

# Guide to Using Silica Fume in Precast/Prestressed Concrete Products

Prepared by

**PCI Committee on Durability**

ANTHONY P. CHREST\*  
Chairman

RALPH BROWN  
PAUL C. BREEZE  
JAMES L. F. CLARKE  
THOMAS J. D'ARCY  
TIMOTHY DURNING†  
DAVID B. EDDY  
SURESH S. GAMI  
PHILLIP J. IVERSON

CHARLES MAGNESIO  
DONALD F. MEINHEIT  
FRANK A. NADEAU  
CARL A. PETERSON  
KENNETH REAR  
MORRIS SCHUPACK  
H. CARL WALKER

\* Principal author

† Contributing author

The committee wishes to acknowledge the  
contributions of the following individuals:

MICHAEL S. GEE  
WESTON T. HESTER  
ROBERT PRISBY



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*This PCI Committee report provides guidelines to the industry for producing high performance precast/prestressed concrete products containing silica fume. The mechanism, physical characteristics, benefits, and production aspects of concrete made with silica fume are described. Recommendations are given for measuring, mixing, handling, transporting, placing, finishing, and curing concrete with silica fume additives.*

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## 1.0 INTRODUCTION

The mission of the Durability Committee is to study and report on the durability of precast and prestressed concrete and to specifically develop position papers on the subjects of silica fume and alkali-aggregate reactivity as related to durability, manufacture, and application.

The purpose of this guide is to fulfill the charge for silica fume. The document provides advice to manufacturers of precast/prestressed concrete products in using silica fume. As much as possible, the guide is written in layman's terms and is not intended to be an exhaustive treatment of the subject, nor does it address topics addressed in other PCI publications.

Although high performance concrete containing silica fume has often been used successfully in precast, prestressed structural concrete members, it may be desirable only in some applications. Carefully fabricated, finished, and cured precast concrete without silica fume has exhibited excellent performance in typical uses. Silica fume may be added to decrease permeability. Though generally not needed to provide required strength, silica fume may also be added to enhance strength. The increased care and expense needed to produce defect-free high performance concrete containing silica fume may make it more trouble than benefit.

Silica fume can also be used as a partial substitute for cement in conventional mixes with moderate water-cement ratios ( $0.45 \pm$ ), producing moderate compressive strengths [3000 to 4000 psi (20.7 to 27.6 MPa)]. When silica fume is used in such conventional concrete mixes, the handling behavior will be very similar to conventional concrete.

Under this mix design approach, silica fume can be used to develop low heat of hydration mixes, low shrinkage mixes, low permeability mixes, moderate strength, and moderate modulus mixes. The handling difficulties associated with high performance concretes are largely eliminated. These mixes will still have permeabilities lower than conventional concretes as measured by either ponding or rapid chloride testing.

The purpose of this document is to provide guidelines for consistently producing high performance precast and prestressed concrete containing silica fume that will perform satisfactorily.

## 2.0 DEFINITIONS

**2.1 Silica Fume** — When silicon metal and ferrosilicon alloys are produced in electric furnaces, a fine powder, high in silicon oxide (that is, silica fume), is released into the atmosphere. To maintain a clean environment, this powder is collected, and until recently was treated as a waste material. Now, recognizing that this fine powder can react with portland cement hydration products, the industry adds it to the concrete as a conventional mineral admixture in powder or slurry form. The exact chemical composition of silica fume is controlled by the products being made in the electric furnace and the degree of control exercised by the furnace operator. In general, however, the silica fume is largely silicon dioxide with small amounts of iron or other impurities.

**2.2 Silica Fume Slurry** — The extremely fine particle size of silica fume powder, as much as 100 times finer than cement, greatly complicates handling of silica fume. To facilitate handling, particularly its addition to the concrete mixes, silica fume is commonly blended with water. A conventional or superplasticizing water-reducing admixture may also be added. The blend of silica fume, water, and water-reducing admixture helps keep the silica fume in a stable, slurry form. The water reducer in the slurry offsets the increased mix water demand associated with the silica fume powder.

**2.3 Microsilica** — A descriptive term that refers to *microscopic* or *micron* sized particles of silica. This term has become synonymous with "silica fume." Both the American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM) use the two terms interchangeably. The American Association of State Highway and Transportation Officials (AASHTO) uses the term "microsilica."

