

Silica Fume User's Manual



U.S. Department
of Transportation

Federal Highway
Administration

FHWA-IF-05-016

SPA
SILICA FUME ASSOCIATION

APRIL, 2005

Technical Report Documentation Page

1. Report No. FHWA-IF-05-016	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Silica Fume User's Manual		5. Report Date April, 2005	
7. Author(s) Terence C. Holland		6. Performing Organization Code HIPT	
9. Performing Organization Name and Address Silica Fume Association 38860 Sierra Lane Lovettsville, VA 22180 www.silicafume.org		8. Performing Organization Report No.	
12. Sponsoring Agency Name and Address Federal Highway Administration 400 7th Street, SW Washington, D 20590		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. DTFH61-99-X-00063	
		13. Type of Report and Period Covered Technical Report	
14. Sponsoring Agency Code			
15. Supplementary Notes FHWA Project Manager: Suneel Vanikar			
16. Abstract <p>This Manual is intended to provide practical information for individuals actually 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:</p> <ul style="list-style-type: none"> • Chapters 1 and 2 provide basic information explaining what silica fume is and how it is used in concrete. • Chapter 3 describes primary uses of silica fume in concrete. • Chapter 4 reviews documents available describing or specifying silica fume from ACI, ASTM, and AASHTO. • Chapter 5 presents recommendations for specifying silica fume and silica-fume concrete. • Chapter 6 presents detailed information on proportioning concrete containing silica fume for different applications. • Chapter 7 presents recommendations for working with silica fume in a concrete plant. • Chapter 8 presents recommendations for placing and finishing silica-fume concrete on bridge decks and other flat work. • 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. 			
17. Key Words silica fume silica-fume concrete bridge decks parking structures		18. Distribution Statement No restrictions. This document is available to the public from the National Technical Information Service, Springfield, VA 22161. Also available from the Silica Fume Association.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 193	22. Price

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	cdela/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	cdela/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)

INTRODUCTION

This Manual is intended to provide practical information for individuals actually 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 is used in concrete.
- **Chapter 3** describes primary uses of silica fume in concrete.
- **Chapter 4** reviews documents available describing or specifying silica fume from ACI, ASTM, and AASHTO.
- **Chapter 5** presents recommendations for specifying silica fume and silica-fume concrete.
- **Chapter 6** presents detailed information on proportioning concrete containing silica fume for different applications.
- **Chapter 7** presents recommendations for working with silica fume in a concrete plant.
- **Chapter 8** presents recommendations for placing and finishing silica-fume concrete on bridge decks and other flat work.
- **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.

This Manual was produced under Cooperative Agreement DTFH61-99-X-00063 between the Federal Highway Administration and the Silica Fume Association.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

INTRODUCTION

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This document does not constitute a standard, specification, or regulation.

Trade or manufacturers' names that appear herein are cited only because they are considered essential to the objectives of the document. The Federal Highway Administration does not endorse products or manufacturers.

The Silica Fume Association was formed in 1998 to serve as a voice for producers of silica fume. Please visit the SFA web site (www.silicafume.org) for information on additional products produced under the FHWA-SFA cooperative agreement.

This manual was prepared by Dr. Terence C. Holland with the cooperation of the members of the Silica Fume Association. Questions or comments regarding this Manual should be addressed to the technical information request portion of the Silica Fume Association web site (www.silicafume.org).

In keeping with the requirements of the FHWA, this document has been prepared using SI units. A conversion table from SI to inch-pound units is provided in the front of the document. The concrete mixture proportioning examples shown in Chapter 6 using SI units are repeated in Appendix 1 using inch-pound units.

This document is available in either printed format or on CD-ROM from the Silica Fume Association. It may also be downloaded from the Silica Fume Association web site.

First edition, first printing: April, 2005.

CONTENTS

Introduction	iii
--------------------	-----

1 WHAT IS SILICA FUME?	1
--	----------

1.1 Silica Fume Definition	2
1.2 Production	4

2 SILICA FUME PROPERTIES AND REACTIONS IN CONCRETE	7
--	----------

2.1 Chemical Properties	8
2.2 Physical Properties	9
2.3 Reactions in Concrete	11
2.4 Comparison with Other Supplementary Cementitious Materials	14

3 WHY IS SILICA FUME USED IN CONCRETE?	15
--	-----------

3.1 Silica Fume and Fresh Concrete	16
3.1.1 Increased Cohesion	17
3.1.2 Reduced Bleeding	18
3.2 Silica Fume and Hardened Concrete	20
3.2.1 Enhanced Mechanical Properties	21
3.2.2 Reduced Permeability	27
3.3 Silica Fume and Constructability	31

CONTENTS

4 ACI GUIDANCE AND ASTM AND AASHTO SPECIFICATIONS FOR SILICA FUME	33
4.1 ACI Guidance.....	34
4.2 Standard Specifications	37
4.2.1 ASTM C 1240	38
4.2.2 AASHTO M307	42
4.3 Silica Fume Reference Material.....	44
5 SPECIFYING AND OBTAINING SILICA FUME AND SILICA-FUME CONCRETE	45
5.1 Densified Silica Fume	46
5.2 Specifying Silica Fume and Silica-Fume Concrete	48
5.3 Obtaining Silica Fume and Silica-Fume Concrete	50
6 PROPORTIONING SILICA-FUME CONCRETE	51
6.1 Basic Considerations	52
6.2 Project Requirements	55
6.3 Construction Considerations	56
6.4 Proportioning Procedure	57
6.4.1 General Rules.....	57
6.4.2 Step-By-Step Procedure.....	58
6.5 Adjusting the Mixture	67
6.6 Mixture Proportioning Examples	68
6.6.1 Example 1 – Bridge Deck.....	68
6.6.2 Example 2 – Cast-in-Place Parking Structure	71
6.6.3 Example 3 – High-Strength Concrete Columns.....	74
6.7 Statistical Approach for Complex Mixtures	77

CONTENTS

7 PRODUCING SILICA-FUME CONCRETE: HANDLING, BATCHING, AND MIXING 79

7.1 General Considerations	80
7.2 Bulk Densified Silica Fume	84
7.2.1 Shipping	84
7.2.2 Storage Requirements	86
7.2.3 Unloading	90
7.2.4 Batching	92
7.2.5 Mixing	94
7.2.6 Other Concerns	96
7.3 Bagged Densified Silica Fume	97
7.3.1 Shipping	98
7.3.2 Storage Requirements	99
7.3.3 Unloading	99
7.3.4 Batching	100
7.3.5 Mixing	102
7.3.6 Other Concerns	103

8 PLACING, CONSOLIDATING, FINISHING, AND CURING SILICA-FUME CONCRETE 105

8.1 General Considerations	107
8.1.1 Coordination	107
8.1.2 Preplacement Considerations	108
8.1.3 Formed Silica-Fume Concrete	109
8.2 Concrete Drying	110
8.2.1 Bleeding	110
8.2.2 Surface Drying	111
8.2.3 Results of Drying	114
8.2.4 Protecting Against Drying	117

CONTENTS

8.3	Placing and Consolidating	121
8.4	Finishing Bridge Decks	122
8.4.1	Determine the Degree of Finishing Required	124
8.4.2	Conduct a Preplacement Conference	124
8.4.3	Conduct a Trial Placement	124
8.4.4	Surface Preparation for Overlays	125
8.4.5	Apply Bond Coat	126
8.4.6	Place the Concrete	127
8.4.7	Consolidate and Finish the Concrete	128
8.4.8	Texture the Surface	129
8.4.9	Protect and Cure	131
8.5	Finishing Parking Structures and Other Flatwork	133
8.5.1	Determine the Degree of Finishing Required	135
8.5.2	Conduct a Preplacement Conference	135
8.5.3	Conduct a Trial Placement	136
8.5.4	Place and Consolidate the Concrete	137
8.5.5	Perform Initial Bull Floating	138
8.5.6	Allow Concrete to Finish Bleeding and Gain Strength	139
8.5.7	Perform Final Floating and Troweling	139
8.5.8	Apply Surface Texture	140
8.5.9	Apply Intermediate Cure	142
8.5.10	Apply Final Cure	142
8.6	Curing	144
8.6.1	Silica Fume Association Recommendations	144
8.6.2	Curing Affects the Surface Durability	145
8.6.3	Curing versus Protection	145
8.6.4	Curing and Cracking	146
8.6.5	Winter Protection	147
8.7	Precast Concrete	148

CONTENTS

8.8	Miscellaneous Concerns	149
8.8.1	Cutting Joints	149
8.8.2	Stressing Post-Tensioning Strands	149
8.8.3	Power Troweled Floors	149
8.8.4	Painting After Curing	150

9 SILICA FUME HEALTH ISSUES 151

9.1	General Considerations and Recommendations	152
9.2	Silica Fume Material Safety Data Sheet	154
9.3	Silica Fume Bag Warning Label	154

10 REFERENCES 157

10.1	American Concrete Institute	158
10.2	ASTM	159
10.3	American Association of State Highway and Transportation Officials (AASHTO)	160
10.4	Cited References	161

APPENDIX 1: PROPORTIONING EXAMPLES IN INCH-POUND UNITS 163

A.1	Proportioning Examples in Inch-Pound Units.....	164
A.1	Example 1 – Bridge Deck	164
A.2	Example 2 – Cast-in-Place Parking Structure	167
A.3	Example 3 – High-Strength Concrete Columns	170

APPENDIX 2: MATERIAL SAFETY DATA SHEET 175

A.2	Material Safety Data Sheet	176
-----	----------------------------------	-----

INDEX 181

Silica fume is a highly reactive material that is used in relatively small amounts to enhance the properties of concrete. It is a by-product of producing certain metals in electric furnaces.

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

1.1	Silica Fume Definition	2
1.2	Production	4

1.1 SILICA FUME DEFINITION

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 116R). It is usually a gray colored 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 C 1240, *Standard Specification for Silica Fume Used in Cementitious Mixtures*, and low-calcium fly ash meeting the requirements of ASTM C 618, *Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, Class F.

1.1 SILICA FUME DEFINITION

- **Cementitious** — will gain strength when mixed with water. Examples include ground granulated blast-furnace slag meeting the requirements of ASTM C 989, *Standard Specification for Ground Granulated Blast-Furnace Slag for use in Concrete and Mortars*, or high-calcium fly ash meeting the requirements of ASTM C 618, 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**
- **Volatile silica**

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.

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. Smelter before installation of equipment to collect silica fume. The “smoke” is silica fume being released to the atmosphere. Today, in the U.S., no silica fume is released — it is all captured and used.

1.2 PRODUCTION

Figure 1.2 shows a smelter in the days before silica fume was being captured for use in concrete and other applications. The “smoke” leaving the plant is actually silica fume. Today in the United States, no silica fume is allowed to escape 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 5.

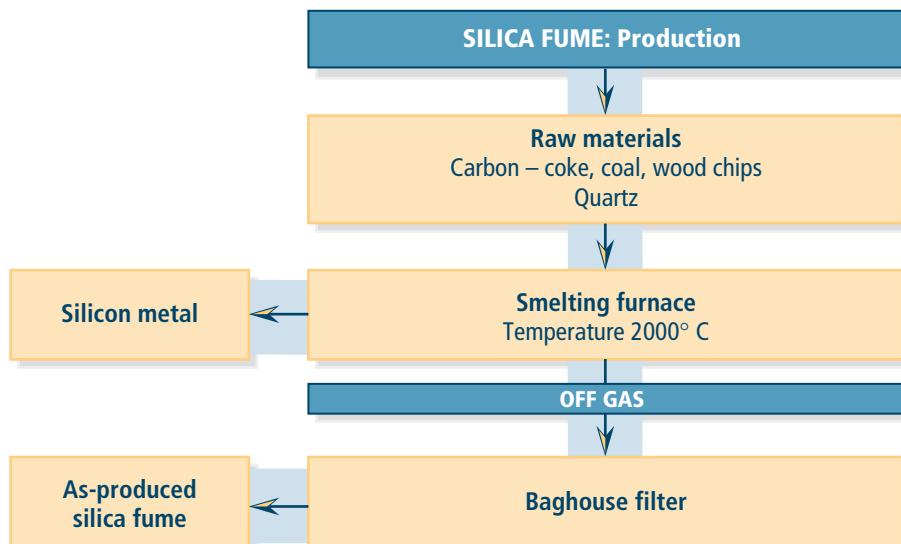


FIGURE 1.3. Schematic of silica fume production.

1.2 PRODUCTION

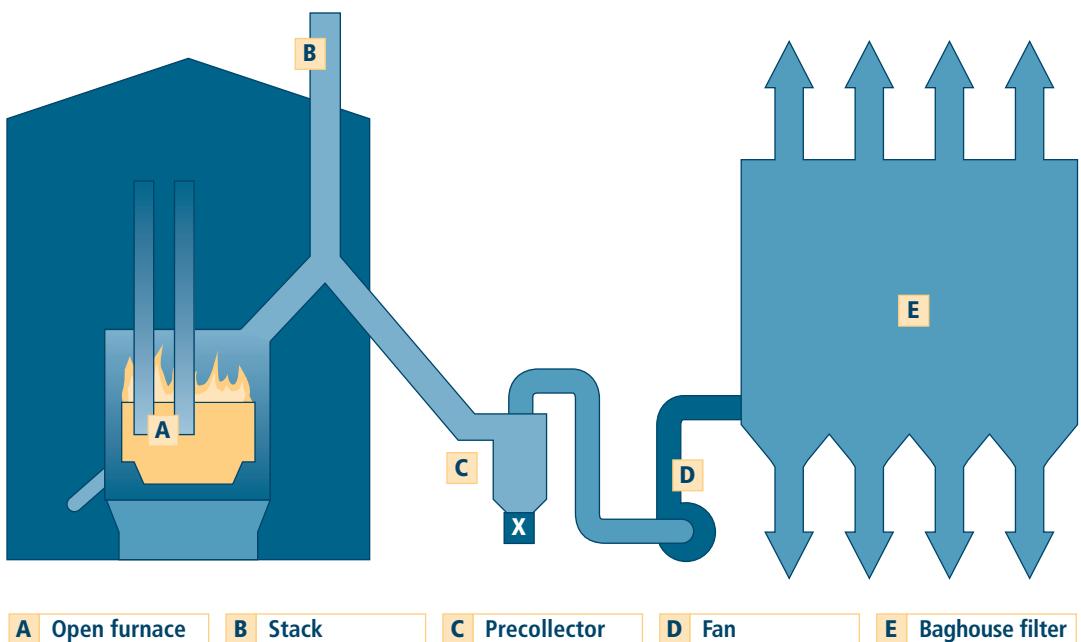


FIGURE 1.4. Schematic of a smelter for the production of silicon metal or ferrosilicon alloy. The silica fume is collected in large bags in the baghouse.

Silica fume affects both the fresh and hardened properties of concrete. The effects on concrete are a result of the physical and chemical properties of silica fume.

This chapter looks at those properties and at how silica fume actually contributes to the improvements in fresh and hardened concrete.

2.1	Chemical Properties	8
2.2	Physical Properties	9
2.3	Reactions in Concrete.....	11
2.4	Comparison with Other Supplementary Cementitious Materials	14

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

- **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. Don't forget that there is a crystalline material in concrete that is 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 2.3.
- **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.

TABLE 2.1

CHEMICAL PROPERTIES OF SILICA FUME

- | |
|--|
| ■ Amorphous |
| ■ Silicon dioxide > 85% |
| ■ Trace elements depending upon type of fume |

The primary physical properties of silica fume are shown in Table 2.2.

Following is a discussion of each of these properties. Note that the major physical properties are included in the standard specifications for silica fume as discussed in Chapter 4.

- **Particle size.** Silica fume particles are extremely small, with more than 95% of the particles being less than 1 μm (one micrometer). Particle size is extremely important for both the physical and chemical contributions (discussed below) of silica fume in concrete. A photograph of portland cement grains and silica fume particles is shown in Figure 2.1.
- **Bulk density.** This is just 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 very economical to transport it for long distances. See Chapter 5 for a discussion of the various product forms of silica fume.
- **Specific gravity.** Specific gravity is a 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 6. 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 “densify” the concrete in terms of increasing the density of the concrete.

TABLE 2.2

PHYSICAL PROPERTIES OF SILICA FUME

Particle size (typical):	< 1 μm
Bulk density: (as-produced):	130 to 430 kg/m^3
(densified):	480 to 720 kg/m^3
Specific gravity:	2.2
Specific surface:	15,000 to 30,000 m^2/kg

■ **Specific surface.** Specific surface is the total surface area of a given mass 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. This fact is 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.

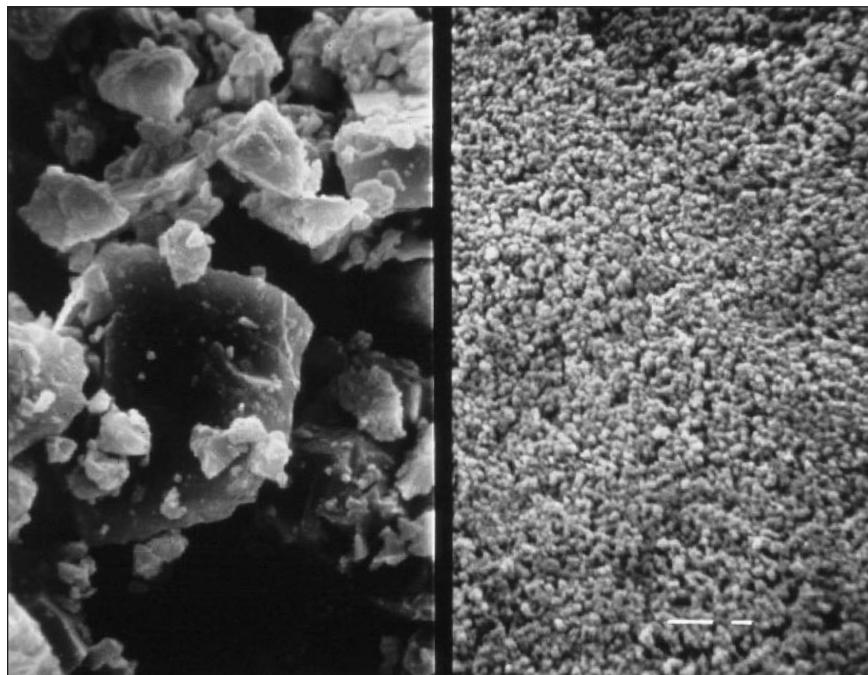


FIGURE 2.1. Photomicrograph of portland cement grains (left) and silica-fume particles (right) at the same magnification. The longer white bar in the silica fume side is 1 micrometer long. Note that ACI 234R, *Guide for the Use of Silica Fume in Concrete*, estimates that for a 15 percent silica-fume replacement of cement, there are approximately 2,000,000 particles of silica fume for each grain of portland cement.

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 and 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 2.3 and Figure 2.2 present a comparison of the size of silica-fume particles to other concrete ingredients to help understand how small these particles actually are.

