-one product. **It will usually be necessary to wet the burlap during the curing period to ensure that adequate water is available for surface hydration.** Final curing should be started as soon as the concrete has enough strength to support necessary foot traffic for placing the curing materials without marring the surface. Final curing is shown in Figure 7.19 and is discussed in more detail in Section 7.6.

FIGURE 7.18. Curing compound is being applied to silica-fume concrete in a parking structure shortly after brooming. In many cases, the use of curing compound is the preliminary curing method; it is intended to protect the concrete until it gains enough strength to allow placing wet curing materials on the deck without marring the surface. On this particular project, wet burlap and plastic sheeting were used for the final curing.

FIGURE 7.19. Burlap and plastic sheeting used for final curing. For most applications of silica-fume concrete, wet curing will provide better in-place concrete quality than the use of a curing compound alone.

7.6 CURING

Curing is probably the most essential element when it comes to working with silica-fume concrete. The performance that is expected, and for which a premium is being paid, will not be achieved if the concrete is not properly cured. This section addresses several aspects of curing silica-fume concrete and presents the SFA recommendations for curing.

There is a difference between curing silica-fume concrete flatwork and structural elements. Because of its large surface to volume ratio, all concrete flatwork, with or without silica fume, is more susceptible to drying and shrinkage cracking. Structural elements such as columns or beams are less susceptible to this type of cracking. The SFA is not aware of instances where cracking of structural members has been an issue on a project.

7.6.1 Silica Fume Association Recommendations

- **We recommend that curing be started within 10 to 15 minutes after concrete placement.** Any delay in starting curing will result in a less durable surface.
- **We strongly recommend wet curing of silica-fume concrete flatwork for a minimum of seven days.** Our reasoning behind this recommendation is explained in the following sections.
- **We recommend protecting of formed surfaces of silica-fume concrete structural elements using curing compound or other suitable means. Once forms are stripped, we recommend coating formed surfaces with a curing compound.** Care must be taken to ensure that any curing compound used is removed in areas where later bond is required.

7.6.2 Curing Affects the Surface Durability

For bridge decks or other flatwork, the usual reason for using silica fume or a ternary blend of cementitious materials is to provide a more durable concrete. This durability begins at the surface of the concrete, which is the zone most affected by curing. Given the typically low w/cm of the concrete used in these placements, additional water needs to be supplied during the curing process to ensure that the surface concrete will hydrate fully and provide the durability that is required.

Curing will also have an effect on concrete strength, but here the impact of inadequate curing may not be as noticeable as on the durability of the surface.

7.6.3 Curing versus Protection

Protecting silica-fume concrete flatwork from crusting and plastic shrinkage cracking has already been discussed in Section 7.3. Remember that protection is necessary during and immediately after the finishing process until the final curing process is started. Usually, final curing is applied as soon as possible. For bridge decks this means that curing must begin after the pass of the finishing machine or after texturing. For other flatwork, curing must begin once the concrete is strong enough to allow workers to walk on it without damaging the surface.

There is sometimes confusion between protection against drying (or intermediate curing) and final curing. Table 7.4 summarizes these procedures.

TABLE 7.4

INTERMEDIATE CURING/DRYING PROTECTION VERSUS CURING

INTERMEDIATE CURING/DRYING PROTECTION	CURING
Short term between finishing steps	Long term to gain strength and durability
Evaporation retarders	Wet cure using burlap and plastic sheeting (or similar material)
Fogging	Minimum of 7 days
Plastic sheeting	Curing compound*
Curing compound*	

**Curing compound can be used for ether step. If curing compound is to be used for final cure, it can be applied as soon as texturing has been completed.*

Regardless of the type of placement, there must not be a period of exposure when the surface of silica-fume concrete is allowed to dry out.

7.6.4 Curing and Cracking

A great deal has been written about the tendency of silica-fume concrete to crack. One fact seems to be consistent: there is nothing inherent in silica-fume concrete that makes it crack. What appears to be critical is curing of the concrete. Following the recommendations for protection and curing in this manual will help minimize the possibility for cracking.

Here are two major findings regarding curing and cracking.

- Whiting and Detwiler (1998), in a study for the National Cooperative Highway Research Program (NCHRP), concluded that silica-fume concretes tend to crack only when they are insufficiently moist cured. Further, they found that if silica-fume concrete mixtures are given seven days of continuous wet curing, there is no association between silica fume content and cracking.

- New York State DOT has reported similar conclusions for their high-performance concrete bridge deck mixture, which contains portland cement, fly ash, and silica fume. After inspecting 84 bridge decks with this concrete mixture, they reported: "Results indicated that Class HP decks performed better than previously specified concrete in resisting both longitudinal and transverse cracking." (Alampali and Owens 2000) NYSDOT specifies seven days of wet curing for this mixture.

7.6.5 Winter Protection

In this aspect silica-fume concrete is no different from concrete without silica fume. If concrete without silica fume would require protection, the concrete with silica fume must be protected under the same conditions. Refer to ACI 306R, *Cold Weather Concreting*, for a discussion of cold weather concreting.

7.7 PRECAST CONCRETE

Silica-fume concrete has been successfully used in a wide variety of precast applications. In general, there is no difference between using silica fume in precast concrete or in ready mixed concrete. However, one issue does warrant attention.

Typically in precast concrete production where elevated temperature curing is applied, there is a preset period before the temperature is increased. This period allows initial hydration reactions to begin so the concrete has enough strength to tolerate the higher temperature. During the preset period, the surface of silica-fume concrete must be protected from drying out to prevent plastic shrinkage cracking. Do not simply leave the concrete surface exposed to drying conditions during this period. Any of the protection methods described earlier can be applied.

7.8 MISCELLANEOUS CONCERNS

This section addresses several other concerns regarding placing, finishing, and curing of silica-fume concrete.

7.8.1 Cutting Joints

Don't forget that silica-fume concrete flatwork will usually gain strength much more quickly than concrete without silica fume. Review the timing of joint cutting to ensure that too much time is not passing before the joints are cut. Cut the joints as soon as possible to preclude cracking. Resume wet curing after cutting joints.

7.8.2 Stressing Post-Tensioning Strands

Stress PT strands when the concrete has developed adequate strength, not at the end of an arbitrary period such as 3 days. Silica-fume concrete will gain strength rapidly and will be ready for stressing sooner than concrete without silica fume. We are aware of instances where stressing was delayed resulting in cracking that could have been prevented.