**2.4 Dry Densified Silica Fume** — Densification is a process that causes the extremely fine individual particles of silica fume to gather into small clusters of particles. Whereas individual particles of silica fume average about 0.1 micron in diameter, the clusters of particles in densified microsilica range from less than 10 microns up to nearly 1 mm (0.04 in.) in diameter. By clustering the particles together, the average spacing between particles is reduced and the bulk density is increased from less than 20 lbs per cu ft to up to 40 lbs per cu ft (320 up to 640 kg/cu m). The other advantage of densified silica fume is that it handles better and produces less dust when charged into the mixer. In order for densified silica fume to perform as well as the slurry or powder forms in concrete, the clusters must be broken down into the original particles during concrete mixing. This requirement makes longer than normal mixing times necessary to ensure breakdown and dispersion whenever densified silica fume is used.

**2.5 High Performance Concrete** — A concrete with or without silica fume having a water-cement ratio of 0.38 or less, compressive strength at or above 8000 psi (55.2 MPa) and permeability 50 percent lower (by AASHTO T-259<sup>1</sup> or T-277<sup>2</sup> methods) than that of conventional mixes.

## 3.0 GENERAL

### 3.1 How Silica Fume Works

Researchers generally agree that silica fume reacts with portland cement concrete in two ways: by altering the hydration reaction, and by the "microfiller effect." When water is added to portland cement, hydration occurs, forming two primary products. The first product is calcium silicate gel, the "glue" that binds the aggregate together in a concrete mix. The other product formed is calcium hydroxide, which can comprise up to 25 percent of the volume of hydration products. Calcium hydroxide is not of any benefit to concrete and may actually become detrimental at high



levels. When a high amount of calcium hydroxide is present, concrete may be more susceptible to sulfate attack, alkali-aggregate reaction, or efflorescence.

Any pozzolanic material added to concrete alters the hydration reaction. (A pozzolan is defined as a finely divided material that is siliceous or siliceous and aluminous in nature that has little or no cementitious value by itself.) Pozzolans react with the calcium hydroxide and water to produce more aggregate-binding calcium silicate gel while simultaneously reducing the calcium hydroxide content. The net effect is an increase in overall strength and durability.

Researchers discovered that silica fume is actually a "super pozzolan" when compared to other materials such as fly ash. The primary reasons are its high percentage of reactive silica ( $\text{SiO}_2$ ) and its fine particle size. Silica fume that is used in concrete typically has an  $\text{SiO}_2$  content in excess of 85 percent, while fly ashes typically have an  $\text{SiO}_2$  content of 30 to 60 percent. Note that while fly ash additives will increase the strength of hardened concrete over the course of months as it ages, silica fume additives will increase concrete strength in a matter of days.

In addition, the extreme fineness of silica fume when compared to most pozzolans allows it to react almost immediately with the free calcium hydroxide in concrete; conventional pozzolans react more slowly. Knowing the exact  $\text{SiO}_2$  content of the silica fume may be necessary. The behavior of concrete containing silica fume with 85 percent  $\text{SiO}_2$  may differ from that containing silica fume with 96 percent  $\text{SiO}_2$ .

The second mechanism by which silica fume improves concrete is through the so-called "microfiller effect." Most silica fume has an average particle size of 0.1 micrometers, while a typical portland cement has an average particle size of 15 micrometers. The extreme fineness of silica fume allows it to fill the microscopic voids between cement particles. The microfiller effect is credited with greatly reduced permeability and improved paste-to-aggregate bond of silica fume concrete compared to conventional concrete. However, there is little difference in the moisture absorption (a property different from permeability) of silica fume concrete vs. conventional concrete.

The addition of silica fume can also influence the color of both plastic and hardened concrete. Typically, silica fume concrete is darker gray than conventional concrete and it can become almost black, in some cases. This difference is a direct result of the color and amount of the silica fume used. The color of the silica fume depends on carbon content and several other variables. Silica fume from one source could be almost white in color, while that from another may be black. The color of the silica fume apparently has no effect on the other properties of concrete. However, in certain applications, such as parking structures, a darker color concrete will reduce the lighting reflectivity of the floor and ceiling members.

### 3.2 Water Demand

The water demand of concrete can increase dramatically when dry bulk silica fume is added to a conventional concrete mix. Of course, adding water can cause a significant increase in the water-cement ratio which, without mix adjustment, could negate the benefits of adding silica fume.

In the case of increased water demand, however, field and laboratory experience has shown that adding high-range water-reducers (HRWRs) overcomes the water demand problem and assures the full performance from the added silica fume. Many commercial silica fume products, either in slurry or dry densified form, contain HRWRs. When comparing water demand among different commercial silica fume product brands, it is important to account for the effects of the specific HRWR in each silica fume product.