TABLE 2.3

COMPARISON OF SIZE OF SILICA FUME PARTICLES AND OTHER CONCRETE INGREDIENTS		
MATERIAL	NOMINAL SIZE	SI UNITS
Silica fume particle	N/A	0.5 µm
Cement grain	No. 325 sieve	45 µm
Sand grain	No. 8 sieve	2.36 mm
Coarse aggregate particle	3/4 inch sieve	19.0 mm

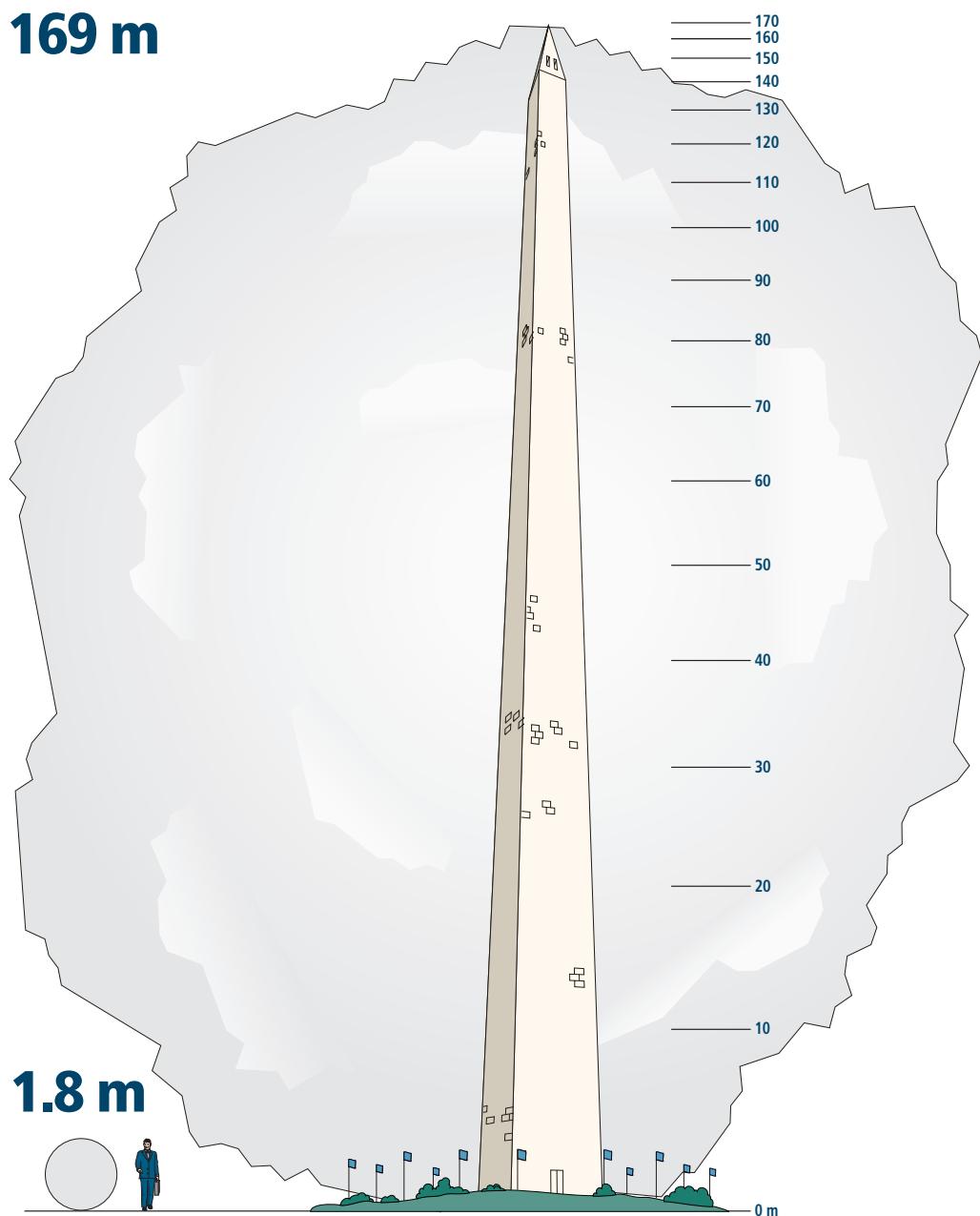


FIGURE 2.2. General size comparison of silica-fume particles. If a person (1.8 m) were the size of a silica-fume particle, then a cement grain would be approximately the size of the Washington Monument (169 m).

- **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, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate, which is very similar to the calcium silicate hydrate formed from the portland cement. It is largely this additional binder that gives silica-fume concrete its improved hardened properties.

2.4

COMPARISON WITH OTHER SUPPLEMENTARY CEMENTITIOUS MATERIALS

Table 2.4 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 because of its very small particle size.

TABLE 2.4

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	PORLAND CEMENT	CLASS F FLY ASH	CLASS C FLY ASH	SLAG CEMENT	SILICA FUME
SiO ₂ content, %	21	52	35	35	85 to 97
Al ₂ O ₃ content, %	5	23	18	12	
Fe ₂ O ₃ content, %	3	11	6	1	
CaO content, %	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 (2002).

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

Silica fume is used in concrete because it significantly improves the properties of fresh and hardened concrete. The potential for the use of 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.

Keep in mind that silica fume is a property enhancing material — it is not a replacement material for portland cement. Fly ash or ground granulated blast-furnace slag can be used as cement replacement materials. Note that these materials are frequently used in combination with portland cement and silica fume.

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

3.1	Silica Fume and Fresh Concrete	16
3.1.1	Increased Cohesion	17
3.1.2	Reduced Bleeding	18
3.2	Silica Fume and Hardened Concrete	20
3.2.1	Enhanced Mechanical Properties	21
3.2.2	Reduced Permeability	27
3.3	Silica Fume and Constructability	31

Figure 3.1 shows the effects of silica fume in fresh concrete. Note that 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. Let's look at both of these effects.

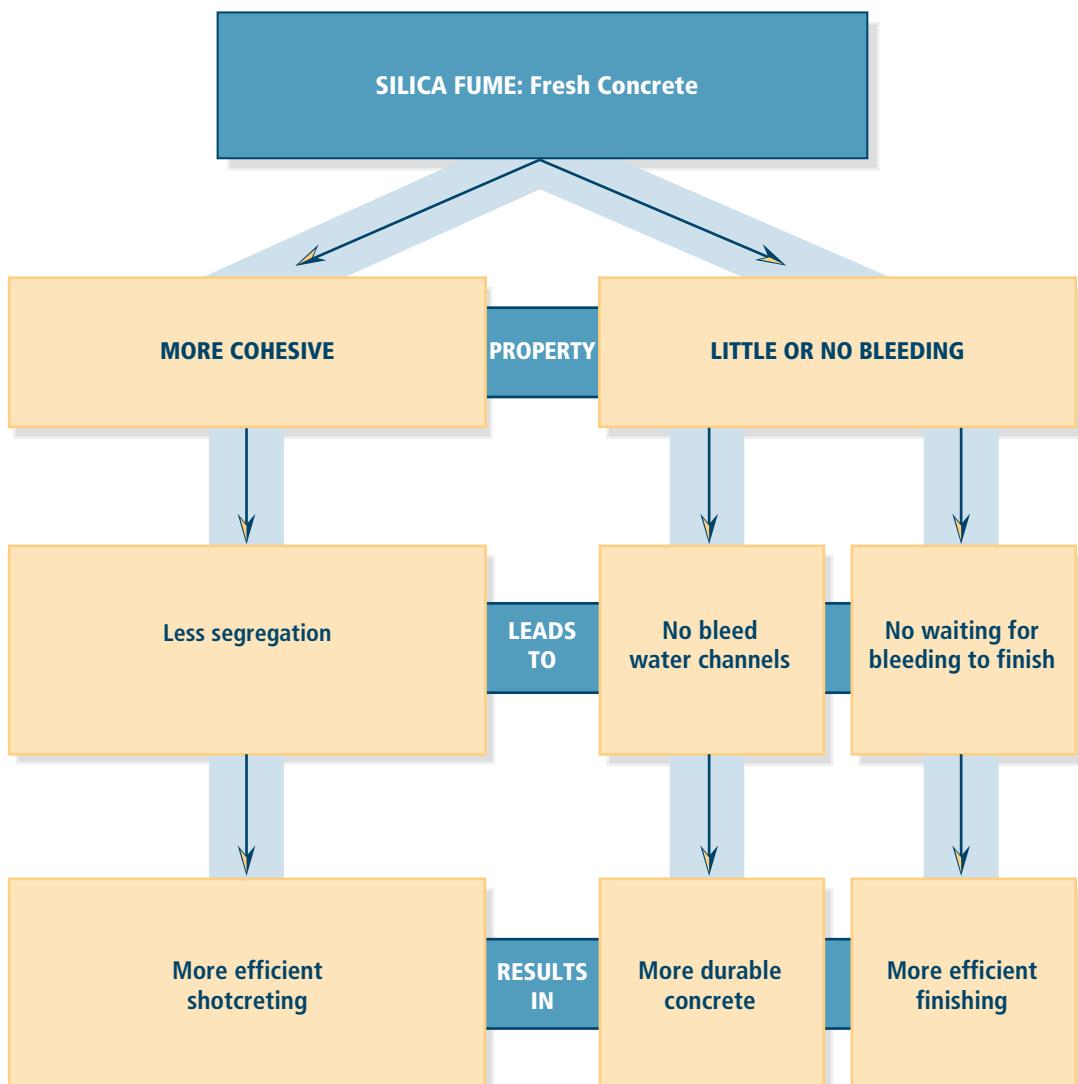


FIGURE 3.1. Effects of silica fume on fresh concrete and how those effects improve constructability and the final concrete.

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. To offset this increased cohesion when placing, silica-fume concrete is typically placed at 40 to 50 mm greater slump than concrete without silica fume in the same placement.

The main benefit from increased cohesion can be seen in shotcrete (Figure 3.2), whether it is for new construction, repair of existing structures, or ground support in tunneling operations. 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 3.2.
Silica-fume shotcrete being used for repair of deteriorated bridge abutment. 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.

3.1.2 Reduced Bleeding

Because of the very high surface area of the silica fume and the usually very 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.

Concrete bleeds as the heavier components (cement and aggregates) 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 3.3. 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.

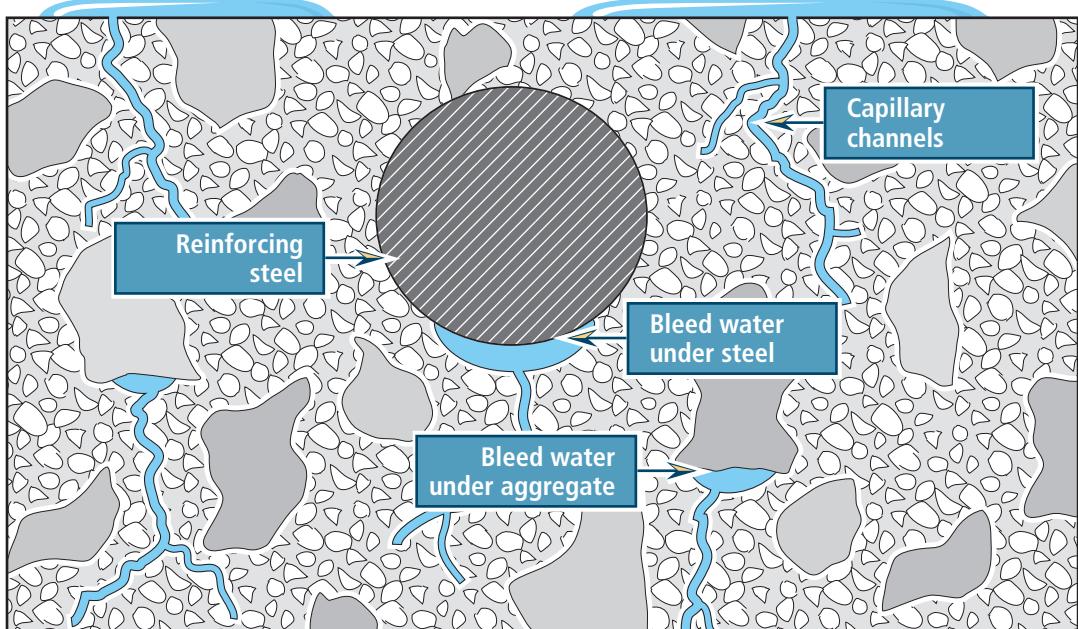


FIGURE 3.3. Schematic of bleeding and capillary channels. Reduction or elimination of bleeding is a benefit of adding silica fume to a concrete mixture.

3.1 SILICA FUME AND FRESH CONCRETE

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.

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 3.4 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 8.



FIGURE 3.4. “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 3.5 shows the effects of silica fume in hardened concrete. Note that there are two distinct effects: enhanced mechanical properties such as strength and modulus of elasticity, and reduced permeability, which directly improves durability. Both of these effects are discussed below.

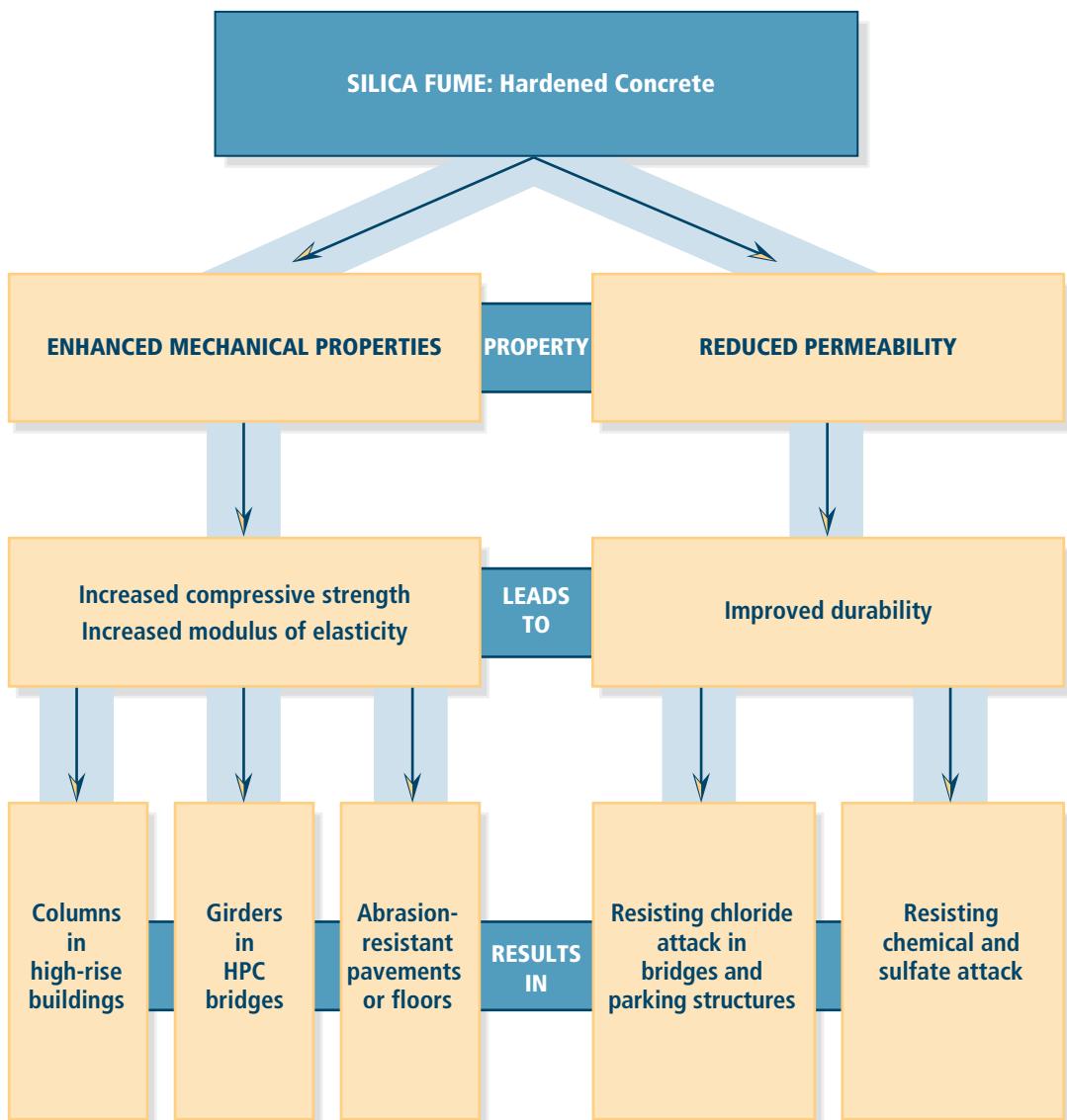


FIGURE 3.5. Effects of silica fume on hardened concrete and how those effects are used in concrete applications.

3.2 SILICA FUME AND HARDENED CONCRETE

3.2.1 Enhanced Mechanical Properties

Silica fume gained initial attention in the concrete market place 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 property of most interest is certainly compressive strength.

Figure 3.6 shows the effects on compressive strength of using different amounts of cement, fly ash, silica fume, and water in concrete. The curves that are shown are typical of what may be expected. There are several important points in this figure:

- 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 silica fume as for concrete without — the 3-day strength will be about 50% and the 7-day strength will be about 70% of the 28-day strength.
- 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.
- 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 C 618 Class F fly ash, which is also a purely pozzolanic material.
- The results presented are from different projects using different materials.
You must test any proposed mixture proportions using your project specific materials.

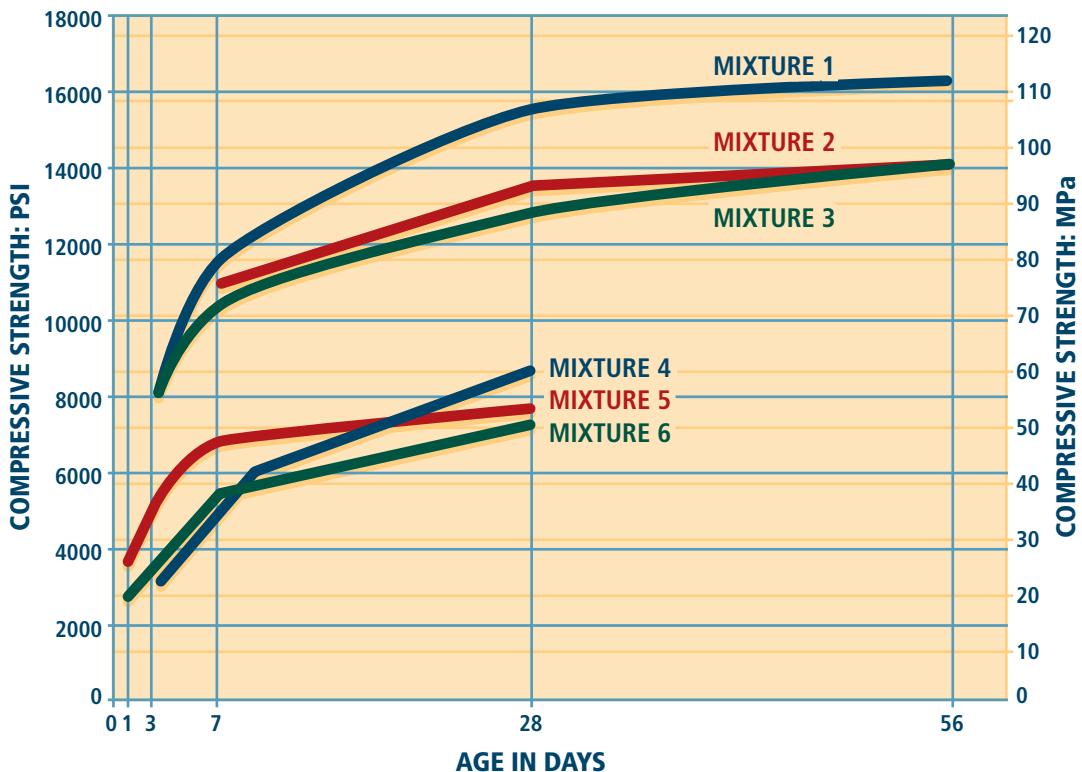


FIGURE 3.6. Strength development of several concrete mixtures containing silica fume. Details for the mixtures are provided in the table below.

STRENGTH DEVELOPMENT OF SEVERAL CONCRETE MIXTURES CONTAINING SILICA FUME					
MIXTURES	CEMENT kg/m ³	FLY ASH kg/m ³	SF kg/m ³	SF % (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 6.2 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 3.7. 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.



FIGURE 3.7. High-strength silica-fume concrete column in a high-rise structure.

More recently, high-strength concrete has been used in high-performance concrete bridges constructed by various state DOTs. In general, these DOTs have used this concrete to achieve one or more of these three objectives:

- **To increase the span of a bridge.** Figure 3.8 shows a bridge constructed by Ohio DOT in which a single span replaced three spans in the previous bridge at this site.



FIGURE 3.8. High-performance concrete bridge. In this bridge in Ohio, the high-strength concrete was used to increase span length and eliminate a pier in the river. For more information of this bridge, see the article by Miller (1999).

- To reduce the number of girders for a given span. Figure 3.9 shows a bridge constructed by New Hampshire DOT where the number of girders was reduced from seven to five.



FIGURE 3.9. High-performance concrete bridge. In this bridge in New Hampshire, the 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 3.10. 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 3.10. High-performance concrete bridge. In this bridge in Colorado, the high-strength concrete was used to increase span length to eliminate two piers and to increase the head room under the bridge. For more information on this bridge, see the article by Leonard (1999).

3.2 SILICA FUME AND HARDENED CONCRETE

3.2.2 Reduced Permeability

In many situations, the durability of concrete is directly related to its permeability. The contribution of silica fume is to reduce the permeability of the concrete. Figure 3.11 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 where it can do its damage. Here are a few examples of how reducing permeability is used in actual structures.