7.8.3 Hard-Troweled Floors

In some instances, the one-pass finishing process with a broomed or tined surface will not be acceptable for the particular application. For example, a food processing facility will require a hard-troweled floor for proper cleaning. Silica-fume concrete can be hard troweled to produce excellent surfaces. To accomplish this type of finishing, take the appropriate steps to protect the concrete from drying out during the period when waiting to get finishing machines on the concrete. These steps are exactly the same ones discussed earlier for protecting flatwork in bridge decks or parking structures. Just remember — never let the concrete surface dry out while waiting to get back on it.

A hard-troweled surface is not recommended for air-entrained concrete. There have been many reports of surface delaminations caused by troweling the concrete before all bleeding has ended. ACI 301, *Specifications for Structural Concrete*, limits maximum air content to three percent for hard troweling. Because a silica-fume concrete typically does not bleed, this becomes a very tricky situation where a test placement would be beneficial.

7.8.4 Painting After Curing

There have been problems applying traffic stripes to silica-fume concrete that has been cured using curing compounds. This problem is most likely more related to the curing compound than to the silica fume. When using a curing compound, be sure to verify that the curing material and paint are compatible or it will be necessary to remove the compound before painting.

8 SILICA FUME AND SUSTAINABILITY

Using silica fume in concrete can provide significant contributions to sustainability when using concrete as a building material. This chapter looks at the various modes of silica fume's contribution to improved sustainability for the use of concrete.

8.1 CARBON (CO_2) FOOTPRINT OF SILICA FUME

As described in Chapter 1, silica fume is an unavoidable by-product of producing silicon metal or ferrosilicon alloys, and the particulate smoke was originally considered a waste. Analysis and testing established the pozzolanic potential of the material. Very little energy is spent to collect and process silica fume into its final product form and thus silica fume has a very low CO_2 footprint. Various CO_2 footprint values have been used for silica fume, ranging between 10 and 20 kg/metric ton, which is approximately only 1.5 percent that of portland cement. Silica fume's CO_2 contribution to concrete is negligible, typically in the range of 1-2 kg/m^3 of concrete, which is less than 0.5 percent of the combined CO_2 footprint of conventional concrete.

A frequently asked question is whether there is an Environmental Product Declaration (EPD) for silica fume as exists for other concrete ingredients. The answer is no. The reason is that the generic EPD prepared by the NRMCA (2019) for concrete treats silica fume as making no CO_2 footprint contribution to concrete. Therefore, an EPD for silica fume is not required.

8.2 RECOVERED MINERAL COMPONENTS (RMC)

RMC as identified by the U.S. Environmental Protection Agency (EPA 2008) are fly ash, slag cement, and silica fume, which are viewed as "replacements" for portland cement, on a kilogram-for-kilogram basis. In Table 8.1 the three identified RMC are compared for their efficiency in producing similar compressive strength at 28 and 56 days. As shown in Table 8.1, one kilogram of silica fume can replace approximately three to four kilograms of portland cement and achieve similar compressive strength. In practice, solely using silica fume to replace portland cement – on an equal strength basis – is not done. This could result in very low paste volumes, which may give the strength but little durability. Rather, silica fume is used as an addition, usually in combination with fly ash or slag cement, to provide specific improved concrete properties, such as higher strength, longer structure life, lower heat, or other improved concrete properties.

Silica fume's effectiveness as an addition to portland cement is more pronounced when addressing concrete durability, because unlike the other RMC, it has a particle size approximately 100 times finer than portland cement. This is particularly useful in particle-packing. See Section 5.7.1 for discussion of particle packing, The particle packing effect is instrumental in decreasing concrete permeability, which in turn increases concrete durability, simply by restricting access of deleterious substances beneath the surface that can cause accelerated deterioration.

TABLE 8.1

PORTLAND CEMENT SUBSTITUTION EFFICIENCY OF RECOVERED MINERAL COMPONENTS

RMC (Class F/Grade 100/densified)	FLY ASH	SLAG CEMENT	SILICA FUME
Customary substitution ranges (by weight of cement) in actual field practice	20–30 percent	30–50 percent	5–15 percent
Average substitution ranges	70 kg/m³	150 kg/m³	30 kg/m³
RMC efficiency percentage: weight substitution factor (lb-RMC/lb-OPC) for similar 28 day compressive strength	65 percent 1.54:1	90 percent 1.11:1	300 percent 0.33:1
RMC efficiency percentage: weight substitution factor (lb-RMC/lb-OPC) for similar 56 day compressive strength	83 percent 1.20:1	100 percent 1.00:1	400 percent 0.25:1

Data from Bühler 2012.

8.3 EXTENDED SERVICE LIFE

Because silica fume makes structures more durable, a longer service life will be achieved. If a structure needs to be repaired or replaced less frequently, it is not only of obvious economic advantage, but it also maximizes the life cycle of building materials employed. If a concrete structure can last twice as long, basically the construction CO_2 footprint has been cut in half.

Specifying and predicting service life of structures such as bridges or parking structures is being done more frequently. The most critical aspect of service life for many structures is resistance to corrosion caused by intrusion of chloride ions into the concrete. Although ACI 318 provides requirements for protection against corrosion, it does not include requirements for service life. However, owners are requiring structures with a longer service life, and 50 to 100-year life cycle specifications for critical infrastructure are becoming more common.

One means of looking at extended service life is to use a model that predicts the rate at which chloride ions will reach the level of the reinforcement in a concrete structure. Life-365 is a model that allows the input of various combinations of concrete materials and exposure conditions to make service-life predictions. Life-365 was developed in the early 1990s. It has been subsequently upgraded and is available for download (www.silicafume.org).

In Chapter 5, Table 5.4 shows several concrete mixtures that were evaluated for the Federal Railroad Administration. The data presented includes predicted service life of the various concrete mixtures using Life-365. The data shows the relationships between estimated service life, mechanical properties, and CO_2 footprint.

8.4 IMPROVED ENGINEERING CHARACTERISTICS

Silica fume can improve various engineered properties in concrete such as compressive and flexural strength, modulus of elasticity, and abrasion and impact resistance. All of these performance characteristics ultimately benefit sustainability by extending the concrete life cycle or producing a more resilient concrete structure, especially in adverse environments.