### 3.3 Rheology

Adding silica fume to concrete affects the rheological (flow) properties of the mix. Generally, the rheology of concrete is measured by the familiar slump test (ASTM C143-78<sup>3</sup>), as well as a subjective observation of its ability to flow and consolidate. Silica fume concrete with an HRWR is more cohesive and sticky than conventional concrete. Once again, this cohesiveness is due to its fine particle content. If the silica fume concrete contains superplasticizers, both the shear resistance and the cohesiveness of the concrete will be reduced, and improved flow will result. Silica fume concrete with a measured slump of 5 in. (127 mm) is typically similar in behavior to conventional concrete with a 4 in. (102 mm) slump. However, silica fume concrete placed with a concrete pump usually requires lower pumping pressure. Due to their size and shape, silica fume particles lubricate the concrete mix, but more importantly, the reduced shear resistance and cohesiveness of the mortar will allow the plastic concrete to be pumped with less friction.

### 3.4 Strength Enhancement

Under average plant production conditions, the addition of silica fume to a conventional concrete mix will significantly increase compressive and flexural strengths. The actual strength contribution of the silica fume will vary widely, depending on the other constituents of the concrete mix. Usually, though, silica fume on a weight basis is three to five times more efficient than cement in producing greater strength. For example, by adding 7.5 percent silica fume by weight of cement and a high-range water-reducer (to maintain a constant water-cement ratio), a mix that normally would give 5500 psi (38 MPa) in 28 days can produce a concrete that reaches 9500 psi (65.5 MPa) in 28 days. Adding an additional 7.5 percent silica fume, for a total of 15 percent silica fume by weight of cement, can produce a 28-day compressive strength of 10,300 psi (71 MPa).

In most instances, the addition of silica fume will allow a concrete producer to provide higher compressive and flexural strengths than previously achieved; strengths of 10,000 psi (69 MPa) and above are obtainable. Even higher compressive strengths are possible when a mix is designed to produce high strength concrete with silica fume. Higher strength concrete with or without silica fume brings with it an increase in modulus of elasticity. This increase may not be desirable. Experience has shown that adding 5 to 7.5 percent silica fume by weight of cement will provide a reasonable balance between strength, impermeability and the operations of finishing and curing. Also see Section 4.4.4.



### 3.5 Permeability

Another concrete property affected by the addition of silica fume is permeability. Adding 5 percent silica fume by weight of cement dramatically reduces permeability when compared to the same concrete without silica fume. The improvement makes concrete less vulnerable to attack by chlorides and chemicals. It appears that dosage rates over 5 percent may create more problems than they solve unless strict controls are followed, particularly for double tees, and even then 100 percent success is not assured.

Concrete permeability is generally measured by the rapid determination of the chloride permeability of concrete, ASTM C1202.<sup>4</sup> When measured by this test method, conventional concrete typically gives a reading of 3500 to 4500 coulombs passed. The addition of 7.5 percent silica fume to the same mix will generally give a reading of 250 to 1000 coulombs passed. Latex-modified concrete mixes sometimes used in bridge deck rehabilitation typically give a reading of 100 to 1000 coulombs passed when measured by this method. AASHTO T-259 (90-day ponding)<sup>1</sup> and hydraulic pressure permeability studies have also demonstrated that permeability drops as silica fume is added, though not to the same degree of magnitude.

It should be noted that at the time of this writing, some controversy exists regarding the effectiveness, accuracy, and reproducibility of the ASTM C1202 test in determining the permeability of concrete.<sup>5</sup> Other tests, such as the 90-day ponding test, can also be used to determine relative permeability. ASTM is currently re-evaluating ASTM C1202.

### 3.6 Caution

Adding silica fume to concrete can improve concrete strength, durability, and impermeability, but it is important to recognize that silica fume is not a miracle product. While it can be an extremely useful tool for improving concrete, it cannot cure a poor concrete mix design or other poor concrete practices. Further, it may be desirable to use a conventional concrete mix for comparative economy when the enhanced properties of silica fume concrete are unnecessary or undesirable.

### 3.7 Safety and Health

It is imperative to follow the silica fume supplier's recommendations for the safe handling of silica fume in whatever form it is used. Further information on all topics within Section 3 may be found in Ref. 6. Note that the bibliography in this publication contains references not found in this report.

## 4.0 TYPICAL CHANGES TO A MIX AFTER ADDING SILICA FUME

### 4.1 Higher Paste Volume

Silica fume may be added to a standard mix without any reduction in cement content to achieve higher strength and lower permeability. Silica fume may also be substituted for cement to as much as 1:2 to 1:4 [for each pound (0.45 kg) of

silica fume added, remove 2 to 4 lbs (0.9 to 1.8 kg) of cement] to achieve comparable strength and lower permeability than the conventional mix.