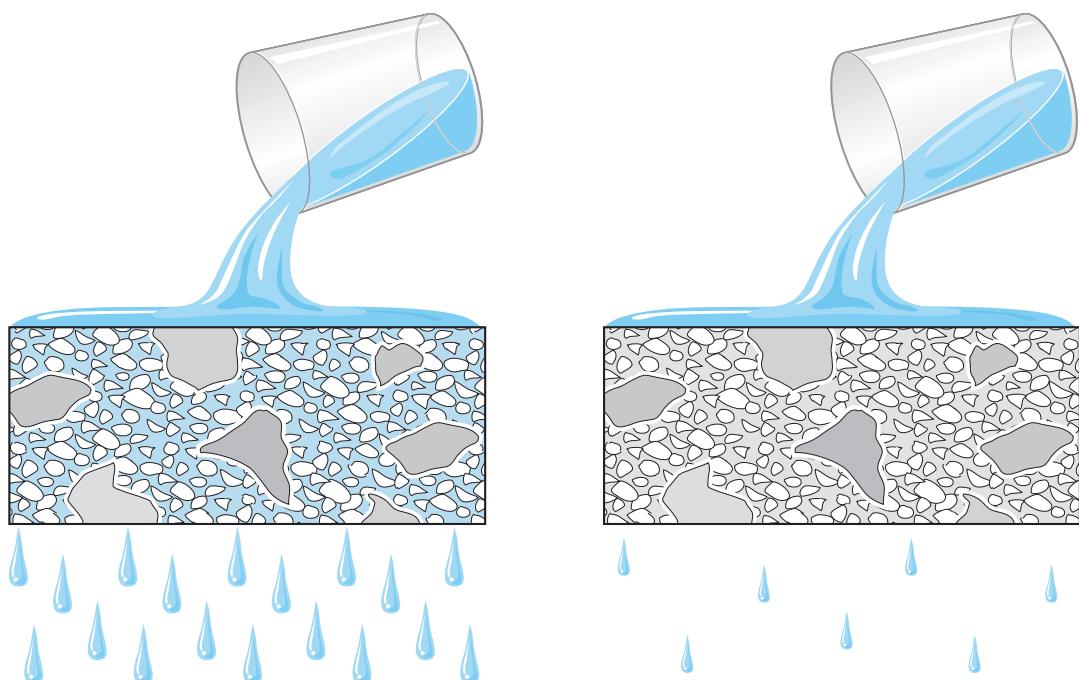


FIGURE 3.11. Schematic of concrete permeability. A high permeability concrete (left) allows water to move into and through the concrete readily. Lowering the w/cm and adding silica fume can reduce permeability to essentially zero. Such a reduction makes it very difficult for water and aggressive chemicals 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 3.12 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.

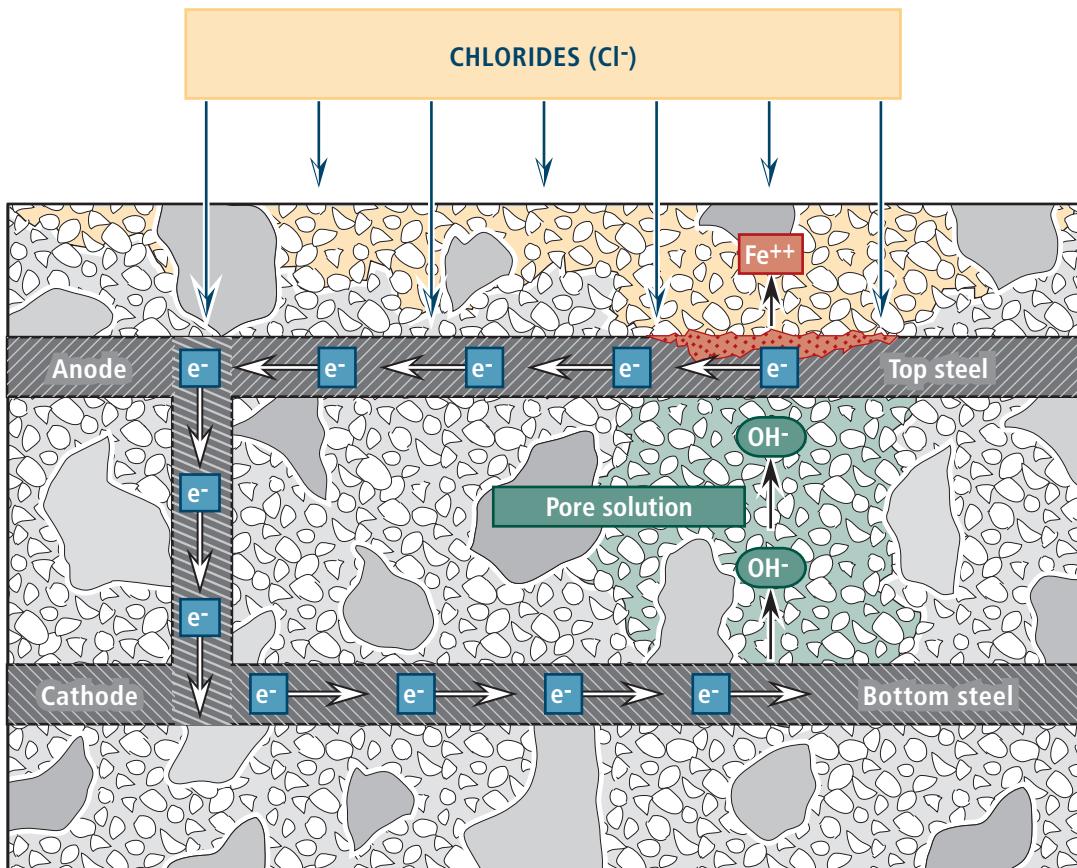


FIGURE 3.12. Schematic of corrosion in reinforced concrete. At the anode chloride ions interact with iron to produce Fe⁺⁺ ions. The electrons released flow through the reinforcing steel to the cathode. The electrical path is completed by OH⁻ ions flowing through the pore solution (electrolyte). In some 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 3.13 and 3.14 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.
2. As the iron ions are removed from the reinforcing steel, they go through several stages of oxidation or rusting. The volume of the iron 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.



FIGURE 3.13. Corrosion damage to a marine structure.



FIGURE 3.14. Chloride induced corrosion on a highway overpass. Note that chlorides have apparently run off of deck and onto this pier. Structural elements as well as decks should be protected.

- **Sulfate attack.** While the chemistry of the portland cement used plays a 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 SILICA FUME AND HARDENED CONCRETE

■ **Acid or other chemical attack.** The overall resistance of silica-fume concrete to attack by an aggressive chemical is not significantly different from that of conventional portland cement concrete. However, the reduced permeability of silica-fume concrete may extend the life of a concrete structure or extend the time between repairs simply by slowing down the rate of the attack. If protection against a particular chemical is required on a project, we strongly urge testing to include exposure of specimens of varying silica fume contents to the particular chemical.

The reduction in permeability is not the only contribution of silica fume to durability. 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-aggregate reaction when reactive aggregates are used. Again, testing will be required to determine the appropriate amount and types of cementitious materials to be used for each particular application.

Finally, the higher strength of silica-fume concrete will add additional abrasion resistance. For concrete made with a particular aggregate, the higher the compressive strength, the higher the abrasion resistance. High-strength silica-fume concrete has been used in applications such as trash transfer stations and stilling basins in major dams. See Figure 3.15.



FIGURE 3.15.

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 actually 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.** In this case, we are taking advantage of the lack of bleeding in silica-fume concrete to complete finishing of flatwork 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.
- **Reduced heat of hydration.** Although silica fume contributes about the same amount of heat of hydration as does portland cement on a pound-for-pound basis, its strength contribution is much greater on the same basis. Therefore, by balancing portland cement and silica fume in a mixture, 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 10 in Table 6.2 of this manual. Note that 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 cementitious material will reduce heat and help prevent early-age cracking.

■ **Use of three cementitious materials.** There is an ever-increasing emphasis on using more waste materials such as fly ash and slag 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. Figure 3.16 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. Usually, using combinations of three cementitious materials will reduce the cost of concrete. Mixtures containing three cementitious materials are referred to as “ternary mixtures.”



FIGURE 3.16. 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).

■ **Shotcrete.** Silica-fume shotcrete is being widely used, in both the wet and dry processes and with and without steel fibers. The cohesive nature of this shotcrete allows for many applications that would have been difficult, uneconomical, or impossible to accomplish without the silica fume.

ACI provides a detailed discussion of silica fume in a committee guide. ASTM and AASHTO both have specifications for silica fume.

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

4.1	ACI Guidance	34
4.2	Standard Specifications	37
4.2.1	ASTM C 1240	38
4.2.2	AASHTO M307	42
4.3	Silica Fume Reference Material	44

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-96). (Note that this document is currently being updated. The revised document should be available from ACI in late 2005.) 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 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-96
(Reapproved 2000)

Guide for the Use of Silica Fume in Concrete*

Reported by ACI Committee 234

Terence C. Holland
Chairman

Rachel Detwiler
Secretary

Pierre-Claude Aitcin
Dennis O. Arney
Bayard M. Call
Menashi D. Cohen
Guy Detwiler
Per Fidjestol
Margaret E. Fiery
Fouad H. Fouad
William Halczak
R. D. Hooton

Allen J. Hulshizer
Tariq M. Jaber
Paul Klieger
Ronald L. Larsen
Mark D. Luther
V. M. Malhotra
Bryant Mather
D. R. Morgan
Jan Olek

H. Celik Ozylidirim
Harry L. Patterson
Michael F. Pistilli
Narasimhan Rajendran
Donald L. Schlegel
Woodward L. Vogt
Thomas G. Weil
David A. Whiting
John T. Wolsiefer

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: alkali-silica reaction, compressive strength, concrete durability, corrosion resistance, curing concrete, drying shrinkage, filler effects, finishing concrete, fresh concrete properties, hardened concrete properties, high-strength concrete, microstructure, permeability, placing concrete, plastic-shrinkage cracking, porosity, pozzolanic reactions, proportioning concrete, shotcrete, silica fume, silica-fume concrete, silica-fume products, specifications.

CONTENTS

Chapter 1—Introduction, p. 234R-2

- 1.1—General
- 1.2—What is silica fume?
- 1.3—Silica fume versus other forms of synthetic silica
- 1.4—Using silica fume in concrete

ACI Committee Reports, Guides, Standard Practices, Design Handbooks, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the application of the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

- 1.5—Using silica fume in blended cements
- 1.6—World-wide availability of silica fume
- 1.7—Types of silica-fume products available
- 1.8—Health hazards

Chapter 2—Physical properties and chemical composition of silica fume, p. 234R-5

- 2.1—Color
- 2.2—Density
- 2.3—Bulk density
- 2.4—Fineness, particle shape, and oversize material
- 2.5—Chemical composition
- 2.6—Crystallinity
- 2.7—Variability
- 2.8—Relating physical and chemical properties to performance in concrete
- 2.9—Quality control

Chapter 3—Mechanism by which silica fume modifies cement paste, p. 234R-8

- 3.1—Physical effects
- 3.2—Pozzolanic reactions
- 3.3—Pore water chemistry
- 3.4—Reactions in combination with fly ash or blast-furnace slag
- 3.5—Reactions with different types of portland cements

ACI 234R-96 (Reapproved 2000) supersedes ACI 226.2R and became effective May 1, 1996.

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

Copyright © 2000, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

234R-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: phone: 248-848-3800; web site: www.concrete.org.

234R-2**ACI COMMITTEE REPORT**

- 3.6—Heat of hydration
- 3.7—Reactions with chemical admixtures

Chapter 4—Effects of silica fume on properties of fresh concrete, p. 234R-12

- 4.1—Water demand
- 4.2—Workability
- 4.3—Slump loss
- 4.4—Time of setting
- 4.5—Segregation
- 4.6—Bleeding and plastic shrinkage
- 4.7—Color of concrete
- 4.8—Air entrainment
- 4.9—Unit weight (mass) of fresh concrete
- 4.10—Evolution of hydrogen gas

Chapter 5—Effects of silica fume on properties of hardened concrete, p. 234R-14

- 5.1—Microstructure modification
- 5.2—Mechanical properties
- 5.3—Durability aspects
- 5.4—Miscellaneous properties
- 5.5—Use of silica fume in combination with fibers
- 5.6—Use of silica fume in conjunction with fly ash
- 5.7—Property variations with respect to type, source, and form of delivery of silica fume

Chapter 6—Applications of silica fume, p. 234R-27

- 6.1—Introduction
- 6.2—Abrasion resistance
- 6.3—Alkali-silica reaction
- 6.4—Cement replacement
- 6.5—Heat reduction
- 6.6—Chemical attack resistance
- 6.7—Corrosion resistance
- 6.8—Grout
- 6.9—High early-strength concrete
- 6.10—High-strength concrete
- 6.11—Lightweight concrete
- 6.12—Offshore and marine structures
- 6.13—Overlays and pavements
- 6.14—Shotcrete
- 6.15—Underwater concrete
- 6.16—Waste isolation

Chapter 7—Proportioning silica-fume concrete, p. 234R-32

- 7.1—General
- 7.2—Cement and silica-fume content
- 7.3—Water content
- 7.4—Aggregate
- 7.5—Chemical admixtures
- 7.6—Proportioning

Chapter 8—Specifications, p. 234R-33

- 8.1—General
- 8.2—Specifying silica fume
- 8.3—Specifying silica-fume admixtures

- 8.4—Specifying silica-fume concrete

Chapter 9—Working with silica fume in field concrete, p. 234R-36

- 9.1—Transporting and handling silica fume and silica-fume admixture products
- 9.2—Producing concrete
- 9.3—Transporting
- 9.4—Placing
- 9.5—Finishing
- 9.6—Curing
- 9.7—Accelerated curing

Chapter 10—Research needs, p. 234R-39

- 10.1—Frost resistance
- 10.2—Sulfate attack
- 10.3—Drying shrinkage and creep
- 10.4—Steel corrosion
- 10.5—Performance under high-temperature conditions
- 10.6—Long-term durability
- 10.7—Pore structure and permeability
- 10.8—Rheology and setting properties
- 10.9—Mechanism of strength development
- 10.10—Role of silica fume in special concretes
- 10.11—Effect of silica fume on hydration
- 10.12—Curing
- 10.13—Recommended field practice

Chapter 11—References, p. 234R-41

- 11.1—Recommended references
- 11.2—Cited references

CHAPTER 1—INTRODUCTION**1.1—General**

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

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

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

FIGURE 4.1. Continued

4.2 STANDARD SPECIFICATIONS

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. There are two major standard specifications of interest: ASTM C 1240, *Standard Specification for Silica Fume Used In Cementitious Mixtures*, and AASHTO M 307, *Standard Specification for Use of Silica Fume as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar, and Grout*.

Both of these specifications are discussed in this chapter. The intent here is to review the parameters that are included in the specifications in an attempt to determine the significance of each. Note that each of these specifications contains both mandatory and optional elements. Both categories are discussed.

Keep in mind that these specifications were derived from specifications for other pozzolans such as ASTM C 618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. 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.

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

4.2.1 ASTM C 1240

The version discussed here is the 2004 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.

- **Silicon dioxide (SiO_2) content (mandatory).** This requirement calls for a minimum SiO_2 content of 85%. 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% after appropriate testing in concrete.
- **Moisture content (mandatory).** This requirement limits maximum moisture content to 3%. The intent here is simply 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%. 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%. 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.



Designation: C 1240 – 04

Standard Specification for Silica Fume Used in Cementitious Mixtures¹

This standard is issued under the fixed designation C 1240; 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 slurred 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, 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 and health 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.

2. Referenced Documents

- 2.1 *ASTM Standards:*²
- C 109/C 109M Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
- C 114 Test Methods for Chemical Analysis of Hydraulic Cement
- C 125 Terminology Relating to Concrete and Concrete Aggregates
- C 183 Practice for Sampling and the Amount of Testing of Hydraulic Cement

C 185 Test Method for Air Content of Hydraulic Cement Mortar

C 219 Terminology Relating to Hydraulic Cement

C 311 Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete

C 430 Test Method for Fineness of Hydraulic Cement by the 45- μm (No. 325) Sieve

C 441 Test Method for Effectiveness of Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction

C 670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials

C 1005 Specification for Reference Masses and Devices for Determining Mass and Volume for Use in the Physical Testing of Hydraulic Cements

C 1012 Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

C 1069 Test Method for Specific Surface Area of Alumina or Quartz by Nitrogen Adsorption

C 1157 Performance Specification for Hydraulic Cement

C 1437 Test Method for Flow of Hydraulic Cement Mortar

3. Terminology

3.1 Definitions:

3.1.1 *silica fume*—very fine pozzolanic material, composed mostly of amorphous silica produced by electric arc furnaces as a by-product of the production of elemental silicon or ferrosilicon alloys (also known as condensed silica fume and microsilica).

3.1.2 Other terms in this specification are defined in Terminologies C 125 and C 219.

4. Ordering Information

4.1 The purchaser shall specify any optional chemical or physical requirements.

5. Chemical Composition

5.1 Silica fume shall conform to the requirements for chemical composition prescribed in Table 1.

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 and Cementitious Materials.

Current edition approved June 1, 2004. Published June 2004. Originally approved in 1993. Last previous edition approved in 2003 as C 1240-03a.

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.

Copyright © ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States.

FIGURE 4.2. Cover page of the ASTM specification for silica fume. Extracted with permission from C 1240-04, 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 purchased from ASTM; phone: 610-832-9585; fax: 610-832-9555; email: service@astm.org; web site: www.astm.org.

4.2 STANDARD SPECIFICATIONS

- **Accelerated pozzolanic activity (mandatory).** This requirement states that the accelerated pozzolanic activity of a silica fume must be at least 105% of the control made without silica fume. This requirement is also a carry over from the fly ash specification. Note that 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 m²/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, 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% 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%, 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% when tested at 14 days. As noted earlier, because silica fume, used in the appropriate levels, 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.

4.2 STANDARD SPECIFICATIONS

- **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. There is no limit established — the value is simply 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 simply 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 simply 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. It is now recognized that silica fume will not contribute to the total alkali content of the concrete. 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 actually developed a standard specification for silica fume before ASTM. The current AASHTO version is M 307, dated 2004. A copy of the cover page of this document is in Figure 4.3.

AASHTO recently 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 C 1240. 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**Use of Silica Fume as a Mineral Admixture in
Hydraulic-Cement Concrete, Mortar, and Grout****AASHTO Designation: M 307-04****ASTM Designation: C 1240-03****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 problems, 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 194, Chemical Admixtures for Concrete
 - T 105, Chemical Analysis of Hydraulic Cement
 - T 106, Compressive Strength of Hydraulic-Cement Mortars (Using 2-in. [50-mm] Cube Specimens)
 - T 127, Sampling and the Amount of Testing of Hydraulic Cement
 - T 137, Air Content of Hydraulic Cement Mortar
 - T 160, Length Change of Hardened Hydraulic-Cement Mortar and Concrete
 - T 192, Fineness of Hydraulic Cement by the 45- μm (No. 325) Sieve
- 2.2. **ASTM Standards:**
 - C 109/C 109M, Test Method for Compressive Strength of Hydraulic-Cement Mortars (Using 2-in. [50-mm] Cube Specimens)
 - C 114, Test Methods for Chemical Analysis of Hydraulic Cement
 - C 125, Terminology Relating to Concrete and Concrete Aggregates

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>.

Different laboratories have encountered difficulties when testing silica fume for compliance with either ASTM C 1240 or AASHTO M 307. In order to reduce these difficulties, a silica fume reference material has been prepared by the Silica Fume Association in cooperation with the 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 SiO₂ content, specific surface area by BET, moisture content, loss on ignition, and the amount of several trace elements that may be present.

Figure 4.4 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 web site (www.silicafume.org) or the NIST web site (<https://srmsors.nist.gov/index.cfm>) for instructions on how to obtain this material.



FIGURE 4.4. Silica fume Standard Reference Material (SRM 2696) available from the National Institute for Standards and Technology. Check either the Silica Fume Association or NIST web sites, as listed in the text, for instructions on how to order this material.

SPECIFYING AND OBTAINING SILICA FUME AND SILICA-FUME CONCRETE

Once the decision to use silica fume is made, the practical questions of actually obtaining silica-fume concrete must be addressed. The first step is to specify silica fume for use on the project. Next, the appropriate concrete performance characteristics must be specified. Finally, the contractor must obtain the silica-fume concrete.

This chapter looks at the specifics of how to specify and obtain silica-fume concrete.

5.1	Densified Silica Fume	46
5.2	Specifying Silica Fume and Silica-Fume Concrete	48
5.3	Obtaining Silica Fume and Silica-Fume Concrete	50

Silica fume has historically been available in three basic product forms: undensified, slurried, and densified. There is no data available, after many years of testing, to show that any one of the product forms will perform better in a concrete mixture than any of the others.

Slurried silica fume is no longer available in the U. S. market. 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. Neither slurried nor undensified silica fume are discussed in detail in this manual.

Figure 5.1 shows densified silica fume, and Table 5.1 shows some of the characteristics of this product form. Densified silica fume is produced by treating undensified silica fume to increase the bulk density up to a maximum of about 400 to 720 kg/m³. 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 5.1.
Densified silica fume.

5.1

DENSIFIED SILICA FUME

TABLE 5.1

PRODUCT CHARACTERISTICS OF DENSIFIED SILICA FUME*
■ Reversible agglomeration process
■ Flows well pneumatically
■ Bulk transportation is economical: 20Mg 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, an undensified silica fume may be more appropriate. Contact the Silica Fume Association for assistance in these types of applications. Additional information on mixing densified silica fume is presented in Chapter 7.

Densified silica fume is available as shown in Table 5.2. 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 7.

TABLE 5.2

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

*Mass in these bags as agreed upon with suppliers.

To specify silica fume, it is best to simply refer to one of the standard specifications that were described in Chapter 4. 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 there is a requirement for a specific quantity of silica fume in a big bag to facilitate batching, include that requirement along with the overall requirements of ASTM C 1240, *Standard Specification for Silica Fume Used in Cementitious Mixtures*.