Originally silica fume was synonymous with high-strength concrete, yet many other advantages have come to light. For example, using larger replacements of fly ash or slag cement may reduce the early-age strength of concrete. By preparing a ternary mixture of portland cement, fly ash or slag cement, and a small amount of silica fume, the early age compressive strength difference can be reduced or eliminated. See Chapter 3 (Section 3.3) for project examples of using multiple cementitious materials.

Using high-strength silica-fume concrete for columns and beams allows for a reduction in member size, or increase in spacing, or both, which in turn results in a reduction in overall concrete volume. The net result is a more sustainable and more functional structure for the owner, as well as a decreased utilization of non-renewable sources. See Chapter 3 (Section 3.2.1.1) for descriptions of using high-strength silica-fume concrete.

8.5 LOW-CARBON CONCRETE

The term “Low-Carbon Concrete” is frequently seen, however there is no widely agreed upon definition of this term. Sustainability within the concrete industry is thus focused on the concept that portland cement contributes around 90 percent of the carbon footprint in concrete. Thus, reducing portland cement content in concrete becomes the key focus. Remember that the concrete must meet the performance requirements first — fresh and hardened — the carbon footprint will derive from the quality of that concrete, rather than the other way around. It is necessary to consider several actions that will also contribute to the total reduction of the carbon footprint for a concrete, seen in the context of the full construction:

1. Use an optimal blend of cementitious components, reducing the CO_2 footprint, yet still producing a concrete that fulfills fresh and hardened properties required.
2. Use a higher strength concrete to reduce overall concrete quantity.
3. Increase concrete durability, increasing structural resilience, leading to a much greater life cycle.

The combination of these three actions of designing sustainably can potentially cut the CO_2 footprint by a factor of as much as 10-fold. Table 8.2 shows three examples of conventional 28 MPa concrete mixtures, ranging from pure portland cement content to RMC-replacement alternate versions, as compared to three actual concrete project examples utilizing high-performance concrete mixtures incorporating higher total cementitious materials contents.

Further sustainability efficiencies in favor of high-performance concrete can be readily envisioned. The reduced concrete volume would translate into transport efficiencies. High workability factors typical in high performance concrete will result in faster, lower energy placement methods, wear-and-tear on machinery and so on.

TABLE 8.2

CO_2 FOOTPRINT COMPARISON OF CONVENTIONAL VERSUS HIGH-PERFORMANCE CONCRETE

Concrete mixture	Cementitious materials, kg/m3 *Footnote 1*	CO_2 contribution of cementitious materials, kg/m3 *Footnote 2*	Compressive strength, 28 days, MPa	CO_2 contribution per 6.8 MPa	Life-365 estimate to initiation of corrosion, years *Footnote 3*	CO_2 contribution per year of estimated life	CO_2 contribution per year per 6.8 MPa, kg
Conventional 28 MPa	PC: 297 w/cm: 0.50	284	31	64	10	28.4	Average 4.48
Alternate 1, 30 percent fly ash replacement	PC: 231 FA(F): 101 w/cm: 0.50	231	31	52	12	19.3	
Alternate 2, 50 percent slag cement replacement	PC: 157 SC: 157 w/cm: 0.50	175	31	52	12	19.3	
Miami high rise structure	PC: 267 SC: 267 SF: 30 w/cm: 0.29	299	81	26	62	4.8	Average 0.42
Nuclear canister storage facility (see Section 3.3)	PC: 232 FA(F): 89 SF: 36 w/cm: 0.37	231	43	38	62	3.7	
Floor, waste transfer station	PC: 343 FA(F): 75 SF: 84 w/cm: 0.34	338	71	33	100+	3.4	

Footnote 1. Notation used: PC, portland cement; FA (F), fly ash class F; SC, slag cement, grade 100; SF, silica fume.

Footnote 2. CO_2 carbon footprint in kilograms per metric ton of material were assumed using industry values as follows: Portland Cement – 959 kg, Slag Cement – 155 kg, Fly Ash, Class F – 93 kg, and Silica Fume – 14 kg.

Footnote 3. Life-365 exposure was the same for all mixtures shown in the table. Estimate of time to corrosion is an average of a northern parking structure and a southern ocean exposure. Cover in both cases is 38 mm.

Data from Bühler 2012.

9 SILICA FUME HEALTH ISSUES

Because it is an amorphous form of silica, silica fume is not associated with severe health conditions such as silicosis. However, as with any dusty material, certain precautions are appropriate.

This chapter looks at health precautions for working with silica fume and silica-fume concrete. A typical silica fume safety data sheet (SDS) and bag warning label are also explained.

9.1 GENERAL CONSIDERATIONS AND RECOMMENDATIONS

Because of the name “silica fume,” there are frequently questions raised regarding health issues of using this material in concrete. The general concern is with silicosis, which has been widely publicized within the construction industry. Because silica fume is amorphous and not crystalline, silicosis is not an issue. This chapter looks at health issues associated with the use of silica fume in concrete and makes appropriate recommendations.

Silica fume has been thoroughly tested and assessed. As a result of this hazard assessment, silica fume does not meet any of the Globally Harmonized System of Classification and Labelling of Chemicals (UN-GHS) classification criteria as physical, health or environmental hazard. Overall, the health-related aspects of silica fume may be summarized as follows:

- Silica fume is essentially a non-hazardous material. It falls into the general category of nuisance dust, which is similar to portland cement and many other fine powders.

- Care should be taken in all operations involving silica fume before it is put into concrete to avoid creating dust.

- An appropriate dust mask or respirator must be worn when handling dry silica fume before it is added to concrete. Personal protective equipment must be selected to meet the exposure and environmental conditions specified by local law. Examples of equipment are shown in Figures 9.1A and 9.1B.

- The SFA is not aware of any case in which a worker exposed to silica fume in any phase of concrete operations has been diagnosed with any disease attributed to the use of silica fume in concrete.