### 4.2 Higher Amount of Fines in the Mix

Over one hundred times finer than cement, silica fume is the finest material normally added to concrete.

### 4.3 Higher Dosages of Superplasticizer

Due to the water demand of the very fine silica fume particles, superplasticizer (HRWR) dosages normally have to be increased by 50 to 100 percent when dry silica fume is added to an already low water-cement ratio mix. As stated above, this increase may be partially or wholly offset if an HRWR is already blended in the silica fume product.

### 4.4 Physical Characteristics

**4.4.1 Plastic Shrinkage** — There is greater potential for plastic shrinkage cracking. See Section 5.8 and the Appendix for further discussion.

**4.4.2 Drying Shrinkage** — There is potential for increased drying shrinkage in the very short term (even overnight for accelerated curing if not protected against moisture loss).

**4.4.2.1 Total Shrinkage** — For long term shrinkage on properly cured specimens, *replacing* cement with silica fume will not increase shrinkage. But if silica fume is *added* to an unreduced volume of cement in a mix, the higher paste volume will lead to increased shrinkage.

**4.4.2.2 Rate of Shrinkage** — The use of silica fume alters the paste structure of concrete, essentially eliminating large capillary pores. However, the total pore volume is usually unchanged — the pores that exist are just much smaller, more evenly distributed, and much less interconnected. Although this altered paste structure is responsible for silica fume concrete's low permeability, it produces conditions that greatly magnify the effect of the surface tension of water. As a portion of the water evaporates from these pores, the surface tension of the remaining water pulls inward, setting up the force that causes concrete to shrink. Because of the finer pore structure of silica fume concrete and the magnification of the pore water surface tension effect, silica fume concrete typically shrinks much quicker than conventional concrete, which can lead to larger or more frequent shrinkage cracks.

**4.4.2.3 Autogenous Shrinkage (Shrinkage Independent of External Influences)** — Some studies suggest that the autogenous shrinkage of silica fume concrete is higher than that of conventional concrete. No studies are known to exist that compare equivalent high performance concrete mixes with and without silica fume to determine the effect of the silica fume. The mechanism



suggested in Section 4.4.2.2 above, with the loss of pore water to the pozzolanic reaction, may increase the rate of shrinkage of silica fume concrete.

**4.4.2.4 Effects of Accelerated Curing** — When radiant heat is used for curing, it will increase the moisture loss on the exposed surface. This increased loss will be especially critical on members such as double tees with a high surface-to-volume ratio. In addition, accelerated curing has been shown to be very effective in producing high performance at early ages with silica fume. The heat obviously accelerates the pozzolanic reaction. Rates of shrinkage during the accelerated curing may then also be accelerated.

#### 4.4.3 Temperature Effects

**4.4.3.1 Higher Heat of Hydration** — When silica fume is mixed on an *addition* basis, the silica fume concrete will produce more heat, and a higher temperature, for the same external temperature compared to conventional concrete. When silica fume is mixed on a *replacement* basis, it can be a useful tool to lower the heat of hydration and the peak temperature of the concrete.

**4.4.3.2 Effect of Higher Superplasticizer Dosage** — Typically, the higher superplasticizer dosage will result in some set retardation of the concrete. This means that the higher heat of hydration occurring when silica fume is mixed on an addition basis in the concrete will occur later in the cycle. This delay will typically result in hotter concrete when curing blankets or sheets are stripped the next morning. Higher thermal stresses can be anticipated when a large surface area, for example a double tee flange, is exposed to cool air upon termination of wet curing and the flange starts to contract due to the temperature decrease. This increased temperature after casting is more of a problem for casting beds outside and not under cover, especially in the colder months.

#### 4.4.4 Higher Strength, Higher Modulus Concrete

— The higher strength and modulus of high performance concrete containing silica fume may have no effect before detensioning, but may have some small effect in the ability of small cracks to propagate during handling and placement at later ages. With higher modulus comes somewhat higher stiffness, which may affect member performance. Though higher paste strength does tend to produce higher modulus and stiffness, the aggregate properties have much greater influence on the modulus of the end product. Hence, increased stiffness of the cement matrix is reflected only to a moderate degree in the hardened concrete. Further, concretes of equal strength, with and without silica fume, will have comparable moduli and stiffnesses.

Further information on all topics within Section 4 may be found in Ref. 6. Note that the bibliography in this publication contains references not found in this report.