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 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 Load and Resistance Factor Design (LFRD) Bridge Construction Specifications* (AASHTO 1998). Section 8 of this specification covers concrete structures and Section 28 covers wearing surfaces. Unfortunately, through the 2003 update of this document, there is no mention of silica-fume concrete for cast-in-place structures, for pre-cast elements, or for bridge deck overlays. The SFA is currently preparing a guide specification to supplement what is currently covered in the AASHTO specification. This guide specification may be used to prepare supplemental or provisional specifications for a specific project using silica-fume concrete.

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 03300. Usually, specifiers will create a separate section for silica-fume concrete that will include all of the specific requirements for the silica-fume concrete. The SFA is also preparing a guide specification for silica-fume concrete with a format as a separate section of Division 3. This guide specification may be used to prepare a separate silica-fume concrete section for a specific project using 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. Either the SFA AASHTO format guide specification or the CSI format guide specification may be used to prepare project specifications that meet the requirements of a particular organization.

Regardless of the format selected, the SFA strongly urges that that 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.

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.

In most cases, silica fume is not purchased directly. When silica fume is specified it will simply come as an ingredient in the concrete. 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.

Proportioning silica-fume concrete is very similar to proportioning any other concrete mixture. However, there are a few differences, particularly in 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. For complex projects where many variables must be evaluated, a statistical approach to proportioning is presented.

6.1	Basic Considerations	52
6.2	Project Requirements	55
6.3	Construction Considerations	56
6.4	Proportioning Procedure	57
6.4.1	General Rules	57
6.4.2	Step-By-Step Procedure	58
6.5	Adjusting the Mixture	67
6.6	Mixture Proportioning Examples	68
6.6.1	Example 1 – Bridge Deck	68
6.6.2	Example 2 – Cast-in-Place Parking Structure	71
6.6.3	Example 3 – High-Strength Concrete Columns	74
6.7	Statistical Approach for Complex Mixtures	77

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

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 performances levels that are typically being 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.

Don't be particularly concerned with the slump resulting from water alone ("water slump" or "initial slump".) Because silica-fume concrete mixtures usually contain so little water, there may not be enough water to develop a measurable slump until after the chemical admixtures are added.

Some specifiers are uncomfortable about using a superplasticizer without first verifying a water slump of 50 to 75 mm. This requirement is 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.

Use chemical admixtures to achieve adequate slump for placement. Usually, both a water-reducer (normal setting or retarding) and a superplasticizer will be used. The water-reducer is frequently added early in the mixing sequence to help loosen up the concrete and the superplasticizer is added later to bring the concrete to the desired slump for transportation and placement.

In some cases it may be necessary to go above manufacturer's 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 dose. In most cases such high dosages will retard the concrete; however, once the concrete begins to set, it will gain strength very rapidly. Testing at the high dose of admixture is recommended to ensure that other properties such as air content are not being affected.

Entrained air is required with silica-fume concrete if it will be exposed to freezing and thawing while saturated. 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, *Building Code Requirements for Structural Concrete* (see Table 6.1.) 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 6.1

RECOMMENDED TOTAL AIR CONTENT FOR CONCRETE EXPOSED TO FREEZING AND THAWING (From ACI 318)

NOMINAL MAXIMUM AGGREGATE SIZE		AIR CONTENT %	
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	1½	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.

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, and 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.

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

Slump: Silica-fume concrete is very cohesive and behaves somewhat differently than conventional concrete. A given slump will not be the same workability for concrete with and without silica fume. Usually, the slump for the silica-fume concrete should be increased by about 40 to 50 mm over concrete without silica fume to achieve the same workability.

Maximum slump: A good rule of thumb for silica-fume concrete is to place it at as high a slump as possible for the placement. 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 slope of the structure. Place at the highest slump that will hold on the slope.

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 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.

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.

6.4.1 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. Here are some general rules for proportioning:

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 very much 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 that was 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, don’t waste time developing a mixture if the project materials have not yet 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.

6.4.2 Step-By-Step Procedure

This section presents a seven step procedure. Examples are given for each step. See Figure 6.1 for a summary of this procedure.

STEP 1

STEP 1. Determine project requirements. Read the specifications carefully.

Look for requirements not only for concrete performance but also for concrete proportioning. Items to look for include:

- Compressive strength
- Chloride exposure
- Freezing and thawing exposure, including specified air content
- Aggregate requirements, including nominal maximum size
- Chemical exposure
- Abrasion resistance
- Temperature restrictions
- Maximum water content
- Cementitious materials contents
- Percentages of fly ash, slag, and silica fume
- Slump

STEP 2

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. 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

STEP 3. Select starting mixture. Table 6.2 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.

[Return to Table of Contents](#)

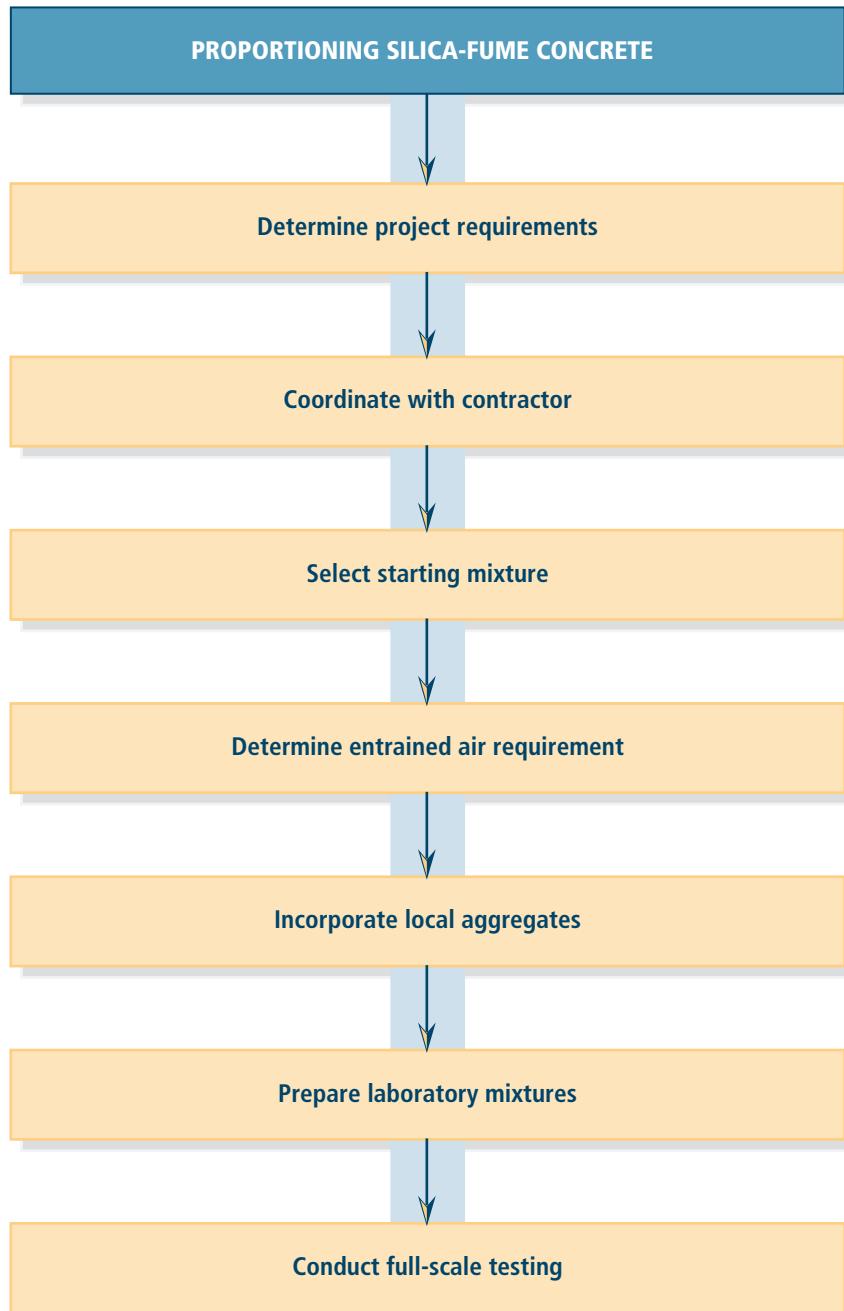


FIGURE 6.1. Steps in proportioning silica-fume concrete. Each of these steps is discussed in detail in the text.

6.4

PROPORTIONING PROCEDURE

TABLE 6.2

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 @ 28 days	69 MPa @ 28 days	> 37 MPa @ 28 days	42 MPa @ 28 days	35 MPa @ 28 days 42 MPa @ 90 days
Rapid chloride test, coulombs	N/A	303 @ 1 year 258 @ 2 years	< 1,600	N/A	N/A
Other requirements	Pumpable, 57 stories	N/A	Minimize plastic and drying shrinkage cracking	59 kg/m ³ of steel fibers to increase toughness	Max delivered < 21°C, Max @ 48 hr < 38°C, Pumpable, early strength for form removal
Entrained air (Note 2)	N/A	N/A	6.50%	8 to 10% as delivered 4 to 6% in place	2 to 6%
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/m ³	406	316	297	405	232
Fly ash, kg/m ³	0	0	80, Class F	0	89, Class F
GGBFS, kg/m ³	169	117	0	0	0
Silica fume kg/m ³	47	37	24	42	35
Maximum w/cm	0.24	0.31	0.40	0.45	0.37
Water, kg/m ³ (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.					

6.4

PROPORTIONING PROCEDURE

TABLE 6.2 (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 @ release 69 MPa ultimate	14 MPa @ 36 hrs 39 MPa @ 56 days	89 MPa @ 28 days 115 MPa @ 3 yrs	107 MPa @ 28 days 126 MPa @ 3 yrs	32 MPa @ 28 days
Rapid chloride test, coulombs	N/A	< 1,000 from cores at 2-10 months	N/A	N/A	1,400–1,600 @ 56 days
Other requirements	N/A	N/A	N/A	N/A	N/A
Entrained air (Note 2)	Unknown	Unknown	N/A	N/A	8.5%
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
GGBFS, 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	0.287	0.231	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.					

STEP 4

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 contain entrained air. Use an industry standard table such as found in ASTM or ACI to determine the volume of air required. Table 6.1 shows one such table. Don't forget that most specifications allow air content to be reduced by one percent for compressive strength above 35 MPa.

STEP 5

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

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

STEP 6

STEP 6. Prepare laboratory trial mixtures. This step is not all that different from what is normally done on a daily basis. However, the Silica Fume Association 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. Following are points to keep in mind when producing silica-fume concrete in a laboratory:

1. 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% of the cement weight. The exact addition rate depends upon the specific performance characteristic to be improved. Compared to the other ingredients in concrete, the amount of silica fume used is small. For the silica fume to be effective, there are two issues that must be addressed:
 - First, the agglomerations that make up the densified silica fume must be broken down.
 - Second, the silica fume must be distributed uniformly throughout the concrete.

When making concrete in the laboratory, the key to both of these issues 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 break down the agglomerations and to disperse the silica fume. The suggested remedy for the issues discussed above is quite straightforward (see Figure 6.2):

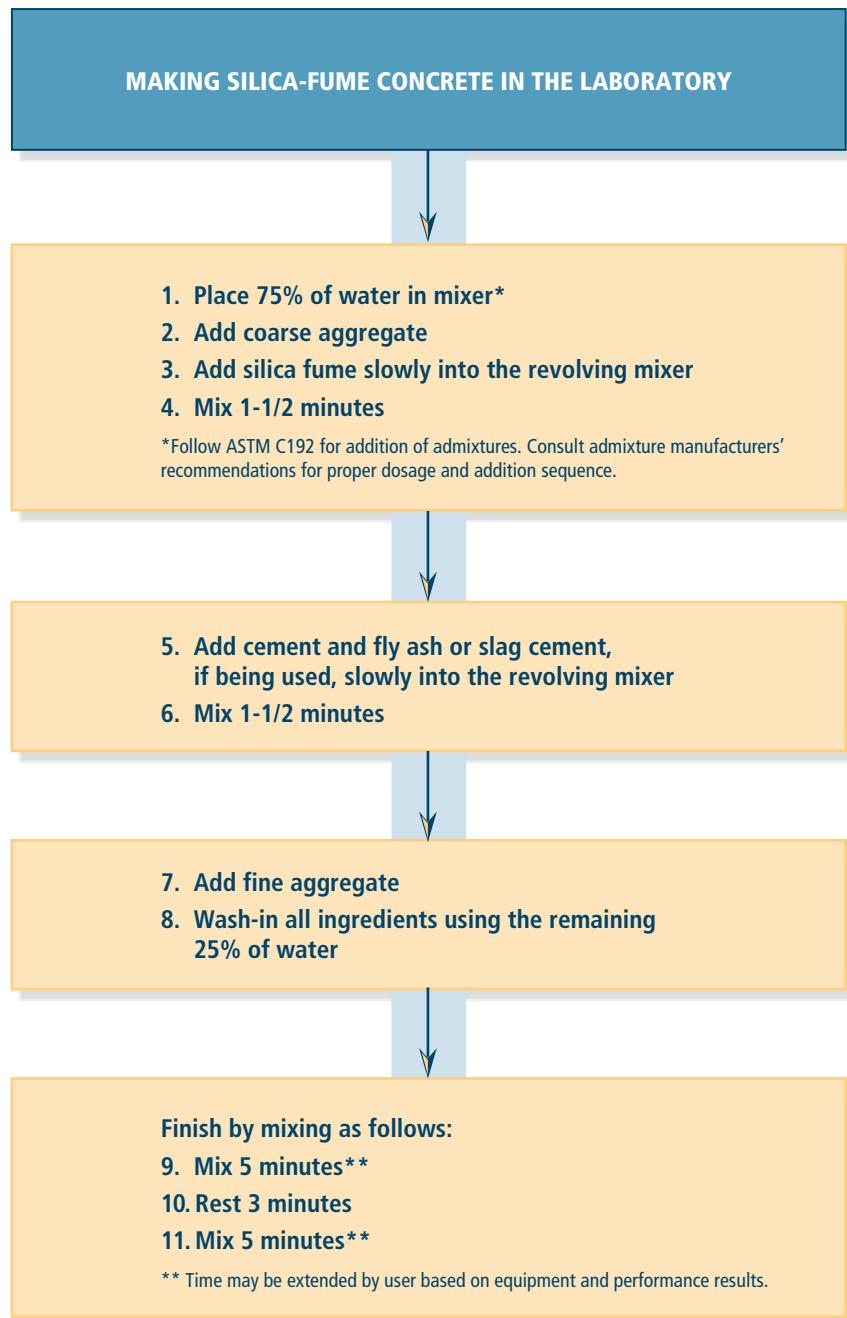


FIGURE 6.2. Recommendations for making silica-fume concrete in a laboratory mixer.

[Return to Table of Contents](#)

6.4 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. Silica-fume concrete cannot be over mixed.

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.

2. The Silica Fume Association's experience is that truck mixers or 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.
3. 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.
4. 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.
5. 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

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:

This is not a time to economize by making very small batches. Make enough concrete to be representative of what will be made during the project.

Remember that it takes a lot of paste to coat the inside of a truck drum or a central mixer. If too small a batch of concrete is used, a significant amount of paste can be lost to the drum. When conducting production trials, make at least 3 m³ 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 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.

6.5 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 stickiness 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 6.2. To get into the very high strength range, there must be a very low water content.

Concrete stickiness. The most common complaint regarding silica-fume concrete is that it tends to be sticky. This stickiness is a result of the high fines content and the high superplasticizer content. If stickiness a problem, here are some suggestions:

- Silica fume from a particular source can behave differently when used with a different superplasticizers. Simply try a different superplasticizer from your admixture supplier and see if that switch makes a difference in stickiness.
- 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 reducing the volume of fine aggregate by a small amount. As stated earlier, silica-fume concrete performs well when slightly under sanded. This success of this approach will depend upon the fineness of the aggregate.
- 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.

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.

EXAMPLE 1 BRIDGE DECK, Figure 6.3.



FIGURE 6.3. Bridge deck project. Mixture proportions for a concrete that could be used on this project are developed in Example 1.

STEP 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

[Return to Table of Contents](#)

STEP 2

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

STEP 3. Select starting mixture. From Table 6.2 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

STEP 4. Determine volume of air required. From Table 6.1 for 25 mm aggregate, the volume of air required for a severe environment is 6%. Because this concrete will not have a compressive strength of over 35 MPa, do not reduce the air content by 1%.

STEP 5

STEP 5. Incorporate local aggregates. First, determine the volume the paste will occupy, as shown in the following table: (Remember: Specific gravity in SI units is expressed as Mg/m³.)

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%	N/A	N/A	0.060

$$\text{Total paste volume} = 0.326 \text{ m}^3$$

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.68

Fine aggregate density: 2.64

**Fine aggregate: 40% 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, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.)*

Aggregate volume = $1.000 \text{ m}^3 - 0.326 \text{ m}^3 = 0.674 \text{ m}^3$

Fine aggregate volume = $0.40 \times 0.674 \text{ m}^3 = 0.270 \text{ m}^3$

Fine aggregate mass = $0.270 \text{ m}^3 \times 2.64 \text{ Mg/m}^3 = 0.713 \text{ Mg} = 713 \text{ kg}$

Coarse aggregate volume = $0.674 \text{ m}^3 - 0.270 \text{ m}^3 = 0.404 \text{ m}^3$

Coarse aggregate mass = $0.404 \text{ m}^3 \times 2.68 \text{ Mg/m}^3 = 1.083 \text{ Mg} = 1,083 \text{ kg}$

STEP 6

STEP 6. Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 6.2 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

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

6.6 MIXTURE PROPORTIONING EXAMPLES

EXAMPLE 2 CAST-IN-PLACE PARKING STRUCTURE, Figure 6.4.



FIGURE 6.4. 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 1

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 2

STEP 3

STEP 3. Select starting mixture. From Table 6.2 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

STEP 4. Determine volume of air required. From Table 6.1 for 25 mm aggregate, the volume of air required for a severe environment is 6%. Because this concrete will have a compressive strength of over 35 MPa, reduce the air content by 1% and proportion for 5%.

STEP 5**STEP 5. Incorporate local aggregates.**

First, determine the volume the paste will occupy, as shown in the following table: (Remember: Specific gravity in SI units is expressed as Mg/m³.)

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)	147	1.00	0.147
Air, 5%	N/A	N/A	0.050

$$\text{Total paste volume} = 0.338 \text{ m}^3$$

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.72

Fine aggregate density: 2.68

*Fine aggregate: 40% 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, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.)

Aggregate volume = $1.000 \text{ m}^3 - 0.338 \text{ m}^3 = 0.662 \text{ m}^3$

Fine aggregate volume = $0.40 \times 0.662 \text{ m}^3 = 0.265 \text{ m}^3$

Fine aggregate mass = $0.265 \text{ m}^3 \times 2.68 \text{ Mg/m}^3 = 0.710 \text{ Mg} = 710 \text{ kg}$

Coarse aggregate volume = $0.662 \text{ m}^3 - 0.265 \text{ m}^3 = 0.397 \text{ m}^3$

Coarse aggregate mass = $0.397 \text{ m}^3 \times 2.72 \text{ Mg/m}^3 = 1.080 \text{ Mg} = 1,080 \text{ kg}$

STEP 6. Prepare laboratory trial mixtures. Don't forget the following:

STEP 6

- Control silica fume dispersion, see Figure 6.2 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:

STEP 7

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

EXAMPLE 3 HIGH-STRENGTH CONCRETE COLUMNS, Figure 6.5.**FIGURE 6.5.**

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

STEP 1

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

STEP 2

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

STEP 3. Select starting mixture. From Table 6.2 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	0.231

STEP 4

STEP 4. Determine volume of air required. None. Assume that 1.5% will be entrapped in this mixture.

STEP 5

STEP 5. Incorporate local aggregates. First, determine the volume the paste will occupy, as shown in the following table: (Remember: Specific gravity in SI units is expressed as Mg/m³.)

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 = 0.231)	151	1.00	0.151
Air, 1.5%	N/A	N/A	0.015

$$\text{Total paste volume} = 0.393 \text{ m}^3$$

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.68

Fine aggregate density: 2.60

*Fine aggregate: 38% 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, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.)

Aggregate volume = $1.000 \text{ m}^3 - 0.393 \text{ m}^3 = 0.607 \text{ m}^3$

Fine aggregate volume = $0.38 \times 0.607 \text{ m}^3 = 0.231 \text{ m}^3$

Fine aggregate mass = $0.231 \text{ m}^3 \times 2.60 \text{ Mg/m}^3 = 0.601 \text{ Mg} = 601 \text{ kg}$

Coarse aggregate volume = $0.607 \text{ m}^3 - 0.231 \text{ m}^3 = 0.376 \text{ m}^3$

Coarse aggregate mass = $0.376 \text{ m}^3 \times 2.68 \text{ Mg/m}^3 = 1.008 \text{ Mg} = 1,008 \text{ kg}$

STEP 6

STEP 6. Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 6.2 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

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

For projects with complex requirements and where portland cement and silica fume may be used in conjunction with either fly ash or slag, 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 define 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, this exact mixture will not have been prepared 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 on-line 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: <http://ciks.cbt.nist.gov/cost>.