9.1 GENERAL CONSIDERATIONS AND RECOMMENDATIONS

FIGURE 9.1A. Dust mask recommended for use when working with dry silica fume before it is mixed into concrete in an open, outdoor location. (This is the N95 mask that has been used as protection during the COVID pandemic.) The selection of a mask or respirator must be made based on exposure and environmental conditions. See the following website for guidance on selecting an appropriate mask or respirator: https://www.cdc.gov/niosh/ppe/

FIGURE 9.1B. Respirator suitable for working in locations where dust concentrations could be expected to be greater than suitable for use of the mask shown in Figure 9.1A.

9.2 SILICA FUME SAFETY DATA SHEET

A Safety Data Sheet (SDS) for silica fume is presented in Appendix 2. This form is for one manufacturer's material, but the form follows the standard format for such information. The most significant aspect of the SDS is the reference to crystalline silicon dioxide. Under California law, any amount of crystalline silicon dioxide must be reported on the SDS. This particular manufacturer has elected to use a single SDS for all of its materials, so the California warning will appear in all locations.

Note also the warning regarding drying of the skin when in contact with dry silica fume. This is a physical effect resulting from the very large surface area of the silica fume.

9.3 SILICA FUME BAG WARNING LABEL

Typical warning labels from bagged silica fume are shown in Figure 9.2. The general warnings on the bag are taken directly from the SDS. The Hazard Diamond on the right of the warning label is in the format defined by the National Fire Protection Association (NFPA). The "1" in the health quadrant indicates that the material "May be irritating."

9.3 SILICA FUME BAG WARNING LABEL

SILICA FUME IS GENERALLY CONSIDERED A NUISANCE DUST. USE AND HANDLING OF SILICA FUME DOES NOT REPRESENT A HEALTH RISK WHEN NORMAL SAFETY RULES ARE OBSERVED.

SAFETY INSTRUCTIONS
READ BEFORE USE
FOR ADDITIONAL INFORMATION, REFER TO SDS

COMPOSITION – INDGREDIENTS

- Silica Fume, Silicon Dioxide CAS number 69012-64-2
- EINECS No: 273-761-1
- Inhalation may cause respiratory irritation resulting in coughing, sneezing and/or other nuisance symptoms
- Eye contact may cause irritation
- Prolonged or repeated use may cause skin irritation or dryness

PRECAUTIONARY MEASURES:

- Prevent airborne emissions and avoid creating dust.
- Equip mixers and hoppers with dust covers.
- Provide ventilation if workplace warrant respirator OSHA 29CFR 1910.134 must be followed. Refer to NIOSH 42 CFR 84 for approved respirators when airborne concentrations equal or exceed the Permissible Exposure Limits.
- Wear tightly fitting safety goggles when a risk assessment indicates this is necessary.
- Choose body protection in relation to the task being performed and the risks involved and should be approved by a specialist. Chemical–resistant gloves should be always worn when handling chemicals.

FIRST AID:

Eye:	Flush eyes with water and carefully rinse under the eyelids. If necessary, seek medical attention.
Skin:	Wash skin with mild soap and water.
Inhalation:	If inhaled to excess remove exposed person to fresh air. If necessary, seek medical attention.
Ingestion:	Obtain first aid or medical assistance immediately.

ACCIDENTAL RELEASE & DISPOSAL:

If product is spilled observe precautions above. Collect using methods that minimize creation of airborne dust. High efficiency vacuum cleaning is recommended to recover spilled material. Place in suitable container for recycling or disposal. Dispose of waste in accordance with Federal, State and Local regulations.

EMERGENCY TELEPHONE NUMBER:

Chemtrec 800-424-9300

HEALTH	0
FLAMMABILITY	0
REACTIVITY	0
SPECIAL	-

SAFETY DATA SHEET AVAILABLE

FOR INDUSTRIAL USE ONLY
KEEP OUT OF REACH OF CHILDREN

FIGURE 9.2. Warning label from bagged silica fume according to US practice. Warning labels in other locations may differ.

10 REFERENCES

This chapter includes all of the references cited in the document.

10.1 AMERICAN CONCRETE INSTITUTE (ACI)

ACI *Concrete Terminology*.

ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*.

ACI 211.6T, *Aggregate Suspension Mixture Proportioning Method*.

ACI 234R, *Guide for Use of Silica Fume in Concrete*.

ACI 301, *Specifications for Structural Concrete*.

ACI 304.2R, *Placing Concrete by Pumping Methods*.

ACI 306R, *Cold Weather Concreting*.

ACI 308R, *Guide to Curing Concrete*.

ACI 309R, *Guide for Consolidation of Concrete*.

ACI 318, *Building Code Requirements for Structural Concrete*.

ACI 546.1R, *Guide for Repair of Concrete Bridge Superstructures*.

Available from:
American Concrete Institute
Post Office Box 9094
Farmington Hills, Michigan 48333
www.concrete.org

10.2 ASTM INTERNATIONAL

ASTM C94, *Standard Specification for Ready-Mixed Concrete.*

ASTM C192, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.*

ASTM C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.*

ASTM C779, *Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces.*

ASTM C989, *Standard Specification for Slag Cement for Use in Concrete and Mortars.*

ASTM C1138, *Standard Test Method for Abrasion Resistance of Concrete (Underwater Method).*

ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.*

ASTM C1240, *Standard Specification for Silica Fume Used in Cementitious Mixtures.*

ASTM C1611, *Standard Test Method for Slump Flow of Self-Consolidating Concrete.*

ASTM C1778, *Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete.*

ASTM C1856, *Standard Practice for Fabricating and Testing Specimens of Ultra-High-Performance Concrete.*

ASTM E965, *Standard Test Method for Measuring Pavement Macrotexture Depth Using Volumetric Techniques.*

Available from:
ASTM International
100 Barr Harbor Drive
West Conshohocken, Pennsylvania 19428
www.astm.org

10.3 AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS (AASHTO)

AASHTO M 307-13, *Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete Mortar and Grout.*

AASHTO, 2017, *LFRD Bridge Construction Specifications*, Fourth Edition, 564 pp.

AASHTO, 2020, *LRFD Bridge Design Specifications*, Ninth Edition, 1920 pp.