## 5.0 RECOMMENDATIONS FOR INCORPORATING SILICA FUME INTO PRECAST PRESTRESSED CONCRETE

### 5.1 General Considerations

If a decision has been made to use high performance concrete containing silica fume to achieve a specific goal — higher strength, increased durability, or both — there are some considerations the precaster should be aware of and some actions that must be taken to achieve the desired goal:

1. Significant improvements in strength or durability cannot be achieved unless generally accepted good concrete production practices are followed. Good practices are those described in technical documents such as the *ACI Manual of Concrete Practice*,<sup>7</sup> in the individual ACI Committee reports, or in the applicable standards of ASTM.

2. Silica fume is not a cure for poor fabrication practices. If good practices are not followed, addition of silica fume to concrete may result in better concrete, but the improvement may not be all that is required or expected. The latter result is more common, particularly in regard to shrinkage cracking and curing.

3. Within the constraints of low water-cement ratio and minimum required water contents, it is desirable to keep the paste content to a minimum. Usually, the use of a proven mix design with the silica fume added on a replacement basis for cement will be the best starting point for changing a mix design.

4. The more silica fume used in a mixture, the more the behavior of the silica fume concrete, while plastic, will differ from a lower paste conventional concrete. Generally, concrete containing up to about 5 percent silica fume by weight of cement will behave about the same as a conventional concrete. Additions of silica fume above 5 percent will cause the concrete to behave less like conventional concrete. The differences in the plastic concrete behavior that may be seen with higher dosage rates of silica fume include increased cohesiveness, delayed setting times, and significantly reduced bleeding. These behaviors can be controlled by good practices; however, the precaster must be prepared beforehand to deal with them.

### 5.2 Measuring

1. Silica fume must be measured with the same degree of accuracy used for other concrete ingredients. ACI 304<sup>8</sup> and ASTM C94<sup>9</sup> describe accuracies typically used in concrete production. Silica fume should be measured by weight or volume to  $\pm 1$  percent of the specified total amount.

2. Since many silica fume products contain ASTM C494<sup>10</sup> chemical admixtures, fluctuations in silica fume dosage may be seen in the water demand or slump of the fresh concrete as well as in the performance of the hardened concrete.

### 5.3 Handling

1. Silica fume slurries are thixotropic materials; they will gel upon standing over an extended period. Typically, the materials will gel without any appreciable settling. Before



being used, the slurries must be returned to a liquid state. Remixing can be achieved for pails or drums by using a paint mixing blade mounted on an electric drill. Bulk storage tanks should be equipped with a mechanical agitation device or with a recirculation system that is designed to move all of the silica fume and not allow any to remain static and gel. Usually, agitation or recirculation will be required for only a brief period each day to maintain the material in a usable condition.

2. If the size of the project indicates that drum delivery is the most practical approach, then a weighing or metering system must be devised that will meet the accuracies mentioned above. Of course, this recommendation applies to any delivery method.

3. For larger placements, mobile units may be leased to dispense the silica fume. These units are vans that contain a working storage tank, a weight or volumetric batching system, and a pump. They are usually parked next to a batch plant so a truck mixer can be charged with silica fume before going into the batch plant.

4. For long term projects or for fixed installations, a permanent dispensing system may be more practical.

## 5.4 Mixing

1. To achieve the goals of high strength and durability, the silica fume must be uniformly distributed throughout the concrete. Compressive strength variations of as much as 3000 psi (21 MPa) within a truck mixer may result from poor mixing. Adequate mixing is a prerequisite for good results and must not be overlooked. An absolute minimum of 100 revolutions at a speed of at least 15 revolutions per minute is recommended for truck-mixed concrete containing silica fume. These recommendations are the minimum acceptable level for truck mixers that meet the requirements of ASTM C94.<sup>9</sup> When using dry densified silica fume, these requirements should be increased to 120 revolutions at the same revolution per minute. Also, the load size should be limited to not more than 75 percent of rated mixing capacity.

2. Use of silica fume in central-mixed concrete works well. In this case, the silica fume should be added after (or, if ribbon fed, along with) other ingredients. The mixing time will vary according to the dosage and the batch size. Central-mixed concrete should also be agitated at the placement site before discharge from the transit vehicle.

3. If the plant uses mixer trucks to deliver concrete, use of silica fume requires strict adherence to the requirements of ASTM C94.<sup>9</sup> In this case, the silica fume should be added to the truck before any other ingredients. Adding silica fume slurry last to a truck mixer may result in "head-packing" and inadequate mixing, particularly in larger loads. Adding dry densified silica fume last to a truck mixer may produce inadequate mixing, particularly with larger loads.