Producing concrete containing silica fume is not significantly different from producing concrete without silica fume. The manner in which 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.

7.1	General Considerations	80
7.2	Bulk Densified Silica Fume	84
7.2.1	Shipping	84
7.2.2	Storage Requirements	86
7.2.3	Unloading	90
7.2.4	Batching	92
7.2.5	Mixing	94
7.2.6	Other Concerns	96
7.3	Bagged Densified Silica Fume	97
7.3.1	Shipping	98
7.3.2	Storage Requirements	99
7.3.3	Unloading	99
7.3.4	Batching	100
7.3.5	Mixing	102
7.3.6	Other Concerns	103

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/m³, in a relatively large amount of concrete, 2,400 kg/m³ 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 form of silica fume that is being used — bulk densified or bagged densified. Figure 7.1 shows which section of the chapter covers each product form.

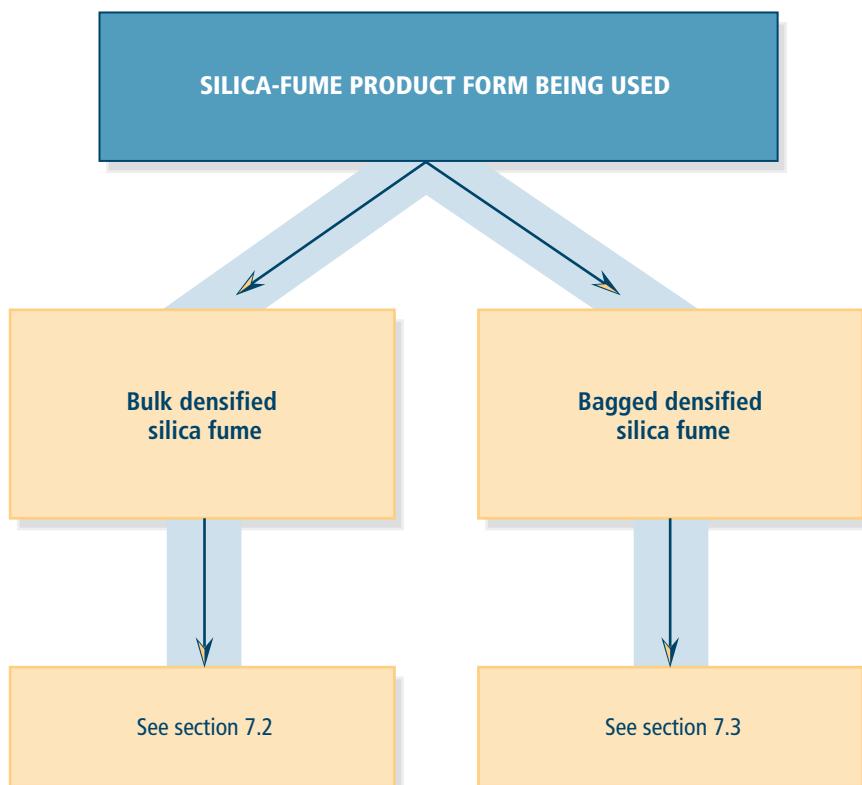


FIGURE 7.1. Organization of Chapter 7. Select the section of the chapter that discusses making concrete with the product form of silica fume that you have selected.

7.1 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. 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 better 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% 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 C 94, *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.

- **Concrete temperature.** Controlling concrete temperature for silica-fume concrete may be a problem, particularly in concretes with low w/cm. If the water content is low enough, there simply may not be enough water for chilled water to be effective in reducing concrete temperature. If a project has stringent concrete temperature controls, it may be necessary to use chipped ice or liquid nitrogen to meet the requirements.
- **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.** Silica-fume concrete may be more difficult to wash out of a mixer. Recommendations on washing out after a silica-fume concrete load from the National Ready Mixed Concrete Association are given in Figure 7.2.

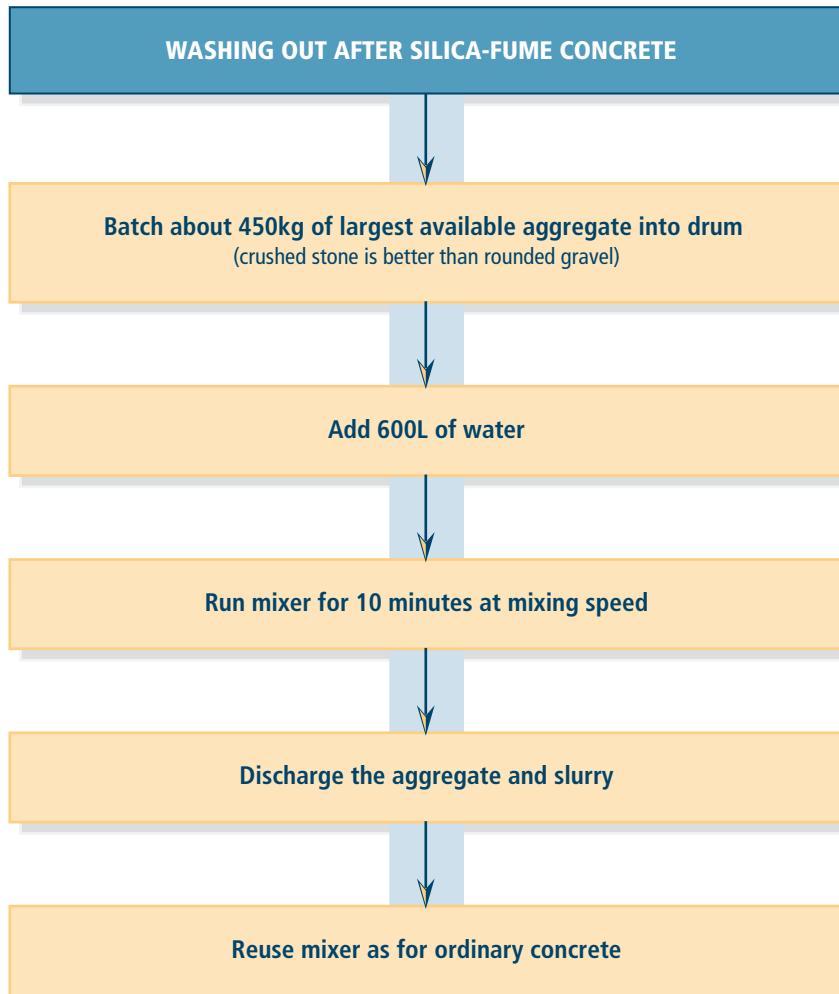


FIGURE 7.2. Recommendations for washing out truck mixers after silica-fume concrete. Based upon the NRMCA *Truck Mixer Driver's Manual* (1999).

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 of about 400 to 720 kg/m³ while portland cement as delivered will be about 1,500 kg/m³. This difference will require some adjustments in storing and handling the material.

7.2.1 Shipping

Bulk densified silica fume is typically shipped in the same types of bulk tankers used to ship cement or other pozzolans. Figure 7.3 shows a typical tanker unloading at a concrete plant. These tankers will have the following characteristics:

- Volume: 40 m³
- Capacity of material: Approximately 20 Mg

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.

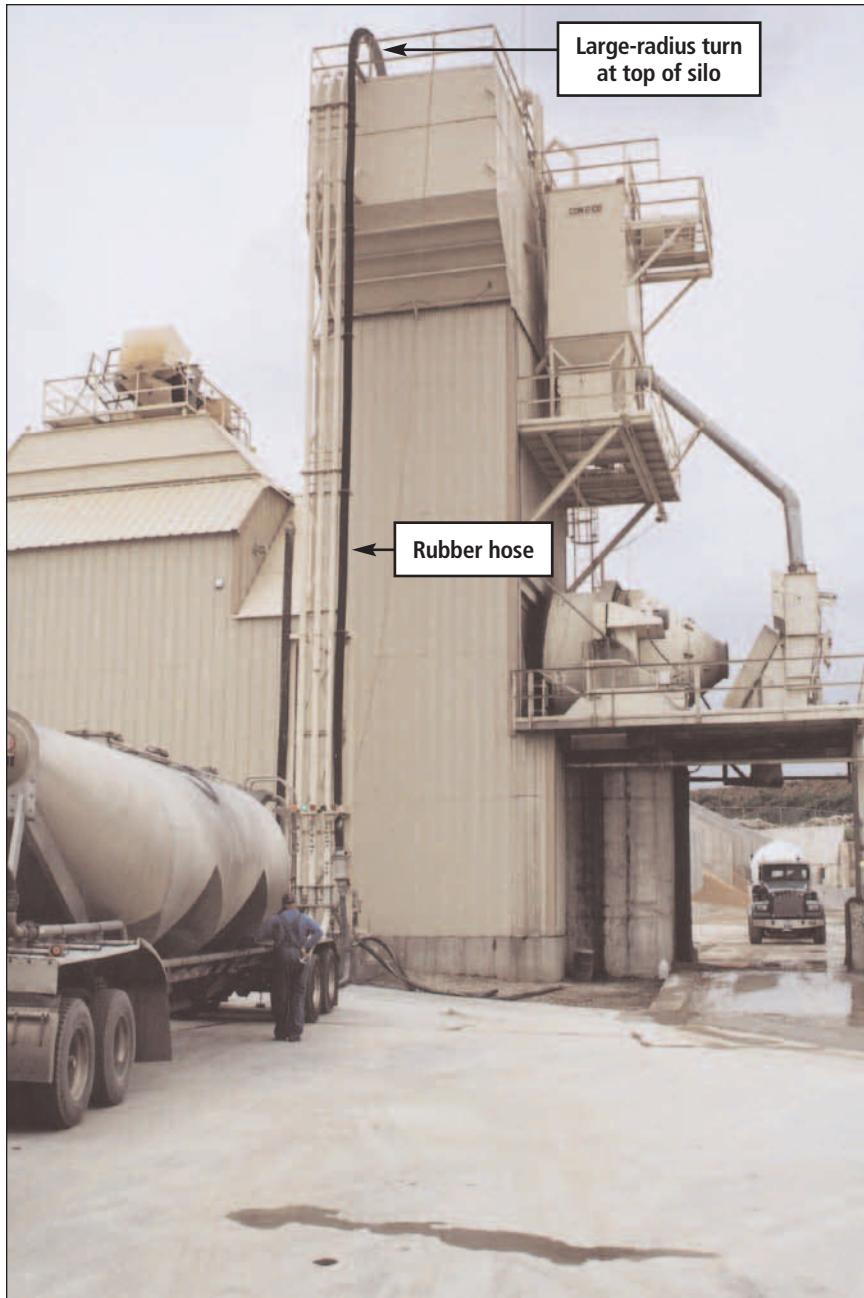


FIGURE 7.3. Unloading bulk densified silica fume into a silo. Note rubber hose and large-radius turn at top of silo.

7.2.2 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 m³ 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.
(Note that 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 m² 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. Figure 7.4 summarizes 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 to the extent 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 7.4B shows two options for connecting the rubber fill hose to the top of a silo. Both options have been successfully used. Note that running the rubber hose directly into the silo (Option B) may cause difficulties in weather proofing 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 eliminated.

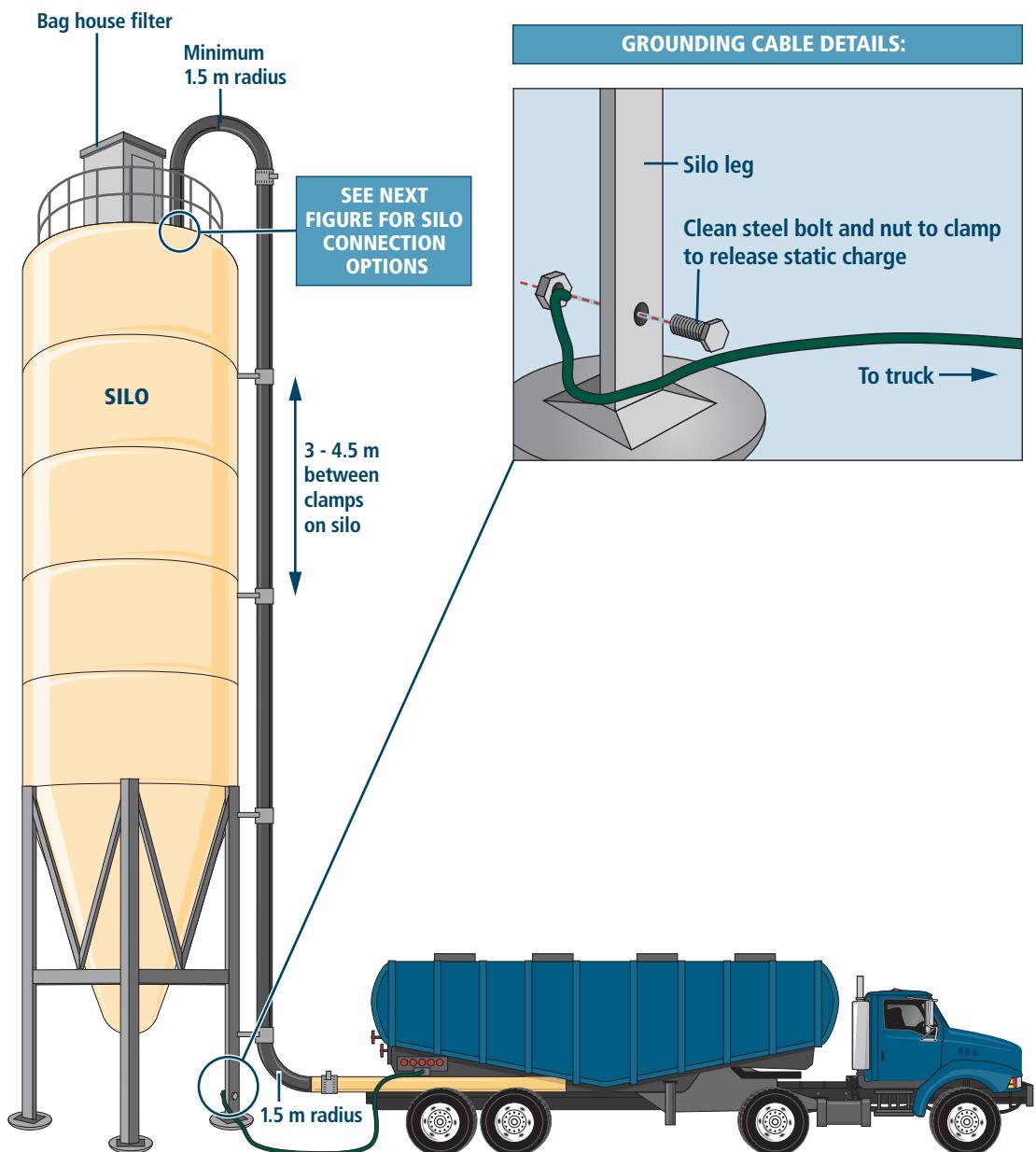
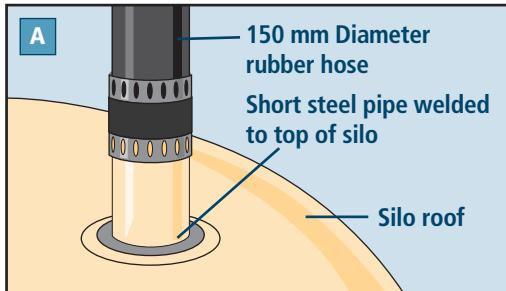
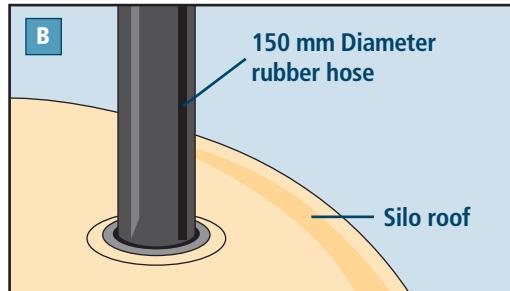


FIGURE 7.4A. Recommendations for silo for storage of bulk densified silica fume. Also note grounding recommendations for unloading. See Figure 7.4B for options for connecting the rubber hose to the top of the silo.

SILO CONNECTION OPTIONS:

OPTION "A" - Rubber hose connected
to steel pipe



OPTION "B" - Rubber hose directly
into silo

FIGURE 7.4B. Options for connecting the rubber silica-fume fill hose to the top of the storage silo.



FIGURE 7.4C. Rubber fill hose connected to steel pipe on silo top. Note support frame for rubber hose being fabricated.

7.2.3 Unloading

Unloading a tanker of bulk silica fume can be a routine operation or a several hour disaster. 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 7.2.2 regarding the fill pipe for the silo. Once the physical configuration is correct, here is a check list 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 bag house filter is clean and operational. If the silo back pressure exceeds 35 kPa, either the rubber hose or the bag house 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.

Figure 7.5 shows a tanker unloading at a concrete plant.



FIGURE 7.5A. Rubber hose used to transfer silica fume from tanker to producer's silo.



FIGURE 7.5B. Connecting rubber hose from tanker to rubber fill hose of silo.

7.2.4 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 weight the correct amount of silica fume. Even if a plant is operating within the tolerances established by ASTM C 94, 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 C 94 and present no problems. If there are any questions regarding the accuracy of a plant, check with the 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 and along with 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.

7.2.5 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% 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 7.1 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 any extra mixing. Make any such adjustments on the basis of concrete results obtained. As is discussed in Section 7.1, mixer uniformity testing may be of assistance, but don't rely entirely on the results obtained from such testing.

7.2

BULK DENSIFIED SILICA FUME

TABLE 7.1

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!**

7.2.6 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.

7.3

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 was originally available in 22.7 kg bags, which were not particularly user friendly. In an effort to make the bags easier to work with, suppliers of silica fume now supply the material in 11.4 kg “repulpable” or “shreddable” bags. Since the introduction of these bags, more than 800,000 m³ 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 7.6. The bags are designed to disintegrate through a combination of wetting and grinding the paper during concrete mixing.



FIGURE 7.6. Adding repulpable bags of densified silica fume directly to truck mixer. See Section 7.3 for precautions regarding unopened bags. Note the use of a dust mask and safety glasses. See Chapter 9 for personal safety recommendations.

7.3

BAGGED DENSIFIED SILICA FUME

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.

7.3.1 Shipping

These bags are usually shrink wrapped on a pallet (Figure 7.7) and shipped by appropriate means depending upon the volume of material ordered.



FIGURE 7.7. Shrink-wrapped bagged silica fume in storage.

7.3

BAGGED DENSIFIED SILICA FUME

7.3.2 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.

7.3.3 Unloading

Use whatever means is typically used for handling palletized materials.

7.3.4 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 7.3.6, 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 7.8 shows bagged silica fume being emptied into a truck mixer. Recommendations for adding bags either unopened or opened are given in Table 7.2. Note that the instructions vary slightly depending upon whether a central mix plant or a batch plant is being used.



FIGURE 7.8. Emptying a bag of densified silica fume into a truck mixer.

7.3

BAGGED DENSIFIED SILICA FUME

TABLE 7.2

RECOMMENDATIONS FOR BATCHING BAGGED SILICA FUME	
USING UNOPENED BAGS CENTRAL MIX PLANT Adding bags to central mixer with other ingredients	USING OPENED BAGS CENTRAL MIX PLANT OR TRUCK MIXERS Adding silica fume through the plant
<ul style="list-style-type: none">■ 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.	<ul style="list-style-type: none">■ 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 Adding bags into truck after concrete is dropped into truck	CENTRAL MIX PLANT OR TRUCK MIXERS Emptying bags into truck after concrete is dropped into truck
<ul style="list-style-type: none">■ 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.	<ul style="list-style-type: none">■ 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 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 7.3.5

LIMIT YOUR LOAD SIZE:
See recommendations in Section 7.3.5

7.3.5 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 C 94 as 63% 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 7.1 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 any extra mixing. Make any such adjustments on the basis of test results for the concrete. As is discussed in section 7.1, mixer uniformity testing may be of assistance, but don't rely entirely on the results obtained from such testing.

7.3.6 Other Concerns

The Silica Fume Association 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 water-cementitious materials ratio, 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 really very 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 7.2.

[Return to Table of Contents](#)

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 flat work 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 actually 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.