Available from:

American Association of State Highway and Transportation Officials
444 N Capitol Street, N. W.
Suite 249
Washington, D. C. 20001
http://www.transportation.org

10.4 EUROPEAN COMMITTEE FOR STANDARDIZATION (CEN)

EN13263-1, *Silica fume for concrete – Part 1: Definitions, requirements, and conformity criteria.*

Available from:

The European Committee for Standardization
Rue de la Science 23 B-1040
Brussels, Belgium
Tel: +32 2 550 08 37
https://standards.cen.eu

Note that each European country that is using the CEN Standards can publish their own version – hence NS EN 13263 for Norway; BS EN 13263 for the UK, etc. CEN is the singular place to go for the generic specification.

10.5 CITED REFERENCES

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Federal Highway Administration, 2022, *Design and Construction of UHPC-Based Bridge Preservation and Repair Solutions*, FHWA-HRT-22-065, Washington, DC. https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/22065/22065.pdf

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10.5 CITED REFERENCES

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APPENDIX 1
PROPORTIONING EXAMPLES IN INCH-POUND UNITS

A.1 PROPORTIONING EXAMPLES IN INCH-POUND UNITS

Following are three examples of the step-by-step mixture proportioning procedure. Table A.1, following the examples, shows starting concrete mixtures.

A.1 EXAMPLE 1. Bridge Deck, Figure A.1.

FIGURE A.1. Bridge deck project. Mixture proportions for a concrete that could be used on this project are developed in Example 1.

STEP 1

Determine project requirements. A review of the specifications develops the following requirements:

- Low chloride permeability, approximately 1,500 Coulombs at 56 days
- Compressive strength of 4,500 psi at 28 days
- Reduced heat and shrinkage
- Reduced rate of strength gain to minimize cracking
- Protection against freezing and thawing in a severe environment

STEP 2

Coordinate with contractor. Discussions with the contractor develop the following additional requirements:

- Maximum size of coarse aggregate is 1 in.
- Desired slump is 4 to 6 in.
- Concrete will primarily be placed by pump

STEP 3

Select starting mixture. From Table A.1 select the Colorado DOT mixture as being a good starting mixture. This mixture has the following characteristics:

Cement	485 lb/yd³
Fly ash	97 lb/yd³
Silica fume	20 lb/yd³
Maximum w/cm	0.41

STEP 4

Determine volume of air required. From Table 5.1 for 1 in. aggregate, the volume of air required for a severe environment is 6 percent. Because this concrete will not have a compressive strength of over 5,000 psi, do not reduce the air content by 1 percent.

STEP 5

Incorporate local aggregates.

First, determine the volume the paste will occupy, as shown in the following table:

MATERIAL	MASS, lb	SPECIFIC GRAVITY	VOLUME, ft³
Cement	485	3.15	2.47
Fly ash	97	2.50	0.62
Silica fume	20	2.20	0.15
Water (w/cm = 0.41)	247	1.00	3.96
Air, 6 percent	—	—	1.62

Total paste volume = 8.82 ft³

Second, calculate aggregate volumes and masses:

Coarse aggregate specific gravity: 2.68
Fine aggregate specific gravity: 2.64
Fine aggregate: 40 percent of total aggregate volume *(Note: If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.)*
Aggregate volume = 27.00 ft^3 – 8.82 ft^3 = 18.18 ft^3
Fine aggregate volume = 0.40 × 18.18 ft^3 = 7.27 ft^3
Fine aggregate mass = 7.27 ft^3 × 62.4 lb/ft^3 × 2.64 = 1,198 lb
Coarse aggregate volume = 18.18 ft^3 – 7.27 ft^3 = 10.91 ft^3
Coarse aggregate mass = 10.91 ft^3 × 62.4 lb/ft^3 × 2.68 = 1,825 lb

STEP 6

Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 5.4 for recommendations
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

STEP 7

Conduct production-scale testing. Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

A.2 EXAMPLE 2. Cast-in-Place Parking Structure, Figure A.2.

FIGURE A.2. Parking structure project. Mixture proportions for a concrete that could be used on this project are developed in Example 2.

STEP 1

Determine project requirements. A review of the specifications develops the following requirements:

- Low chloride permeability, less than 1,500 Coulombs at 42 days
- Early strength of 4,000 psi to allow for stressing of tendons
- Compressive strength of 6,000 psi at 28 days
- Reduced heat and shrinkage
- Protection against freezing and thawing in a severe environment

STEP 2

Coordinate with contractor. Discussions with the contractor develop the following additional requirements:

- Maximum size of coarse aggregate is 1 in.
- Desired slump is 5 to 7 in.
- Concrete will primarily be placed by pump

STEP 3

Select starting mixture. From Table A.1 select the Milwaukee Airport Parking Structure mixture as being a good starting mixture. This mixture has the following characteristics:

Cement	565 lb/yd^3
Fly ash (Class C)	100 lb/yd^3
Silica fume	40 lb/yd^3
Maximum w/cm	0.35

STEP 4

Determine volume of air required. From Table 5.1 for 1 in. aggregate, the volume of air required for a severe environment is 6 percent. Because this concrete will have a compressive strength of over 5,000 psi, reduce the air content by 1 percent and proportion for 5 percent.

STEP 5

Incorporate local aggregates.

First, determine the volume the paste will occupy, as shown in the following table:

MATERIAL	MASS, lb	SPECIFIC GRAVITY	VOLUME, ft^3
Cement	565	3.15	2.87
Fly ash	100	2.50	0.64
Silica fume	40	2.20	0.29
Water (w/cm = 0.35)	247	1.00	3.96
Air, 5 percent	—	—	1.35

Total paste volume = 9.11 ft^3

Second, calculate aggregate volumes and masses:

Coarse aggregate specific gravity: 2.72
Fine aggregate specific gravity: 2.68
Fine aggregate: 40 percent of total aggregate volume *(Note: If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.)*
Aggregate volume = 27.00 ft^3 – 9.11 ft^3 = 17.89 ft^3
Fine aggregate volume = 0.40 × 17.89 ft^3 = 7.16 ft^3
Fine aggregate mass = 7.16 ft^3 × 62.4 lb/ft^3 × 2.68 = 1,200 lb
Coarse aggregate volume = 17.89 ft^3 – 7.16 ft^3 = 10.73 ft^3
Coarse aggregate mass = 10.73 ft^3 × 62.4 lb/ft^3 × 2.72 = 1,820 lb

STEP 6

Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 5.4 for recommendations
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

STEP 7

Conduct production-scale testing. Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

A.3 EXAMPLE 3. High-Strength Concrete Columns, Figure A.3.