4. For truck mixing, the rated mixing capacity of the truck must not be exceeded. As defined by ASTM C94,<sup>9</sup> the volume of mixed concrete should not exceed 63 percent of the total volume of the drum. Based upon the condition of the trucks and the dosage of silica fume, the precaster should establish specific mixing requirements for the project.

5. Extra care should also be given to the routine aspects of concrete production. For example, the amount of wash water in the truck must be accurately accounted for in the mixture calculations. Similarly, drivers must be cautioned not to add additional water to the drum when washing dust off a truck after loading.

6. The best method to determine adequacy of mixing is to conduct a mixer evaluation as specified in ASTM C94.<sup>9</sup> If this test cannot be made, the discharge of the concrete from the truck mixer should be examined visually very carefully. The most common symptom of inadequate mixing is rapid slump loss during discharge of the concrete. For example, if during a continuous discharge the slump changes by several inches from the front to the back of the load, it is highly probable that the concrete was not properly mixed and that a uniform slump never existed in the drum.

Another common symptom is the appearance of "concrete balls" in the discharge. Usually, additional mixing or reducing the size of the load will eliminate this problem. On some projects, it has been possible to determine that a specific truck mixer was more prone to producing the concrete balls (probably because of worn fins).

7. Silica fume slurries (see Section 2.2) have been successfully used with mobile mixing equipment. If silica fume is to be made in a mobile mixer, a thorough testing and calibration program is recommended before the placements begin.

## 5.5 Transporting the Mix

1. Concrete containing silica fume may be transported in equipment typically used to transport conventional concrete. Silica fume concrete will be more cohesive and less prone to segregation during transportation than conventional concrete.

2. The use of non-agitating trucks to transport concrete containing silica fume is not recommended.

3. Equipment used to transport concrete containing silica fume should be cleaned following the same procedures used for clean-up after discharging conventional concrete.

## 5.6 Placing

1. Concrete containing silica fume can be successfully placed using conventional placement devices such as buckets, pumps, and tremies.

2. Because of the increased cohesiveness of high performance concrete containing silica fume, for the same type of placement, using a concrete with a slump of 1 to 2 in. (25 to 50 mm) higher than conventional concrete is recommended. For overall ease of placing and finishing, using as high a slump as possible is also recommended.

3. Concrete containing silica fume has been pumped successfully on many projects. Low dosages of silica fume tend to reduce pumping pressure, while higher dosages may increase pressures.

4. As is true for any concrete, concrete containing silica fume should not be retempered with water beyond the design or specified water-cement ratio. Again, one should not expect to achieve significant improvements in concrete performance if water is injudiciously added to a truck during

discharge. If retempering is required to maintain a suitable slump, a high-range water-reducing admixture meeting the requirements of ASTM C494<sup>10</sup> is recommended, but the effects on other properties should then be examined after such addition.

## 5.7 Consolidating

High-slump flowing concrete produced with silica fume requires consolidation. The increased internal cohesiveness of the mix causes air to be entrapped, even in concretes with higher slumps. Thorough vibration is required; the recommendations of ACI 309<sup>11</sup> should be followed.

## 5.8 Curing and Placing — General

1. No matter how well a concrete mix is proportioned, placed, and consolidated, the success of the project will depend on the degree of care taken during finishing and curing.

2. With regard to finishing and curing concretes containing silica fume, there are two general recommendations (note that these recommendations apply equally well to conventional concretes, but even more so to silica fume concrete): First, under-finish; and second, over-cure!

(a) Under-finishing means not specifying a greater degree of finishing than is actually necessary for the intended use of the concrete. By limiting the finishing to only that absolutely necessary, finishing costs will be minimized and the time before curing is started will be reduced, thus lessening the potential of plastic shrinkage cracking. Also, by limiting finishing, the potential for dusting, scaling, and surface crazing will be reduced.

(b) Over-curing means that in order to get the maximum benefit from high performance concrete containing silica fume, curing must be effective and more curing effort must be made compared with conventional concrete in the same placement. Extra curing efforts include maintaining moisture content and temperature to allow desired concrete properties to develop. One important key is that curing must begin directly after finishing. Insufficient curing frequently leads to excessive shrinkage cracking. Curing is not the operation to try to save money.

## 5.9 Finishing

1. The greatest noticeable difference between conventional concrete and high performance concrete containing silica fume will be in finishing. The difference between the two will become greater with increasing dosages of silica fume and increasing paste contents.

2. Concrete containing silica fume will bleed much less than conventional concrete. At higher dosages, bleeding will be essentially eliminated. Thus, most concretes containing silica fume are more susceptible to plastic shrinkage cracking from surface drying than conventional concrete.