8.1	General Considerations	107
8.1.1	Coordination	107
8.1.2	Preplacement Considerations	108
8.1.3	Formed Silica-Fume Concrete	109
8.2	Concrete Drying	110
8.2.1	Bleeding	110
8.2.2	Surface Drying	111
8.2.3	Results of Drying	114
8.2.4	Protecting Against Drying	117
8.3	Placing and Consolidating	121
8.4	Finishing Bridge Decks	122
8.4.1	Determine the Degree of Finishing Required	124
8.4.2	Conduct a Preplacement Conference	124
8.4.3	Conduct a Trial Placement	124
8.4.4	Surface Preparation for Overlays	125
8.4.5	Apply Bond Coat	126
8.4.6	Place the Concrete	127
8.4.7	Consolidate and Finish the Concrete	128
8.4.8	Texture the Surface	129
8.4.9	Protect and Cure	131

8.5	Finishing Parking Structures and Other Flatwork	133
8.5.1	Determine the Degree of Finishing Required	135
8.5.2	Conduct a Preplacement Conference	135
8.5.3	Conduct a Trial Placement	136
8.5.4	Place and Consolidate the Concrete	137
8.5.5	Perform Initial Bull Floating	138
8.5.6	Allow Concrete to Finish Bleeding and Gain Strength	139
8.5.7	Perform Final Floating and Troweling	139
8.5.8	Apply Surface Texture	140
8.5.9	Apply Intermediate Cure	142
8.5.10	Apply Final Cure	142
8.6	Curing	144
8.6.1	Silica Fume Association Recommendations	144
8.6.2	Curing Affects the Surface Durability	145
8.6.3	Curing Versus Protection	145
8.6.4	Curing and Cracking	146
8.6.5	Winter Protection	147
8.7	Precast Concrete	148
8.8	Miscellaneous Concerns	149
8.8.1	Cutting Joints	149
8.8.2	Stressing Post-Tensioning Strands	149
8.8.3	Power Troweled Floors	149
8.8.4	Painting After Curing	150

8.1 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:

8.1.1 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 40 to 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 in this situation — 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 the screeding and bull floating operations. 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.
- **Stickiness.** Finishers frequently report that silica-fume concrete is “sticky” and difficult to work with. Experience has shown that stickiness may result from the interaction of the silica fume and the chemical admixtures (water reducers and supers) that are in the concrete. One approach is simply to substitute one chemical admixture for another of a different chemistry. Another approach is to remove about one-third of the super and replace it by 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 of the fine aggregate. 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. See additional discussion of stickiness in Section 6.5.

8.1.2 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:

- **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. 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.
- **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.
- **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.
- **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 what the consequences may be. This is also an opportunity to determine how well different protection schemes will work.

8.1.3 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 a silica-fume concrete with a high dosage of superplasticizer, don't forget to consider the form pressures from the fluid concrete.

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. Note that the descriptions and recommendations in this section apply to concrete with and without silica fume.

8.2.1 Bleeding

Because of the very high surface area of silica fume that tends to absorb 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 concert during finishing. Drying can also lead to plastic crusting and, eventually, plastic shrinkage cracking.

8.2.2 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 8.1. 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 $1.0 \text{ kg/m}^2/\text{hr}$, 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: $0.5 \text{ kg/m}^2/\text{hr}$.

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.

However, it is important to look at this approach to estimating evaporation a little more closely. Table 8.1 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.

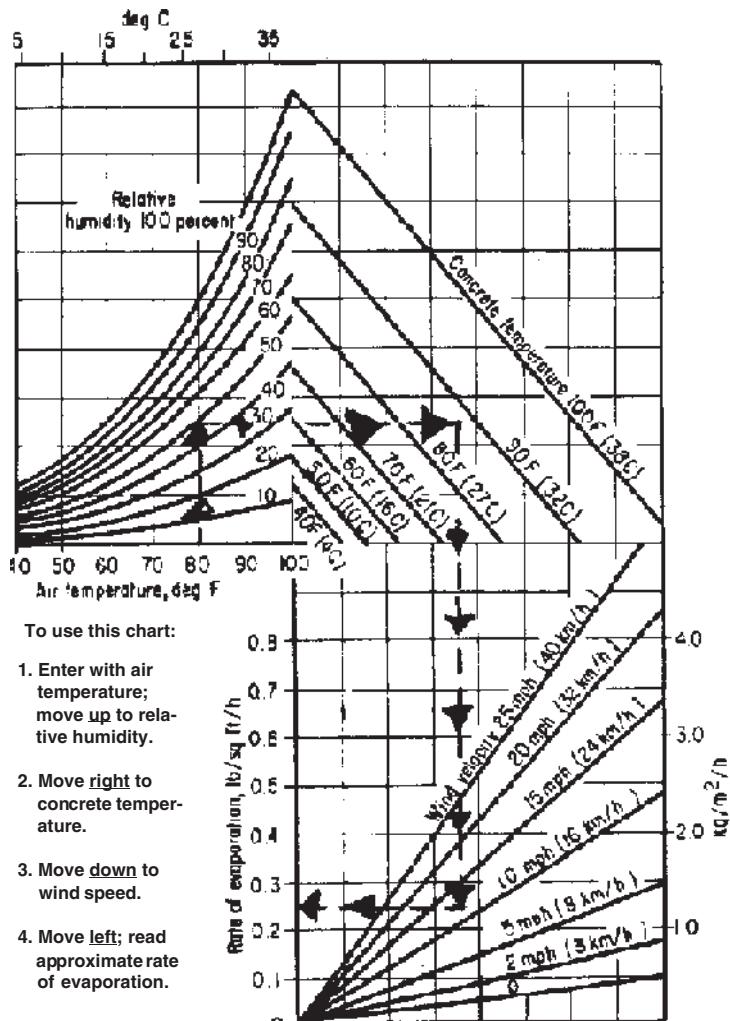


FIGURE 8.1.
ACI evaporation estimation chart.
Source: ACI 308R,
Guide to Curing
Concrete.

TABLE 8.1

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/m²/hr. Apply a little common sense and look at the particulars of the actual project site. Is the placement in direct sun, is the wind increasing, is the humidity high enough to make workers uncomfortable? Remember, the more uncomfortable workers are personally from the temperature and humidity, the less likely that the concrete will dry out. **Don't forget — 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 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.

8.2.3 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 8.2. 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.

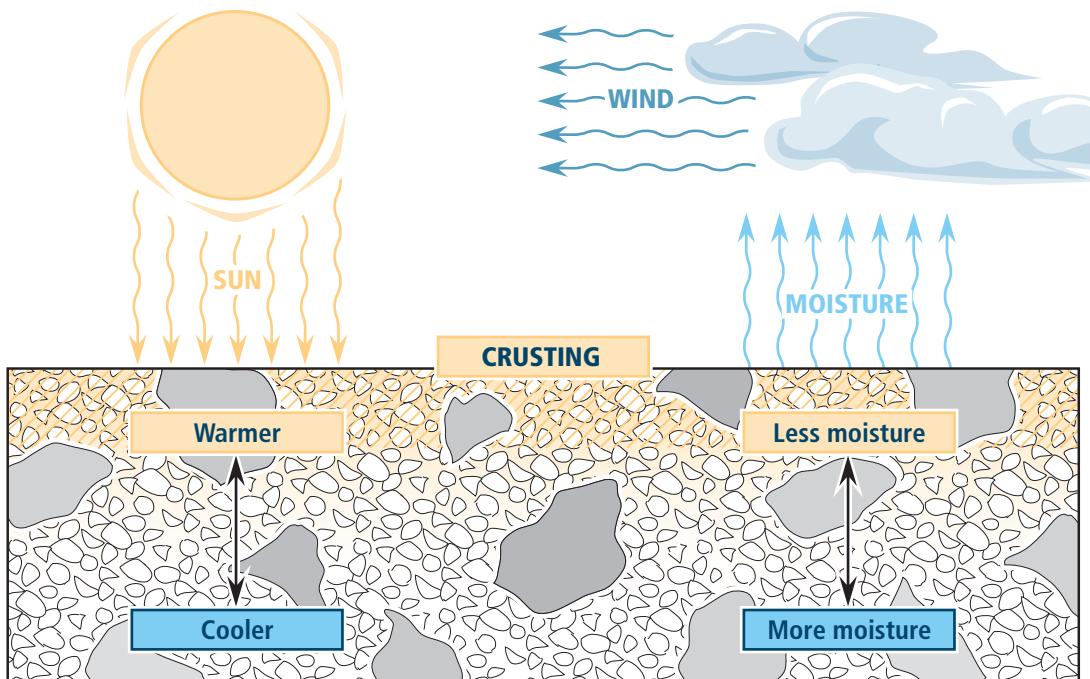


FIGURE 8.2. Crusting of concrete surface. Under some circumstances, crusting may lead to plastic cracking.

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 8.3 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 8.3. Plastic shrinkage cracks in silica-fume concrete.

When does the drying leading to plastic crusting or plastic shrinkage cracking take place? Look at the typical finishing procedure presented in Table 8.2. The time when the concrete is most likely to dry and cause 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 in a less durable surface.

TABLE 8.2

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.

8.2.4 Protecting Against Drying

Table 8.3 presents some of the commonly recommended approaches for protection against drying. Of all 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 8.3

APPROACHES FOR PREVENTING PLASTIC CRUSTING AND PLASTIC SHRINKAGE CRACKING	
■ One pass finishing	
■ Synthetic fibers	
■ Cool concrete	
■ Dampen sub grade	
■ Erect wind breaks	
■ Erect sunshades	
■ Use evaporation retarder	
■ Use fogging	
■ Work at night	
■ Cover concrete with plastic between finishing operations	
■ See ACI 308R, <i>Guide to Curing Concrete</i> , for additional recommendations	

■ **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.



FIGURE 8.4A.
Proper fogging of
silica-fume concrete
in a parking structure
to increase humidity
and prevent drying of
the concrete surface.



FIGURE 8.4B.
Fogging equipment
mounted on paving
machine. Note that
fog nozzles are
pointed upward so
moisture is not added
to concrete surface.

Fogging is best accomplished using a nozzle that combines compressed air and a very small amount of water. Figure 8.4 shows a hand-held fogging device being used on a parking structure and 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.

There are frequently concerns expressed by inspectors 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.

- **Evaporation retarders.** These are probably the most abused material in concrete finishing. 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.



FIGURE 8.5.
Applying evaporation retarder to silica-fume concrete to prevent loss of moisture before curing begins.

How are they supposed to be used? Figure 8.5 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.

Because of the nature of the active ingredient in these products, they tend to “slick” up the surface very well and make it very easy to work the surface. But don’t forget that the products are more than 90% water. Working this water into the surface will ultimately result in a less durable concrete.

- **One-pass finishing.** The final 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 8.5.

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 8.1, 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% 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*.

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 8.5.

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 8.6. Note that 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:

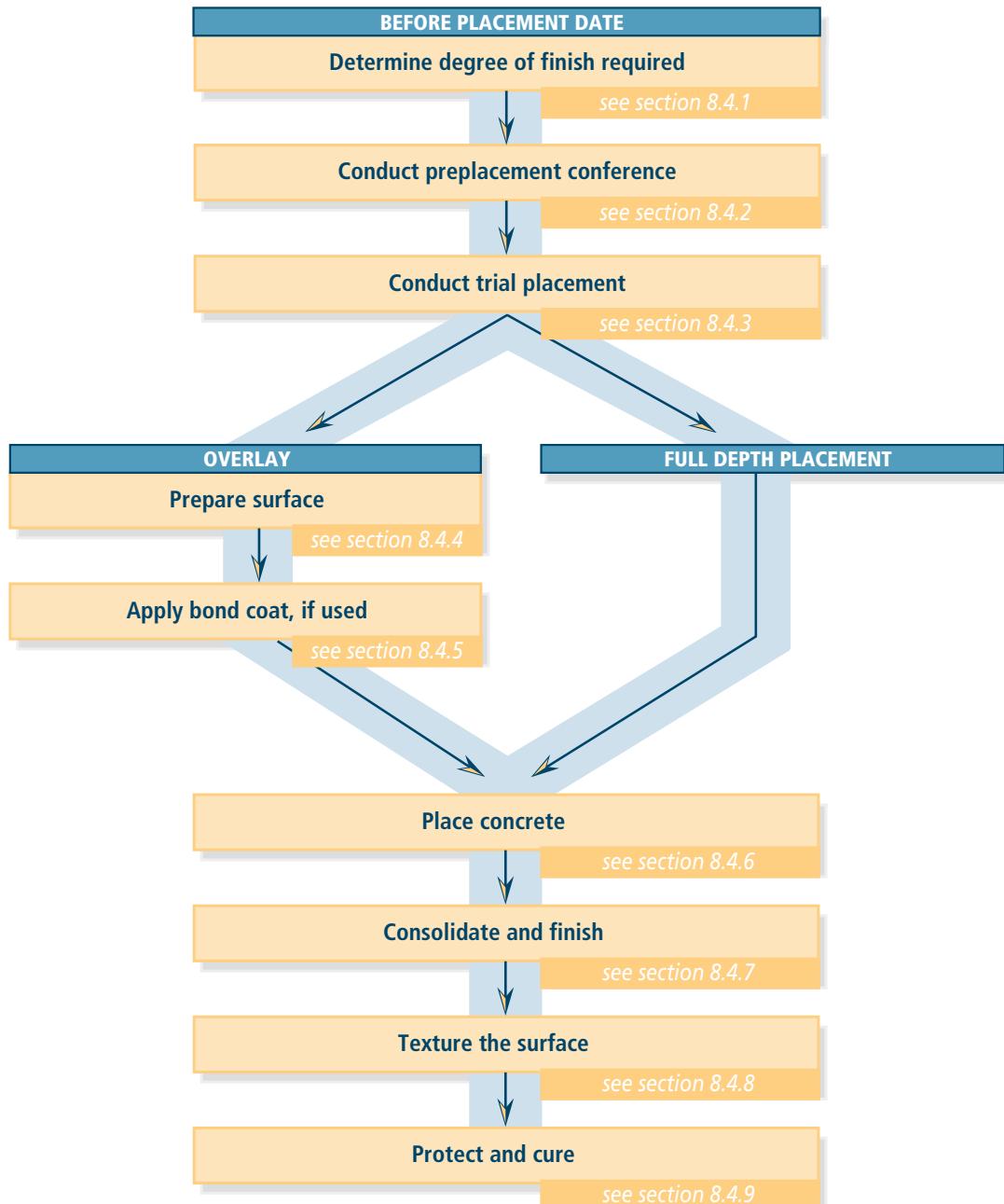


FIGURE 8.6. Finishing steps for concrete bridge decks. The steps are described in the text section noted.

8.4.1 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.

8.4.2 Conduct a Preplacement Conference

As is discussed in Section 8.1.2, 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.

8.4.3 Conduct a Trial Placement

Also as is discussed in Section 8.1.2, 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 having the finishing crew conducting the trial placement be the same crew to be used 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.

8.4.4 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 8.7. 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 8.7. 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 Silica Fume Association. 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.

8.4.5 Apply Bond Coat

Different states specify different requirements for the use of a bond coat between an overlay and the underlying concrete. 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.

8.4.6 Place the Concrete

For almost all bridge decks, concrete placement will be directly from a delivery vehicle or by a pump (Figure 8.8). If pumping, particularly if the pump is located beneath the bridge deck, don't forget the considerations mentioned in Section 8.3 regarding pump boom configuration and air loss.



FIGURE 8.8. 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.

8.4.7 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 8.9). 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 not be allowed to 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.

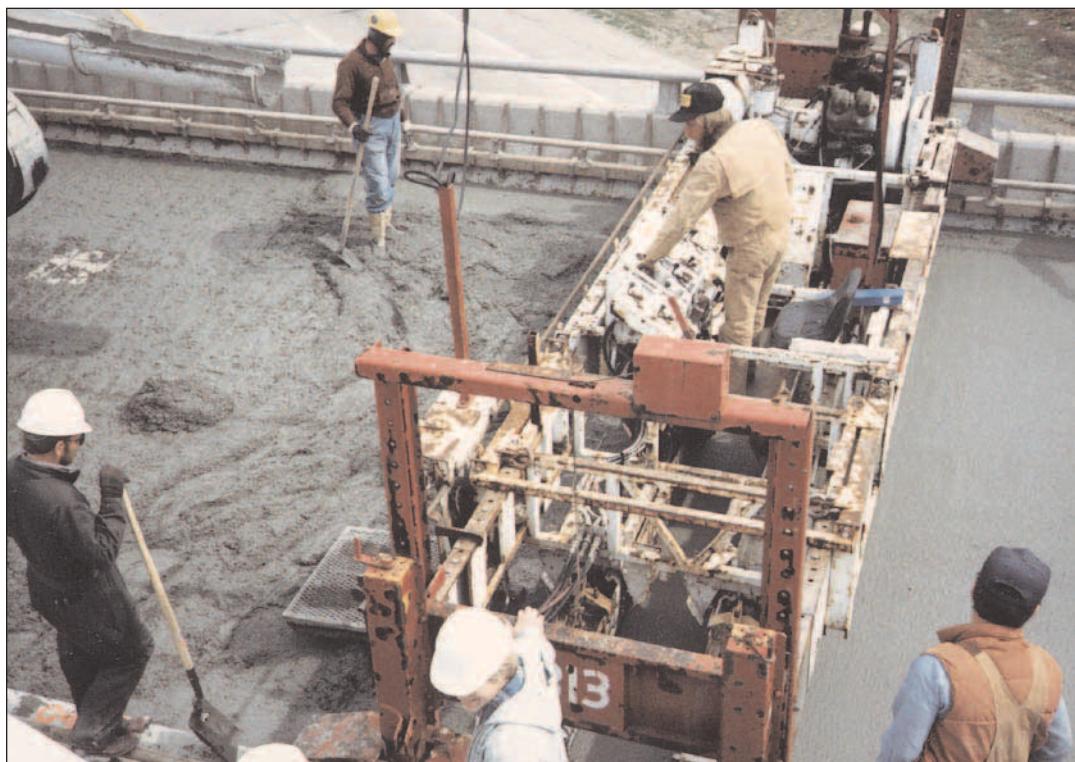


FIGURE 8.9. Bridge deck machine being used to place silica-fume concrete overlay.

8.4.8 Texture the Surface

The requirements for surface texture vary from state to state. Figure 8.10 shows a deck being broomed or tined immediately behind the finishing machine. Other states incorporate a drag behind the finishing machine while other 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 8.10A. 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. State DOTs differ in their requirements for texturing of bridge decks — some require brooming, some tining, and some require that the texture be sawn into the concrete after hardening.



FIGURE 8.10B. Applying a tined finish. Note that some DOTs prefer to have the grooves ground in after the concrete has hardened.



FIGURE 8.10C. Surface of a properly tined deck.

8.4.9 Protect and Cure

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 fogging, evaporation retarders, 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 Silica Fume Association recommends that curing be started within 10 to 15 minutes after concrete placement.** 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 any waiting period for the concrete to harden to allow workers to walk on it. This type of curing is shown in Figure 8.11.

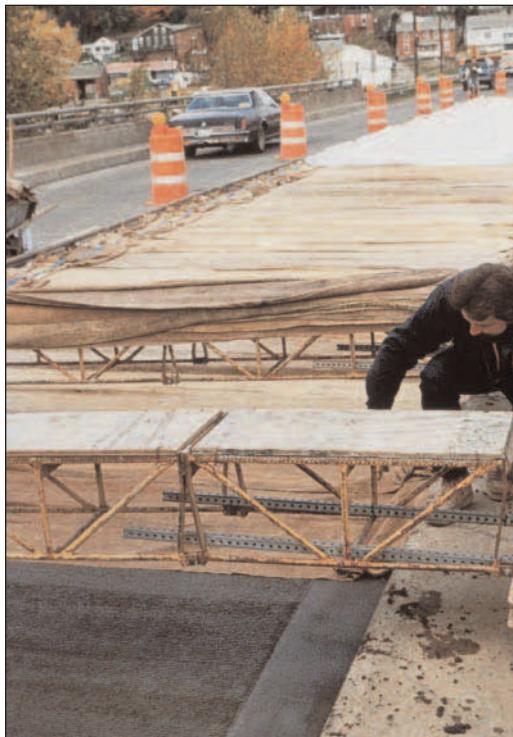


FIGURE 8.11A. Wet curing using burlap and plastic sheeting applied to a silica-fume concrete bridge deck.



FIGURE 8.11B. Curing silica fume bridge deck. Note that curing is following placement and finishing without any delay.

Two frequently asked questions are:

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

The Silica Fume Association 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 8.6 for additional discussion on the importance of curing for silica-fume concrete.



FIGURE 8.11C. Curing silica-fume concrete bridge deck. Applying wet burlap.

This section discusses finishing silica-fume concrete used in flatwork such as parking structures. Finishing bridge decks is covered in Section 8.4.

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 Silica Fume Association 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 8.12. Note that this approach to finishing is actually very similar to that used in bridge decks.

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.



FIGURE 8.12.
One-pass finishing.
Concrete is being
placed, screeded,
floated, textured, and
cured without any
waiting between
operations.