FIGURE A.3. High-strength columns project. Mixture proportions for a concrete that could be used on this project are developed in Example 3.

STEP 1

Determine project requirements. A review of the specifications develops the following requirements:

- Design compressive strength of 14,000 psi at 28 days
- No exposure to freezing and thawing

STEP 2

Coordinate with contractor. Discussions with the contractor develop the following additional requirements:

- Maximum size of coarse aggregate is ½ in.
- Desired slump is 8 to 10 in.
- Concrete will primarily be placed by pump

STEP 3

Select starting mixture. From Table A.1 select the high-strength mixture (Mixture 9) as being a good starting mixture. This mixture has the following characteristics:

Cement	800 lb/ft^3
Fly ash	175 lb/ft^3
Silica fume	125 lb/ft^3
Maximum w/cm	0.23

STEP 4

Determine volume of air required. None. Assume that 1.5 percent will be entrapped in this mixture.

STEP 5

Incorporate local aggregates.

First, determine the volume the paste will occupy, as shown in the following table:

MATERIAL	MASS, lb	SPECIFIC GRAVITY	VOLUME, ft^3
Cement	800	3.15	4.07
Fly ash	175	2.50	1.12
Silica fume	125	2.20	0.91
Water (w/cm = 0.23)	254	1.00	4.07
Air, 1.5 percent	—	—	0.41

Total paste volume = 10.58 ft^3

Second, calculate aggregate volumes and masses:

Coarse aggregate specific gravity: 2.68
Fine aggregate specific gravity: 2.60
Fine aggregate: 38 percent of total aggregate volume *(Note: If an appropriate starting ratio of fine to coarse aggregate is not known, guidance on selecting starting aggregate proportions may be found in ACI 211.1.)*
Aggregate volume = 27.00 ft^3 – 10.58 ft^3 = 16.42 ft^3
Fine aggregate volume = 0.38 × 16.42 ft^3 = 6.24 ft^3
Fine aggregate mass = 6.24 ft^3 × 62.4 lb/ft^3 × 2.60 = 1,012 lb
Coarse aggregate volume = 16.42 ft^3 – 6.24 ft^3 = 10.18 ft^3
Coarse aggregate mass = 10.18 ft^3 × 62.4 lb/ft^3 × 2.68 = 1,702 lb

STEP 6

Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 5.4 for recommendations
- Carefully control and account for moisture on the aggregates
- Mix thoroughly
- Conduct necessary testing on fresh and hardened concrete
- Adjust mixture as necessary to obtain the properties that are required

STEP 7

Conduct production-scale testing. Once satisfied with the results of the laboratory testing program, conduct production-scale testing. Consider these points:

- Use large enough batches to be representative
- Test more than once
- Work with the contractor to conduct placing and finishing trials as required

A.1 PROPORTIONING EXAMPLES IN INCH-POUND UNITS

TABLE A.1

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS

	HIGH-STRENGTH CONCRETE Key Tower, Cleveland	HIGH-STRENGTH CONCRETE Scotia Plaza, Toronto	BRIDGE DECK, WITH FLY ASH New York State DOT HP Mix	WET SHOTCRETE REPAIR	TEMPERATURE CONTROLLED CONCRETE Hanford Storage Facility
	MIXTURE 1	**MIXTURE 2**	**MIXTURE 3**	**MIXTURE 4**	**MIXTURE 5**
References	None	Bickley, et al, 1991	Alcompalle and Owens, 2000	Forrest, et al, 1995	Holland, 1998
Compressive strength (Note 1)	12,000 psi at 28 days	10,000 psi at 28 days	> 5,400 psi at 28 days	6,000 psi at 28 days	5,000 psi at 28 days 6,000 psi at 90 days
Rapid chloride test, coulombs	—	303 at 1 year 258 at 2 years	< 1,600	—	—
Other requirements	Pumpable, 57 stories	—	Minimize plastic and drying shrinkage cracking	100 lb/cyd of steel fibers to increase toughness	Max delivered < 70°F, Max at 48 hr < 100°F, Pumpable, early strength for form removal
Entrained air (Note 2)	—	—	6.50 percent	8 to 10 percent as delivered 4 to 6 pecent in place	2 to 6 percent
Slump	> 10 in.	4 in.	Unknown	2 to 4 in.	Unknown
Maximum aggregate size	½ in.	¾ in.	¾ in.	$^{3}/_{8}$ in.	1 in.
Cement, lb/cyd	685	532	500	682	391
Fly ash, lb/cyd	0	0	135, Class F	0	150, Class F
Slag cement, lb/cyd	285	198	0	0	0
Silica fume lb/cyd	80	62	40	70	60
Maximum w/cm	0.24	0.31	0.40	0.45	0.37
Water, lb/cyd (Note 3)	252	244	270	338	167

Note 1. Strength shown is f′c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 5,000 psi has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

TABLE A.1 (continued)

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS

	HIGH-PERFORMANCE BRIDGE GIRDERS Colorado DOT	PARKING STRUCTURE Milwaukee Airport	TEST HIGH-STRENGTH MIX	TEST HIGH-STRENGTH MIX	BRIDGE DECK Colorado DOT
	MIXTURE 6	**MIXTURE 7**	**MIXTURE 8**	**MIXTURE 9**	**MIXTURE 10**
References	Leonard, 1999	Data from SFA Member	Burg & Ost, 1994	Burg & Ost, 1994	Xi, et al, 2003
Compressive strength (Note 1)	6.500 psi at release 10,000 psi ultimate	2,000 psi at 36 hrs 5,700 psi at 56 days	12,840 psi at 28 days 16,760 psi at 3 yrs	15,520 psi at 28 days 18,230 psi at 3 yrs	4,700 psi at 28 days
Rapid chloride test, coulombs	—	< 1,000 from cores at 2-10 months	—	—	1,400–1,600 at 56 days
Other requirements	—	—	—	—	—
Entrained air (Note 2)	Unknown	Unknown	—	—	8.5 percent
Slump	Unknown	6 to 7½ in.	9¾ in.	9¼ in.	5½ in.
Maximum aggregate size	Unknown	Unknown	½ in.	½ in.	Unknown
Cement, lb/cyd	730	565	800	800	485
Fly ash, lb/cyd	0	100, Class C	100, Class C	175, Class C	97, Class F
Slag cement, lb/cyd	0	0	0	0	0
Silica fume lb/cyd	35	39	40	125	20
Maximum w/cm	0.28	0.35	0.29	0.23	0.41
Water, lb/cyd (Note 3)	214	246	270	254	247