3. Plastic shrinkage cracking can affect concrete, with or without silica fume, during two periods. The first period is during the time after the initial finishing operations of screeding and bull floating but before final finishing. The second period is after final finishing and before initiation of curing.

4. Plastic shrinkage is a result of rapid moisture loss from the surface of fresh concrete. If the moisture lost is not replenished by bleeding, tensile stresses will develop and cracking will result. Since most silica fume concretes do not have bleed water, great care must be taken during curing. Factors affecting plastic shrinkage cracking are humidity, wind, and concrete and air temperature.

5. Listed below are several preventive steps that may be taken to minimize plastic shrinkage (see ACI 305<sup>12</sup> for more information):

(a) If the casting operation is outdoors, erect wind-breaks. These might consist of properly supported plastic sheets or temporary plywood walls.

(b) Use a light fog-mist of water to keep the concrete surface moist between finishing operations. Do not finish the concrete if water from the fog-spray can be seen on the surface.

(c) Cover fresh concrete surfaces with plastic sheets, or moist burlap covered with plastic, between finishing operations, or immediately after single-stage finishing.

(d) Use one of the proprietary evaporation retarders to prevent moisture loss between initial and final finishing.

(e) Begin curing immediately after completion of final finishing.

(f) Use fibers (polypropylene or steel) in the concrete when marginal curing conditions may contribute to plastic shrinkage. Fibers will not prevent plastic shrinkage cracking if severely adverse conditions exist.

(g) Dampen forms to prevent moisture loss from the concrete in directions away from the exposed surface.

(h) Reduce the concrete temperature by using cooled aggregates or water or by using appropriate amounts of ice to replace a portion of the batch water.

(i) Have an adequate crew and all required equipment prepared so that the placement, finishing, and curing can proceed as rapidly as possible without interruption.

(j) If casting beds are outside, consider placing concrete late in the day to minimize exposure to direct sunlight and higher temperatures.

6. If plastic shrinkage cracks do occur, they can generally be closed by prompt reworking of the fresh concrete. Concrete that has been reworked after plastic cracking must be promptly and thoroughly cured, or the cracks may reappear.

7. Steel finishing tools are recommended for final finishing of concrete containing silica fume.

8. Because concrete containing higher dosages of silica fume does not bleed, finishers experienced in working with a wet surface have found silica fume concrete difficult to finish. If the application requires a dosage of more than 5 percent silica fume by weight of cement, consider a one pass finishing procedure of screeding, bull floating, and brooming or other texturing followed immediately by curing. If the application requires a higher dosage of silica fume to achieve a particular level of strength or durability and a high degree of finishing, consult the silica fume admixture vendor's technical representative.

9. In some situations, although plastic shrinkage cracks may not occur, the surface of silica fume concrete will dry out and begin to harden before the underlying concrete. This



surface drying will give the fresh concrete a "spongy" consistency, and make it difficult to finish. The same procedures used to prevent plastic shrinkage cracking will also be effective in preventing surface drying and hardening.

### 5.10 Curing

1. Concrete, whether it contains silica fume or not, will not perform well unless it is properly cured. This rule is doubly important for high performance concrete containing silica fume — do not expect to achieve high strength or low permeability if the silica fume supplier's guidelines are not followed.

2. ACI 308<sup>13</sup> discusses curing in detail and describes the changes in concrete properties that result from improper curing. Proper curing involves two aspects — maintenance of proper moisture conditions and proper temperature conditions until the desired concrete property levels are developed. The concrete property of lower permeability develops more slowly than does compressive strength. A longer curing time may, therefore, be required to produce a specified low permeability. This extended curing can be accomplished by applying a membrane-forming curing compound or evaporation retarder immediately after removing the hardened concrete from its form.

3. It is recommended that curing of silica fume concrete begin immediately after finishing, whatever the finishing process may be. High dosages of silica fume produce concrete that will not bleed. Therefore, there is no requirement to wait for the bleeding to conclude before initiating curing. A curing compound or evaporation retarder should be applied within a few minutes after final finishing.

4. Silica fume concrete has been successfully cured using most of the generally accepted practices including wet burlap, sheets of plastic, and curing compounds. As with any concrete, the secret is to maintain the curing once it has been initiated. A single cycle of drying can have a significant detrimental effect on the properties of the concrete.

5. If silica fume is used in concrete that will be subjected to accelerated curing, the curing cycle may have to be modified. The concrete must reach an initial set before beginning the accelerated curing. ACI 517<sup>14</sup> contains additional information on accelerated curing.