Typical flatwork finishing steps are shown in the flow chart of Figure 8.13. Note that this flow chart describes both conventional and one-pass finishing procedures. Each of the steps in the flow chart is described below:

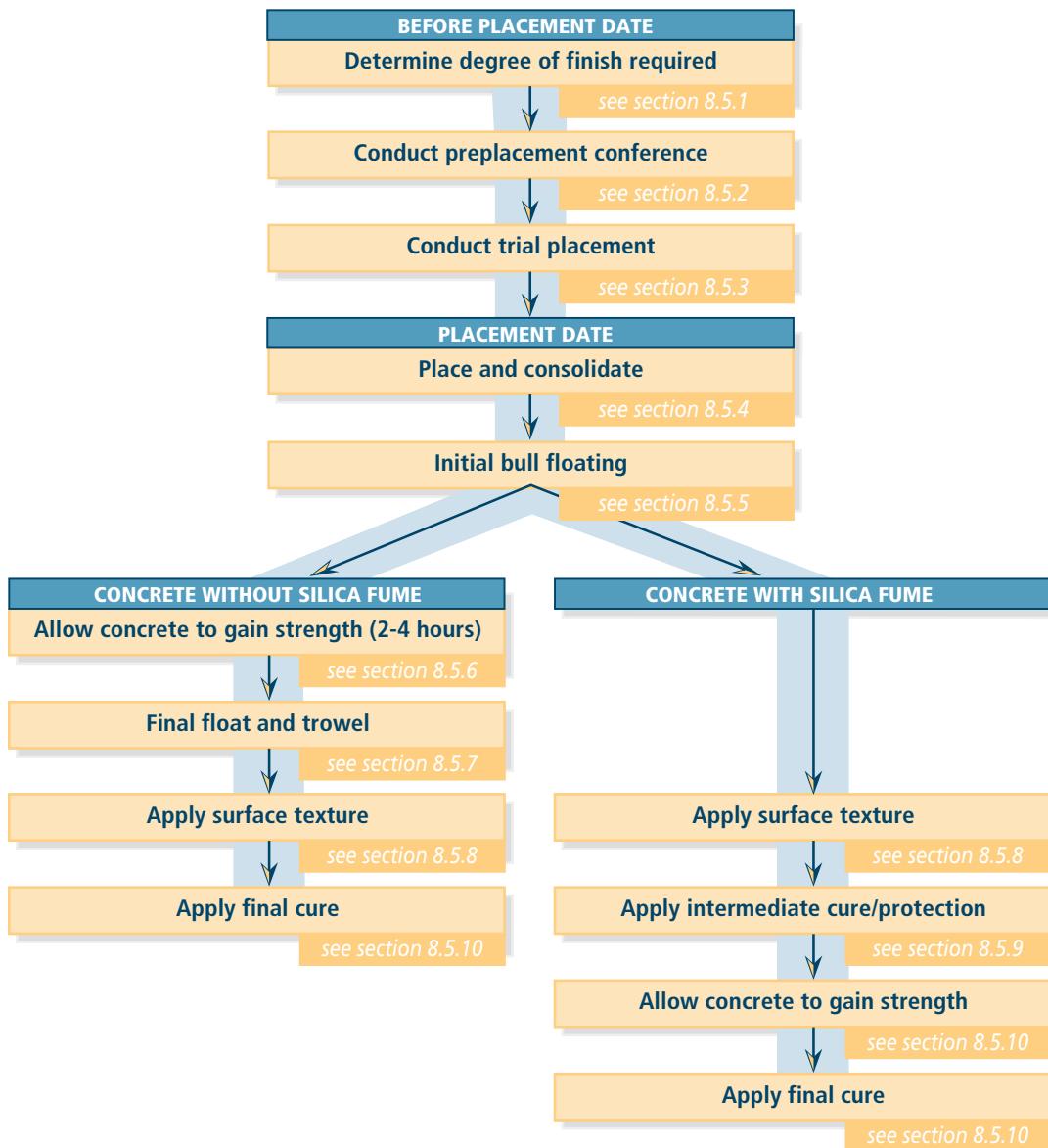


FIGURE 8.13. Finishing steps for concrete flatwork with and without silica fume. The steps are described in the text section noted.

8.5.1 Determine the Degree of Finishing Required

Much concrete flatwork tends to be over finished simply 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 simply 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.

8.5.2 Conduct a Preplacement Conference

As is discussed in Section 8.1.2, 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.

8.5.3 Conduct a Trial Placement

Also as is discussed in Section 8.1.2, 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 having the finishing crew conducting the trial placement be the same crew to be used on the structure. The trial placement must be large enough to allow for realistic finishing techniques to be demonstrated as is shown in Figure 8.14. 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 8.14. Conducting a trial placement using the one-step finishing procedure. Note that the trial is a slab on ground on the actual structure. Note that placing the wire mesh on the bottom of the slab is not recommended practice.

8.5.4 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. By far, the most effective method of consolidating silica-fume concrete flatwork is to use a vibrating screed as shown in Figure 8.15B. 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 8.15A.
Consolidating
silica-fume concrete
using a hand screed.

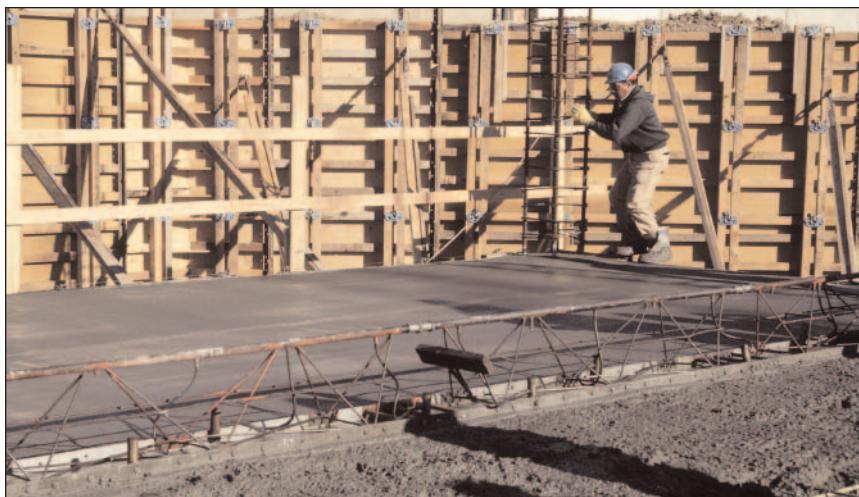


FIGURE 8.15B.
Consolidating
silica-fume concrete
using a vibrating truss
screed.

8.5.5 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 8.16. Note that 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 8.16. 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.

8.5.6 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 completed 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 8.2.)

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.

8.5.7 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. (Note that there may be silica-fume concrete floors where conventional procedures of floating and troweling are required. This process is described in Section 8.8.3.)

8.5.8 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 the troweling process 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 8.17B and 8.17C.



FIGURE 8.17A. 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 8.17B. 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 8.17C. 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.

8.5.9 Apply Intermediate Cure

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 fogging, using evaporation retarder, or applying curing compound. 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.

8.5.10 Apply Final Cure

There is a great deal of evidence available supporting wet curing for silica-fume concrete. The Silica Fume Association 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. Curing is shown in Figure 8.18 and is discussed in more detail in Section 8.6.



FIGURE 8.18A. 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 8.18B. 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 curing compound alone.

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 Silica Fume Association recommendations for curing.

Note that 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 Silica Fume Association is not aware of instances where cracking of structural members has been an issue on a project.

8.6.1 Silica Fume Association Recommendations

- **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 unformed 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.

8.6.2 Curing Affects the Surface Durability

For bridge decks or other flatwork, the usual reason for using silica fume or a ternary blended 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 concretes 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.

8.6.3 Curing versus Protection

Protecting silica-fume concrete flatwork from crusting and plastic shrinkage cracking has already been discussed in Section 8.2. 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 textruing. For other flatwork, curing must begin once the concrete is strong enough to allow workers to walk on it without damaging the surface.

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.

8.6.4 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. Table 8.4 summarizes our recommendations for curing to prevent cracking.

TABLE 8.4

PROTECTING, CURING, AND PREVENTING CRACKING OF SILICA-FUME CONCRETE FLATWORK

MOST CRACKING OF SILICA-FUME CONCRETE FLATWORK CAN BE PREVENTED BY FOLLOWING THESE THREE STEPS:

1. Protect silica-fume concrete while it is still plastic

- Fogging
- Using evaporation retarder
- Covering with plastic sheets
- Applying curing compound

2. Cure silica-fume concrete as soon as possible

- Wet cure for a minimum of 7 days

3. Never allow plastic or hardened silica-fume concrete to dry out until the wet curing has been completed

8.6 CURING

Here are two major findings regarding curing and cracking.

- Whiting and Detwiler (1988), 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) Note that NYSDOT originally specified seven days of wet curing. Because of the success of this approach, they have recently extended their requirement for wet curing to fourteen days.

8.6.5 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.

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.

8.8 MISCELLANEOUS CONCERNS

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

8.8.1 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.

8.8.2 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.

8.8.3 Power 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. In order 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 for protection the concrete, such as fogging or using an evaporation retarder. Just remember — never let the concrete surface dry out while waiting to get back on it.

8.8.4 Painting After Curing

There have been problems applying traffic stripes to silica-fume concrete that has been cured using curing compound. 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.

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

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

9.1	General Considerations and Recommendations	152
9.2	Silica Fume Material Safety Data Sheet	154
9.3	Silica Fume Bag Warning Label	154

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.

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 U. S. law. Examples of equipment are shown in Figure 9.1.
- The Silica Fume Association 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.



FIGURE 9.1A. Dust mask meeting the requirements of 29 CFR 1910.134 and CSA Z94.4-M1982. This mask is recommended for use when working with dry silica fume before it is mixed into concrete in an open, outdoor location. Note that the selection of a mask or respirator must be made on the basis of exposure and environmental conditions. See the following web site for guidance on selecting an appropriate mask: <http://www.cdc.gov/niosh/userguide.html>.



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 MATERIAL SAFETY DATA SHEET

A Material Safety Data Sheet (MSDS) 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 MSDS is the reference to crystalline silicon dioxide. Under California law, any amount of crystalline silicon dioxide must be reported on the MSDS. This particular manufacturer has elected to use a single MSDS 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 and 9.3. The general warnings on the bag are taken directly from the MSDS. 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.”

For Industrial Use Only

Elkem Materials Inc
Health and emergency information - CHEMTRIC (800-424-9300)

and Elkem (412-239-7200)
Product name - Microsilica - CAS Registry #69012-64-2

"Microsilica is of low toxicity. Handling of microsilica does not represent a health risk when usual safety rules are observed. Microsilica is generally considered to be a nuisance dust. High dust concentrations may cause irritation. Microsilica is unlikely to cause harmful effect when handled and stored as advised. Microsilica may contain trace amounts (<1%) of crystalline silica which has been shown to cause silicosis, and has been identified by IARC and NTP as a probable human carcinogen.

Eye protection, Eye flushing facilities and protective gloves are recommended. Ensure adequate ventilation. Wear and appropriate particulate respirator in accordance with 29 CFR 1910.134, or CSA Standard Z94.4-M1982 for dust exposure that may exceed exposure limits. If adequate ventilation is not possible, a self contained breathing apparatus or an air supplied respirator is recommended. Please refer to the product MSDS for more information."

HAZARD RATING



MATERIAL SAFETY DATA SHEET AVAILABLE

ELKEM MATERIALS INC.
800-433-0535
POST OFFICE BOX 266
PITTSBURGH, PA 15230

FIGURE 9.2. Warning label from bagged silica fume.

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 MSDS.

WARNING! SILICA FUME MAY CAUSE IRRITATION.

- Contains silica fume CAS number 69012-64-2.
- 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 and respiratory protection.
- Avoid contact with skin and eyes.
- Wear skin, eye and respiratory protection to avoid contact with dust.

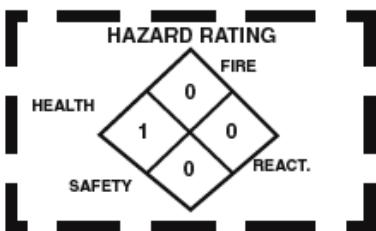
FIRST AID:

Eye:	Immediately flush with large amounts of water. If irritation develops or persists seek medical attention.
Skin:	Wash with soap and water.
Inhalation:	Remove to fresh air. Obtain medical attention as needed.
Ingestion:	Drink large amounts of water. Do not induce vomiting. Obtain medical assistance as needed.

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



A diamond-shaped hazard rating diagram with 'HAZARD RATING' at the top. It has three horizontal bars above and below it. The left side is labeled 'HEALTH', the right side 'FIRE', and the bottom 'SAFETY'. The diamond is divided into four quadrants by a cross. The top-right quadrant is labeled '0', the bottom-right '0', the bottom-left '0', and the top-left '1'.

MATERIAL SAFETY DATA SHEET AVAILABLE

**FOR INDUSTRIAL USE ONLY
KEEP OUT OF REACH OF CHILDREN**

FIGURE 9.3.

Warning label from
bagged silica fume.

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

10.1 American Concrete Institute	158
10.2 ASTM.....	159
10.3 American Association of State Highway and Transportation Officials (AASHTO)	160
10.4 Cited References.....	161

ACI 116R, *Cement and Concrete Terminology*.

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

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

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

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

ASTM C 94, *Standard Specification for Ready-Mixed Concrete.*

ASTM C 192, *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.*

ASTM C 618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.*

ASTM C 989, *Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortar.*

ASTM C 1240, *Standard Specification for Silica Fume Used in Cementitious Mixtures.*

ASTM E 965, *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.*

Available from:

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

AASHTO LRFD Bridge Construction Specifications, First Edition, 1998
(with annual interim updates).

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

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 CITED REFERENCES

Alampalli, S., and Owens, F., 2000, "In-Service Performance of High-Performance Concrete Bridge Decks," *Fifth International Bridge Engineering Conference*, Transportation Research Record 1696, Volume 2, Transportation Research Board, Washington, D.C., pp. 193-196.

Bickley, J. A., Ryell, J., Rogers, C., and Hooton, R. D., 1991, "Some Characteristics of High-Strength Structural Concrete," *Canadian Journal of Civil Engineering*, Vol. 18, No. 5, October, pp. 889.

Burg, R. G., and Ost, B. W., 1994, *Engineering Properties of Commercially Available High-Strength Concrete (Including Three-Year Data)*, Research and Development Bulletin RD104T, Portland Cement Association, Skokie, Illinois, 58 pp.

Forrest, M. P., Morgan, D. R., Obermeyer, J. R., Parker, P. L., and LaMoreaux, D. D., 1995, "Seismic Retrofit of Littlerock Dam," *Concrete International*, Vol. 17, No. 11, November, pp. 30-36.

Holland, T. C., 1998, "High-Performance Concrete: As High as It Gets," *The Concrete Producer*; V. 16, No. 7, July, pp. 501-505.

Holland, T. C., Krysa, A., Luther, M., and Liu, T., 1986, "Use of Silica-Fume Concrete to Repair Abrasion-Erosion Damage in the Kinzua Dam Stilling Basin," *Proceedings, CANMET/ACI Second International Conference on the Use of Fly Ash, Silica Fume, Slag, and natural Pozzolans in Concrete*, Madrid, SP-91, Vol. 2, American Concrete Institute, Detroit, pp. 841-864.

Kosmatka, S., Kerkhoff, B., and Panerese, W., 2002, *Design and Control of Concrete Mixtures*, 14th Edition, Portland Cement Association, Skokie, Illinois.

Leonard, Mark A., 1999, "I-25 Over Yale Avenue — The Thin Solution," *HPC Bridge Views*, No. 3, May-June, p. 2.

Luciano, John J., Nmai, Charles, K., and DelGado, James, R. 1991, "A Novel Approach to Developing High-Strength Concrete," *Concrete International*, Vol. 13, No. 5, pp. 25-29.

10.4 CITED REFERENCES

Luciano, John J., and Bobrowski, G. S., 1990, "Using Statistical Methods to Optimize High-Strength Concrete Performance," *Cement, Admixtures, and Concrete*, Transportation Research Record 1284, Transportation Research Board, Washington, D.C., pp. 60-69.

Miller, R. A., 1999, "From Three Spans to One with HPC," *HPC Bridge Views*, No. 4, July-August, p. 5.

NRMCA, 1999, *Truck Mixer Driver's Manual*, Fourth Edition, NRMCA Publication No. 118, National Ready Mixed Concrete Association, Silver Spring, MD.

Praul, Michael F., 2001, "Curing for HPC Bridge Decks — Bring on the Water!," *HPC Bridge Views*, No. 15, May/June, p. 1.

Waszczuk, C., 1999, "Crack Free HPC Bridge Deck — New Hampshire's Experience," *HPC Bridge Views*, No. 4, July-August, pp. 2-3.

Whiting, D., and Detwiler, R., 1988, "Silica-Fume Concrete for Bridge Decks," *Report 410*, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., 107 pp.

Xi, Yunping, Shing, Benson, Abu-Hejleh, Naser, Asiz, Andi, Suwito, a., Xie, Zhaohui, and Ababneh, Ayman, 2003, *Assessment of the Cracking Problem in Newly Constructed Bridge Decks in Colorado*, Colorado Department of Transportation Report CDOT-DTD-R-2003-3, Denver, Colorado, 136 pp.

APPENDIX 1

PROPORTIONING EXAMPLES IN INCH-POUND UNITS

A.1	Proportioning Examples in Inch-Pound Units	164
A.1	Example 1 – Bridge Deck	164
A.2	Example 2 – Cast-in-Place Parking Structure	167
A.3	Example 3 – High-Strength Concrete Columns	170

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

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

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

[Return to Table of Contents](#)

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 2

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:

STEP 3

Cement	485 lb/yd ³
Fly ash	97 lb/yd ³
Silica fume	20 lb/yd ³
Maximum w/cm	0.41

STEP 4. Determine volume of air required. From Table 6.1 for 1 in. aggregate, the volume of air required for a severe environment is 6%. Because this concrete will not have a compressive strength of over 5,000 psi, do not reduce the air content by 1%.

STEP 4

STEP 5. Incorporate local aggregates.

STEP 5

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

MATERIAL	MASS, lb	SPECIFIC GRAVITY	VOLUME, ft ³
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%	N/A	N/A	1.62

$$\text{Total paste volume} = 8.82 \text{ ft}^3$$

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.68

Fine aggregate density: 2.64

**Fine aggregate: 40% 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, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.)*

Aggregate volume = $27.00 \text{ ft}^3 - 8.82 \text{ ft}^3 = 18.18 \text{ ft}^3$

Fine aggregate volume = $0.40 \times 18.18 \text{ ft}^3 = 7.27 \text{ ft}^3$

Fine aggregate mass = $7.27 \text{ ft}^3 \times 62.4 \text{ lb/ft}^3 \times 2.64 = 1,198 \text{ lb}$

Coarse aggregate volume = $18.18 \text{ ft}^3 - 7.27 \text{ ft}^3 = 10.91 \text{ ft}^3$

Coarse aggregate mass = $10.91 \text{ ft}^3 \times 62.4 \text{ lb/ft}^3 \times 2.68 = 1,825 \text{ lb}$

STEP 6

STEP 6. Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 6.2 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

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

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 1

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 2

STEP 3

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

STEP 4. Determine volume of air required. From Table 6.1 for 1 in. aggregate, the volume of air required for a severe environment is 6%. Because this concrete will have a compressive strength of over 5,000 psi, reduce the air content by 1% and proportion for 5%.

STEP 5**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%	N/A	N/A	1.35

Total paste volume = 9.11 ft³

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.72

Fine aggregate density: 2.68

*Fine aggregate: 40% 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, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.)

$$\text{Aggregate volume} = 27.00 \text{ ft}^3 - 9.11 \text{ ft}^3 = 17.89 \text{ ft}^3$$

$$\text{Fine aggregate volume} = 0.40 \times 17.89 \text{ ft}^3 = 7.16 \text{ ft}^3$$

$$\text{Fine aggregate mass} = 7.16 \text{ ft}^3 \times 62.4 \text{ lb/ft}^3 \times 2.68 = 1,200 \text{ lb}$$

$$\text{Coarse aggregate volume} = 17.89 \text{ ft}^3 - 7.16 \text{ ft}^3 = 10.73 \text{ ft}^3$$

$$\text{Coarse aggregate mass} = 10.73 \text{ ft}^3 \times 62.4 \text{ lb/ft}^3 \times 2.72 = 1,820 \text{ lb}$$

STEP 6. Prepare laboratory trial mixtures. Don't forget the following:

STEP 6

- Control silica fume dispersion, see Figure 6.2 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:

STEP 7

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

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

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:

STEP 2

- Maximum size of coarse aggregate is $\frac{1}{2}$ 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:

STEP 3

Cement	800 lb/ft ³
Fly ash	175 lb/ft ³
Silica fume	125 lb/ft ³
Maximum w/cm	0.231

STEP 4. Determine volume of air required. None. Assume that 1.5% will be entrapped in this mixture.

STEP 4

STEP 5. Incorporate local aggregates.