Note 1. Strength shown is f′c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 5,000 psi has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

TABLE A.1 (continued)

RECOMMENDED STARTING SILICA-FUME CONCRETE MIXTURE PROPORTIONS FOR VARIOUS APPLICATIONS	WORLD TRADE CENTER 1 New York City	EAST SEA BRIDGE China
	MIXTURE 11	**MIXTURE 12**
References	SCC mix data from Norchem (2012)	Data from Elkem (2002)
Compressive strength (Note 1)	12,000 psi at 28 days	7,250 psi at 28 days
Rapid chloride test, coulombs	—	< 750
Other requirements	—	—
Entrained air (Note 2)	—	—
Slump	25-28 in. (slump flow)	10 in.
Maximum aggregate size	0.60 in.	Unknown
Cement, lb/cyd	292	317
Fly ash, lb/cyd	86, Class F	47, Class F
Slag cement, lb/cyd	470	476
Silica fume lb/cyd	51	25
Maximum w/cm	0.29	0.32
Water, lb/cyd *(Note 3)*	261	276

Note 1. Strength shown is f'c. Add appropriate overdesign for mixture development.
Note 2. Allowed reduction in air content for strength above 5,000 psi has been taken.
Note 3. Includes water in HRWRA for mixes with very low w/cm.

APPENDIX 2
SAFETY DATA SHEET

Safety Data Sheet – Silica Fume

1. Substance and Source Identification

Product Name: Silica Fume (Dry Powder)

Product Uses or Application: Cementitious Mixtures

Company Information:

Plant Location:

Telephone:

Website:

Emergency Telephone: CHEMTREC: 1-800-424-9300

2. Hazards Identification

Classification: Does not meet the criteria of the UN Globally Harmonized System (GHS) for hazard classification.

Physical Hazard: Not classified
Health Hazard: Not classified

Label Elements:
Symbol: No Symbol

Signal Word: No Signal Word

Hazard Statement (s): Not applicable.

Precautionary Statement(s) Not applicable.

3. Composition/Information on Ingredients

Substance: Silica Fume
Synonyms: Amorphous Silica, Silicon Dioxide, Microsilica, Corrochem, Micropoz.
CAS No: 69012-64-2
EINECS No: 273-761-1

Silica Fume may contain trace amounts (<0.05%) of crystalline silica (quartz), which has been shown to cause silicosis, and has been identified by IARC and NTP as a possible human carcinogen.

Safety Data Sheet – Silica Fume

4. First Aid Measures

Inhalation:	If inhaled to excess remove exposed person to fresh air. If necessary, seek medical attention.
Skin Contact:	Wash skin with mild soap and water.
Eye Contact:	Flush eyes with water and carefully rinse under the eyelids. If necessary, seek medical attention
Ingestion:	Obtain first aid or medical assistance immediately.

Most Important Symptoms/Effects, Acute and Delayed: Dust may result in irritation.

5. Fire Fighting Measures

Fire and Explosion Hazards:	Silica fume is non-combustible and presents no danger of explosion
Extinguishing Media:	N/A, Use extinguishing agents appropriate for surrounding fire
Protective Equipment for Fire Fighters:	Wear NIOSH approved self-contained breathing apparatus (SCBA)
NFPA Ratings:	0 = Minimal: 1 = Slight: 2 = Moderate: 3 = Serious: 4 = Severe

Health = 0 Fire = 0 Reactivity = 0

6. Accidental Release Measures

Personal Precautions, Protective Equipment and Emergency Procedures:	Use 42 CFR 84 NIOSH/MSHA approved respirators when airborne concentrations equal or exceed the Permissible Exposure Limit.
Methods and Materials for Containment and Cleanup:	Collect using methods that minimize creation of airborne dust. High efficiency vacuum cleaning is recommended to recover spilled material. Place in suitable container for recycling or disposal. Handle with adequate ventilation for dust.

7. Handling and Storage

Safe Handling Precautions:	Avoid generating dust. Handle with adequate ventilation for dust.
Storage:	Best in closed containers, ambient air temperature, keep dry.

Safety Data Sheet – Silica Fume

8. Exposure Controls and Personal Protection

Exposure Limits: No occupational exposure limits have been established for this material.

Components:	CAS Registry #	OSHA-PEL TWA	ACGIH-TWA
Silica, Amorphous Silica Fume	69012-64-2		TLV Withdrawn due to insufficient data
Silica – Crystalline α-Quartz	14808-60-7	0.05 mg/ m^3	0.025 mg/m^3

[R] Measured as respirable fraction of the aerosol.
*Total Dust
**Respirable dust
There is no hazard classification for the amount of respirable crystalline silica in the product because when measured by X-Ray diffraction the level is below 0.1%

Engineering Controls: Provide sufficient mechanical (general and/or local exhaust) ventilation to maintain exposures below PELs or TLVs in processing areas.

Personal Protection: In accordance with OSHA 29 CFR 1910.132 subpart I, wear appropriate Personal Protective Equipment (PPE) to minimize exposure to this material.

Respiratory Protection: If workplace conditions warrant a respirator OSHA 29CFR 1910.134 must be followed. Refer to NIOSH 42 CFR 84 for approved respirators when airborne concentrations equal or exceed the Permissible Exposure Limits.

Eye/Face Protection: Wear tightly fitting safety goggles when a risk assessment indicates this is necessary.

Skin/Body Protection: Choose body protection in relation to the task being performed and the risks involved and should be approved by a specialist. Chemical–resistant gloves should be worn at all times when handling chemicals.

9. Physical and Chemical Properties

Physical State:	Amorphous sub-micron powder – dust has a tendency to agglomerate		
Color:	Light to medium gray	**Odor:**	None
Melting Point:	1200ºC - 1300ºC*	**Specific Gravity:**	2.2 – 2.50 Water = 1.0
pH:	6.0 to 9.0		
Solubility in Water:	Insoluble	**Particle Size:**	Approx. 0.4 µm
Bulk Density:	Approx. 8 to 48 lb./ft^3 or 128-769 kg/m^3		
Solubility Solvents:	Insoluble to slightly soluble in organic solvents		

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10. Stability and Reactivity

Conditions to avoid:	See Below
Substances to avoid:	Hydrofluoric acid (HF)
Hazardous reactions:	Silica fume is soluble in hydrofluoric acid (HF) and can form toxic gas (SiF_4).
Decomposition products:	Heating at temperatures above 500ºC (930ºF) for prolonged time periods will convert amorphous silica to crystalline phases.

11. Toxicological Information

Route of Exposure: Inhalation: X Skin: X Ingestion: N/A Eyes: X

Acute Toxicity:

Inhalation:	Airborne Silica Fume dust generated by the use or handling of this product may result in respiratory tract irritation.
Ingestion:	Silica Fume dust may irritate and dehydrate throat and mouth.
Eye Contact:	Silica Fume dust may cause eye mechanical irritation and dryness.
Skin Contact:	Silica Fume dust may cause exposed skin mechanical irritation.

Chronic Effects:

Silica Fume is generally considered a nuisance dust of low toxicity consequently it is considered to pose minimal risk of pulmonary fibrosis (silicosis). Avoid prolonged exposure to silica fume dust concentrations above the recommended exposure limits, unless the protective equipment is used.

It is possible for Silica Fume to contain trace amounts (<0.05%) of crystalline silica, which has been shown to cause silicosis, and has been identified by IARC and NTP as a Positive/Known human carcinogen.

Heating Silica Fume at temperatures above 500ºC (930ºF) for prolonged time periods will convert amorphous silica to the crystalline phases Cristobalite and Tridymite that may cause silicosis. Increased temperatures will increase the formation rate of these phases.

12. Ecological Information:

No adverse effects are expected. Silica Fume is not considered dangerous to the environment.

13. Disposal Considerations:

Dispose of waste in accordance with applicable Federal, State and Local regulations.

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14. Transport Information:

DOT Not regulated

IATA Not regulated

IMDG Not regulated

Special Precautions for user: None

Transport in bulk according to Annex II of MARPOL 73/78 and the IBC code: Not classified

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15. Regulatory Information:

SARA TITLE III:	Section 302/304 (extremely hazardous substances)	Not regulated
	Sections 311/312 Hazardous Categories (40 CFR 370.21) Acute Health: No Chronic Health: No Fire: No Reactive: No Pressure: No	
	Section 313 This product contains no chemicals subject to the supplier notification requirements.	Not regulated
CERCLA:	Comprehensive Response Compensation and Liability Act (40 CFR 30.4)	Not regulated
TSCA:	CAS #69012-64-2 There are no TSCA 12(b) chemicals in this product	Listed None
CEPA (Canadian DSL):	#69012-64-2 is listed on the public Portion of the Domestic Substances List.	
WHMIS:		Not classified
California Proposition 65:	This product may contain trace amounts < 0.05% of crystalline silica a chemical known to the State of California to cause cancer, birth defects or other reproductive harm.	

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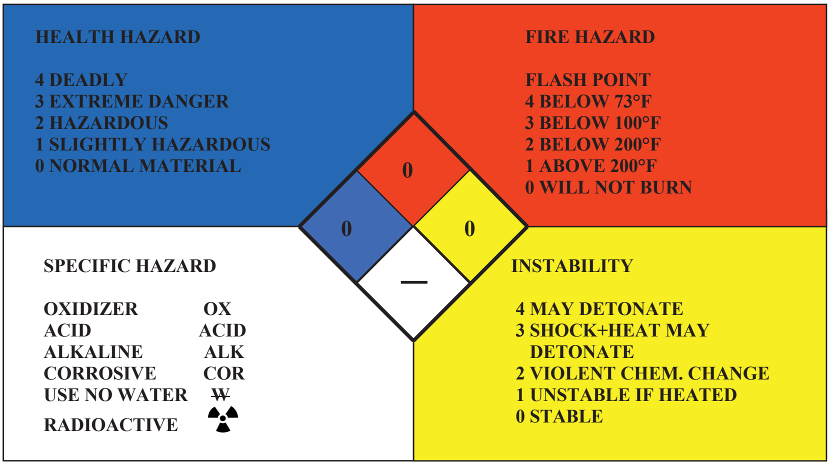
16. Other Information:

The UN Globally Harmonized System of Classification and Labeling of Chemicals (GHS) safety data sheets (SDS) are required only for substances and mixtures that meet the harmonized criteria for physical, health or environmental hazards. Based on Chapter 1.5.2 this product does not fit into these criteria.

National Fire Protection Association (NFPA) Rating Label:



Hazardous Material Identification System (HMIS) Label:

Silica Fume	
HEALTH	1
FLAMMABILITY	0
REACTIVITY	0
PERSONAL PROTECTION	E

All information, recommendations, and suggestions in this SDS, concerning our products are based on tests and data believed to be reliable, it cannot be guaranteed. Since the actual use by others is beyond our control it is the user's responsibility to determine the safety, toxicity and suitability for their own use of the product described herein.

Photo on back cover: One World Trade Center in New York City where silica fume was used in a ternary blend with portland cement and slag cement to produce the 69 MPa and 97 MPa high-strength concrete columns and to achieve the required modulus of elasticity of 48 GPa.

This Manual is intended to provide practical information for individuals working with silica fume and silica-fume concrete. Different chapters of the Manual may be of interest to concrete specifiers, concrete producers, concrete contractors, or concrete inspectors. The Manual is organized as follows:

- **Chapters 1 and 2** provide basic information explaining what silica fume is and how it reacts in concrete.
- **Chapter 3** describes the primary uses of silica fume in concrete.
- **Chapter 4** reviews ACI guidance and standard specifications for silica fume.
- **Chapter 5** presents detailed information on proportioning concrete containing silica fume for different applications.
- **Chapter 6** presents recommendations for working with silica fume in a concrete plant.
- **Chapter 7** presents recommendations for placing and finishing silica-fume concrete on bridge decks and other flatwork.
- **Chapter 8** discusses the role of silica fume in making concrete more sustainable.
- **Chapter 9** discusses health concerns associated with working with silica fume and presents recommendations for personal protection.
- **Chapter 10** is a collection of references from the other chapters.