STEP 5

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 = 0.231)	254	1.00	4.07
Air, 1.5%	N/A	N/A	0.41

Total paste volume = 10.58 ft³

Second, calculate aggregate volumes and masses:

Coarse aggregate density: 2.68

Fine aggregate density: 2.60

**Fine aggregate: 38% 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, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.)*

$$\text{Aggregate volume} = 27.00 \text{ ft}^3 - 10.58 \text{ ft}^3 = 16.42 \text{ ft}^3$$

$$\text{Fine aggregate volume} = 0.38 \times 16.42 \text{ ft}^3 = 6.24 \text{ ft}^3$$

$$\text{Fine aggregate mass} = 6.24 \text{ ft}^3 \times 62.4 \text{ lb/ft}^3 \times 2.60 = 1,012 \text{ lb}$$

$$\text{Coarse aggregate volume} = 16.42 \text{ ft}^3 - 6.24 \text{ ft}^3 = 10.18 \text{ ft}^3$$

$$\text{Coarse aggregate mass} = 10.18 \text{ ft}^3 \times 62.4 \text{ lb/ft}^3 \times 2.68 = 1,702 \text{ lb}$$

STEP 6

STEP 6. Prepare laboratory trial mixtures. Don't forget the following:

- Control silica fume dispersion, see Figure 6.2 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

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 PROCEDURE

TABLE A.1

	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 @ 28 days	10,000 psi @ 28 days	> 5,400 psi @ 28 days	6,000 psi @ 28 days	5,000 psi @ 28 days 6,000 psi @ 90 days
Rapid chloride test, coulombs	N/A	303 @ 1 year 258 @ 2 years	< 1,600	N/A	N/A
Other requirements	Pumpable, 57 stories	N/A	Minimize plastic and drying shrinkage cracking	100 lb/cyd of steel fibers to increase toughness	Max delivered < 70°F, Max @ 48 hr < 100°F, Pumpable, early strength for form removal
Entrained air (Note 2)	N/A	N/A	6.50%	8 to 10% as delivered 4 to 6% in place	2 to 6%
Slump	> 10 in.	4 in.	Unknown	2 to 4 in.	Unknown
Maximum aggregate size	½ in.	¾ in.	¾ in.	⅜ in.	1 in.
Cement, lb/cyd	685	532	500	682	391
Fly ash, lb/cyd	0	0	135, Class F	0	150, Class F
GGBFS, 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
<p>Note 1. Strength shown is $f'c$. Add appropriate overdesign for mixture development.</p> <p>Note 2. Allowed reduction in air content for strength above 5,000 psi has been taken.</p> <p>Note 3. Includes water in HRWRA for mixes with very low w/cm.</p>					

(continued)

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 @ 36 hrs 10,000 psi @ 56 days	2,000 psi @ 36 hrs 5,700 psi @ 56 days	12,840 psi @ 28 days 16,760 psi @ 3 yrs	15,520 psi @ 28 days 18,230 psi @ 3 yrs	4,700 psi @ 28 days
Rapid chloride test, coulombs	N/A	< 1,000 from cores at 2-10 months	N/A	N/A	1,400–1,600 @ 56 days
Other requirements	N/A	N/A	N/A	N/A	N/A
Entrained air (Note 2)	Unknown	Unknown	N/A	N/A	8.5%
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
GGBFS, lb/cyd	0	0	0	0	0
Silica fume lb/cyd	35	39	40	125	20
Maximum w/cm	0.28	0.35	0.287	0.231	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.					

APPENDIX 2

MATERIAL SAFETY DATA SHEET

A.2 Material Safety Data Sheet 176

**Elkem**Microsilica EMS 965; EMS 970DA
Microlite-P, EMS-960

Page: 1 of 5

DATE PRINTED: November 1, 2004
MSDS No.: EMS-965

1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

Product Identifier: Microsilica EMS-965; EMS-970DA; Microlite-P; EMS-960

Synonyms/Trade Names: Amorphous Silica; Silica Fume; Condensed Silica Fume.

MANUFACTURER:
NUMBERS:Elkem Materials Inc.
P.O. Box 266
Pittsburgh, PA 15230
(412) 299-7200 (800) 433-0535

EMERGENCY TELEPHONE

CHEMTREC (800) 424-9300

2. COMPOSITION/INFORMATION ON INGREDIENTS

	<u>wt. %</u>	<u>CAS Registry #</u>
Silicon Dioxide (SiO_2) amorphous	>85%	69012-64-2
Carbon (C)	<10%	7440-44-0
Aluminum Oxide (Al_2O_3)	<1%	1344-28-1
Calcium Oxide (CaO)	<1%	1305-78-8
Iron Oxide (Fe_2O_3)	<1%	1309-37-1
Magnesium Oxide (MgO)	<1%	1309-48-4
Sodium Oxide (Na_2O)	<1%	1310-73-2
Potassium Oxide (K_2O)	<1%	1310-58-3
Silicon Dioxide (SiO_2) crystalline	<0.5%	14808-60-7

OSHA HAZARDOUS COMPONENTS (29 CFR 1910.1200):

	<u>EXPOSURE LIMITS (mg/m³)</u>	
	<u>OSHA PEL</u>	<u>ACGIH TLV</u>
Silicon dioxide (SiO_2) Amorphous	15 (total) 5 (respirable)	2 (respirable)
Silicon dioxide (SiO_2) Crystalline	0.05 (respirable)	0.05 (respirable)

¹ Elemental analysis of the fume. The manufacturer can provide a more detailed analysis, including other trace elements.

3. HAZARDS IDENTIFICATION

Microsilica is of low toxicity. Handling of microsilica does not represent a health risk when usual safety rules are observed. Microsilica is generally considered to be a nuisance dust. High dust concentrations may cause irritation. Microsilica is unlikely to cause harmful effect when handled and stored as advised. Microsilica may contain trace amounts (<0.5%) of crystalline silica which has been shown to cause silicosis, and has been identified by IARC and NTP as a possible human carcinogen. (See Section 11).

A.2 MATERIAL SAFETY DATA SHEET

MATERIAL SAFETY DATA SHEET



Microsilica EMS 965; EMS 970DA
Microlite-P, EMS-960

Page: 2 of 5

DATE PRINTED: November 1, 2004
MSDS No.: EMS-965

4. FIRST AID MEASURES

INHALATION:

Remove exposed person from dusty area to fresh air.

SKIN CONTACT:

Wash skin with water and/or a mild detergent. Moisturizing cream or lotion may be applied to avoid skin dryness.

EYE CONTACT:

Flush with water/saline solution to ensure no particles remain in eye. See a physician on persistent feeling of discomfort.

INGESTION:

Not applicable.

5. FIRE FIGHTING MEASURES

Microsilica is not combustible and the dust presents no danger of explosion.

Extinguishing media: Not applicable (if involved in fire: cool with water).

6. ACCIDENTAL RELEASE MEASURES

Contain spills or leaks. Transfer spilled material into an appropriate container. Collect spilled material using a vacuum cleaner or wash down with water. Do not use compressed air to maneuver dried material. Avoid generation of airborne dust.

7. HANDLING AND STORAGE

HANDLING:

Avoid handling that generates airborne dust.

STORAGE:

Store in closed containers. Store away from hydrofluoric acid and fluorides.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Eye protection, eye flushing facilities and protective gloves are recommended. Ensure adequate ventilation. Wear an appropriate particulate respirator in accordance with 29 CFR 1910.134 or CSA Standard Z94.4-M1982 for dust exposure that may exceed exposure limits. If adequate ventilation is not possible, a self contained breathing apparatus or an air supplied respirator is recommended.



Microsilica EMS 965; EMS 970DA
Microlite-P, EMS-960

Page: 3 of 5

DATE PRINTED: November 1, 2004

MSDS No.: EMS-965

MATERIAL SAFETY DATA SHEET

8. EXPOSURE CONTROLS/PERSONAL PROTECTION (Con't)

OCCUPATIONAL EXPOSURE LIMITS (OSHA and ACGIH):

	8hr TWA mg/m ³	
	OSHA PEL	ACGIH TLV
Total inhalable dust	15	10
Respirable dust	5	3
Silicon Dioxide, Amorphous	15 (total)	2 (respirable)
Silicon Dioxide, Crystalline	0.05 (respirable)	0.05 (respirable)

9. PHYSICAL AND CHEMICAL PROPERTIES

Physical State:	Ultrafine amorphous powder (respirable dust), dust forms agglomerates
Color:	Light to dark gray
Odor:	Odorless
Solubility (Water):	Insoluble to slightly soluble.
Melting Point (°C):	Approx. 1230
Solubility (Organic solvents)	Insoluble to slightly soluble.
Specific Gravity (water=1)	2.2-2.3
Bulk density (kg/m ³) approx	150-700 (10-45 lb/ft ³)
Particle size (μm)	Approx 0.5

10. STABILITY AND REACTIVITY

STABILITY:

Microsilica is stable and does not react with water.

MATERIALS TO AVOID:

Avoid contact with hydrofluoric acid and fluorides

HAZARDOUS REACTIONS:

Microsilica reacts with hydrofluoric acid (HF) forming toxic gas (SiF₄).

HAZARDOUS DECOMPOSITION PRODUCTS:

Prolonged heating above 500°C (930°F) will convert amorphous silica to the crystalline phases. See Section 11.

11. TOXICOLOGICAL INFORMATION

ACUTE EFFECTS:

INGESTION: Dust from Microsilica may irritate and dehydrate mucous membranes.

INHALATION: Dust from Microsilica may irritate and dehydrate mucous membranes.

**Elkem**

Microsilica EMS 965; EMS 970DA
Microlite-P, EMS-960

Page: 4 of 5

DATE PRINTED: November 1, 2004
MSDS No.: EMS-965

MATERIAL SAFETY DATA SHEET

11. TOXICOLOGICAL INFORMATION (Con't)

SKIN CONTACT: Dust from Microsilica may cause irritation and dehydration.

EYE CONTACT: Dust from Microsilica may cause irritation and dehydration.

CHRONIC EFFECTS:

Microsilica dust may contain impurities of crystalline quartz (<0.5%). Inhalation of Microsilica dust is considered to entail minimal risk of pulmonary fibrosis (silicosis). Cases of lung fibrosis have been reported among workers exposed to amorphous silica in the ferrosilicon industry. The lung changes have either been transient or may have been caused by simultaneous exposure to crystalline silica (quartz).

Heating Microsilica above 500°C can result in the formation of crystalline SiO₂-modifications (Cristobalite/Tridymite) which may cause silicosis. The formation rate increases with increasing temperature.

Periodic health examinations of persons exposed to the dust are recommended to include: pulmonary examination, spirometry and possibly x-ray.

12. ECOLOGICAL INFORMATION

Microsilica is not characterized as dangerous for the environment.

13. DISPOSAL CONSIDERATIONS

Reuse all product when possible. Dispose of waste Microsilica according to applicable federal, state and local rules for non-hazardous solid waste materials. No special precautions are necessary during repacking. Microsilica is not a listed RCRA Hazardous Wastes (40 CFR 261).

14. TRANSPORT INFORMATION

DOT (DEPARTMENT OF TRANSPORTATION):

Proper Shipping Name: Not regulated
Hazard Class: Not regulated
I.D. Number and Initials: Not regulated
Packing Group: Not regulated
Label(s): Not regulated

15. REGULATORY INFORMATION

OSHA - Hazardous by definition of hazardous communication standard (29 CFR 1910.1200)

TSCA (Toxic Substance Control Act):

Components of this product are listed on the TSCA Inventory

A.2 MATERIAL SAFETY DATA SHEET

MATERIAL SAFETY DATA SHEET



Elkem

Microsilica EMS 965; EMS 970DA
Microlite-P, EMS-960

Page: 5 of 5

DATE PRINTED: November 1, 2004

MSDS No.: EMS-965

15. REGULATORY INFORMATION (Con't)

CERCLA (Comprehensive Response Compensation, and Liability Act):
Microsilica is not listed in 40 CFR 302.4

RCRA (Resource Conservation/Recovery Act):
Microsilica is not a listed hazardous waste.

SARA TITLE III (Superfund Amendments and Reauthorization Act):
311/312 Hazard Categories:
Immediate Health, Delayed Health.
313 Reportable Ingredients:
None.

CALIFORNIA PROPOSITION 65:
This product contains chemical(s) known to the State of California to cause cancer:
Silica, crystalline

16. OTHER INFORMATION

APPLICATION OF MICROSILICA:

For use in refractory compositions, concrete and other systems containing hydraulic cement.

Literature references are available upon request from the manufacturer.

Elkem Microsilica® is a registered trademark owned by Elkem ASA.

The information presented in this material safety data sheet relates to this specific material. It may not be valid for this material if used in combination with any other materials or in any process. It is the user's responsibility to verify the suitability and completeness of this information for the particular use intended.

INDEX

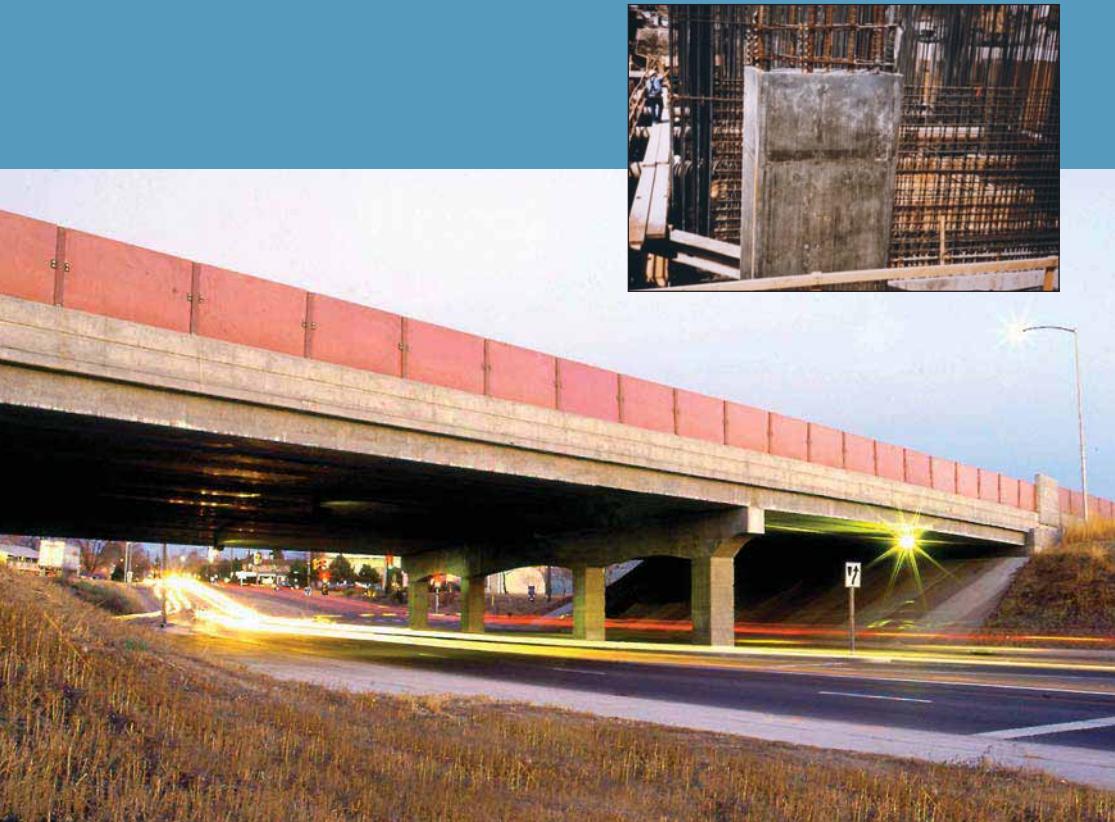
- AASHTO M 307, 42
ACI Guidance, 34, 35, 36
American Association of State Highway and Transportation Officials (AASHTO), 160
American Concrete Institute, 158
ASTM, 159
ASTM C 1240, 38
Bagged densified silica fume, 97-103
batching, 100-101
mixing, 102
other concerns, 103
shipping, 98
storage requirements, 99
unloading, 99
Bulk densified silica fume, 84-96
batching, 92
mixing, 94
other concerns, 96
shipping, 84
storage requirements, 86
unloading, 90
Chemical properties, 8
amorphous, 8
silicon dioxide, 8
trace elements, 8
Comparison with other supplementary cementitious materials, 14
Concrete drying, 110-120
bleeding, 110
protecting against drying, 117
evaporation retarders, 119
fogging, 118
one-pass finishing, 120
results of drying, 114
plastic crusting, 114
plastic shrinkage cracking, 115
surface drying, 111
Constructability, 31-32
one-pass finishing, 31
reduced heat of hydration, 31
shotcrete, 32
use of three cementitious materials, 32
Curing, 144-147
curing affects surface durability, 145
curing and cracking, 146
curing versus protection, 145
Silica Fume Association recommendations, 144
winter protection, 147
Cutting joints, 149
Definition, 2-3
cementitious, 3
pozzolanic, 2
pozzolanic and cementitious, 3
Densified silica fume, 46-47
Finishing bridge decks, 122-132
apply bond coat, 126
conduct a preplacement conference, 124
conduct a trial placement, 124
consolidate and finish the concrete, 128
determine the degree of finishing required, 124
place the concrete, 127
protect and cure, 131
surface preparation for overlays, 125
texture the surface, 129

INDEX

- Finishing parking structures & other
 - flatwork, 133-143
 - allow concrete to finish bleeding and gain strength, 139
 - apply final cure, 142
 - apply intermediate cure, 142
 - apply surface texture, 140
 - conduct a preplacement conference, 135
 - conduct a trial placement, 136
 - determine the degree of finishing required, 135
 - perform final floating and troweling 139
 - perform initial bull floating, 138
 - place and consolidate the concrete, 137
- Fresh concrete, 16-19
 - increased cohesion, 17
 - reduced bleeding, 18
- Formed silica-fume concrete, 109
- Hardened concrete, 20-30
 - acid or other chemical attack, 30
 - chloride damage to reinforcing steel, 28
 - enhanced mechanical properties, 21
 - reduced permeability, 27
 - sulfate attack, 29
 - to increase the span of a bridge, 24
 - to reduce the number of girders for a given span, 25
 - to reduce the section height for a given span, 26
- Health issues, 151
- General considerations & recommendations, 152-153
- Material Safety Data Sheet, 175-180
- Obtaining silica fume, 50
- One-pass finishing, 31
- Painting after curing, 150
- Physical properties, 9-10
 - bulk density, 9
 - particle size, 9
 - specific gravity, 9
 - specific surface, 10
- Placing and consolidating, 121
- Placing, consolidating, finishing, and curing silica-fume concrete, 105
- coordination, 107
- Preplacement considerations, 108
 - acceptable finish, 109
 - concrete mixture, 109
 - finishing approach, 109
 - preplacement conference, 108
 - protecting the concrete, 109
 - test placement, 108
- Power troweled floors, 149
- Precast concrete, 148
- Producing silica-fume concrete, 79
 - general considerations 80-83
 - air entraining, 81
 - batching, 82
 - concrete temperature, 82
 - mixer uniformity, 81
 - mixer wash out procedures, 82
 - mixing, 82
 - remixing, 82
- Production, 4-6
- Properties and reactions in concrete, 7
- Proportioning examples in inch-pound units, 163-172
 - bridge deck, 164
 - cast-in-place parking structure, 167
 - high-strength concrete columns, 170
- Proportioning examples in SI units, 68-76
 - bridge deck, 68
 - cast-in-place parking structure, 71
 - high-strength concrete columns, 74

INDEX

- Proportioning silica-fume concrete, 51
adjusting the mixture, 67
 compressive strength, 67
 concrete stickiness, 67
basic considerations, 52-54
construction considerations, 56
proportioning examples, 68-76, 163-172
 bridge deck, 68, 164
 cast-in-place parking structure,
 71, 167
 high-strength concrete
 columns, 74, 170
project requirements, 55
proportioning procedure, 57-66
general rules, 57
 performance specifications, 57
 prescriptive specifications, 57
step-by-step procedure, 58
recommended starting silica-fume
 concrete mixture proportions
 for various applications
 in inch-pound units, 173, 174
 in SI units, 60, 61
statistical approach for complex
 mixtures, 77-78
Reactions in concrete, 11
chemical contributions, 13
physical contributions, 11
- Recommended starting silica-fume
 concrete mixture proportions for
 various applications
 in inch-pound units, 173-174
 in SI units, 60-61
Reference material, 44
References, 157-162
Shotcrete, 32
Silica Fume Material Safety Data
 Sheet, 154
Specifying silica fume, 48-49
Standard specifications, 37-43
 AASHTO M 307, 42
 ASTM C 1240, 38
 accelerated pozzolanic activity, 40
 bulk density, 41
 density, 41
 loss on ignition, 38
 moisture content, 38
 oversize material, 38
 reactivity with cement alkalies, 40
 silicon dioxide content, 38
 specific surface, 40
 sulfate resistance expansion, 41
 total alkalies, 41
 uniformity requirements, 40
Stressing post-tensioning strands, 149
Warning label, 154-156



This Manual is intended to provide practical information for individuals actually 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 is used in concrete.
- **Chapter 3** describes primary uses of silica fume in concrete.
- **Chapter 4** reviews documents available describing or specifying silica fume from ACI, ASTM, and AASHTO.
- **Chapter 5** presents recommendations for specifying silica fume and silica-fume concrete.
- **Chapter 6** presents detailed information on proportioning concrete containing silica fume for different applications.
- **Chapter 7** presents recommendations for working with silica fume in a concrete plant.
- **Chapter 8** presents recommendations for placing and finishing silica-fume concrete on bridge decks and other flat work.
- **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.