6. Use the minimum amount of heat during the accelerated curing period necessary to attain the necessary strengths because heat may accelerate shrinkage and drying.

7. Consider the use of Type I cement vs. Type III cement. This change may reduce the rate of early shrinkage.

8. When rapid drying conditions exist, fog-mist exposed surfaces and cover them as quickly as possible.

9. Steam curing should be used.

10. The concrete surface must be protected against moisture loss. Plastic covers on or just inches above the surface have been used successfully. Curing compounds have been used with some limited success. The curing compound's effectiveness will depend on the resulting amount of moisture loss allowed by the particular compound. Consider using a curing compound and plastic covers. Cover quickly after finishing.

11. Minimize temperature differentials between the concrete mass and the ambient air to which the top surface is exposed. Detension strands immediately upon stripping off covers, or develop a way to detension strands before stripping the covers (or partially detension before stripping covers). High performance concrete containing silica fume may mature more rapidly than a conventional concrete. Detensioning should occur as soon as the concrete has developed sufficient strength to accommodate the prestressing forces.

### 5.11 Handling and Transporting Members

1. Stripping double tees with equalizers is recommended.

2. Transporting double tees in rocker supports so that they are not warped may be necessary because, with high strength members, the increased modulus increases the likelihood of accidental cracking.

For further information on all topics within Section 5, the reader may wish to consult "Emsac" User Notes, #5 and #6, dated April 1986 and July 1989, respectively, available from Elkem Materials Inc., Park West Office Center, P.O. Box 266, Pittsburgh, PA 15230.

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## APPENDIX — NOTES ON PLASTIC SHRINKAGE CRACKING

**A1.** Plastic shrinkage cracks are cracks that appear on the surface of concrete before it has hardened. These cracks are typically randomly located in the concrete, are usually parallel to one another, and vary from a few inches to a few feet in length. The cracks may be 1 to 3 in. (25 to 75 mm) deep and can extend through a double tee flange. They usually do not extend to the perimeter of the concrete placement.

**A2.** Plastic shrinkage cracking can occur when the rate of water loss from the surface of fresh concrete, because of evaporation, exceeds the rate at which the surface water is replaced by bleeding. The drying of the surface concrete develops tensile stresses that can ultimately lead to cracking.

**A3.** The rate of evaporation of moisture from the concrete is governed by air and concrete temperature, wind speed, and relative humidity. The warming and drying action of direct sunlight also plays an important role in evaporating moisture. For conventional concrete, ACI 305<sup>12</sup> recommends taking precautions for plastic shrinkage wherever the predicted rate of moisture loss exceeds 0.2 lb/ft<sup>2</sup>/hr (1.0 kg/m<sup>2</sup>/h). For concretes with dosages of slurry in excess of 10 percent or dry silica fume in excess of 5 percent, precautions are recommended whenever the predicted rate of loss exceeds 0.1 lb/ft<sup>2</sup>/hr (0.5 kg/m<sup>2</sup>/h).

**A4.** Evaporation of water from freshly placed concrete is affected by concrete temperatures warmer than air tempera-

ture, low relative humidity, and surface winds. These conditions can occur at any time of the year. Plastic shrinkage cracks often take contractors and engineers by surprise during the spring and fall. Consider a fairly typical day in April, in the northeastern United States: a clear blue sky, air temperature around 60°F (16°C), low relative humidity of 30 percent, a moderate breeze of 15 miles per hour (24 km/h). Does this scenario sound like good weather conditions for placing concrete? Consider further that even if the fresh concrete temperature is 60°F (16°C), by the middle of the day, the surface of freshly placed concrete could be warmed to 80°F (27°C) by bright sunlight. Under these conditions, the evaporation rate will be over 0.3 lb/ft<sup>2</sup>/hr (1.5 kg/m<sup>2</sup>/h). Plastic shrinkage cracks will almost certainly occur under these conditions unless steps are taken to reduce the effective rate of evaporation. Therefore, beware of sunny, breezy weather at any time of the year.

**A5.** There is a general misconception that high performance concrete will not exhibit plastic shrinkage cracking. In fact, because high performance concrete typically exhibits low water-cement ratios, there is little water available for bleeding to replace that lost by evaporation. Lower performance concrete will typically have a high water-cement ratio and, therefore, more bleed water will be available. However, silica fume concretes typically have no bleed water and, therefore, are a high risk for shrinkage cracking.

**A6.** During the cooling phase of the steam curing process, high evaporation may occur at the concrete surface. This condition has not been well documented. ACI 517.2R<sup>14</sup> states, "When steam is first applied, a temperature differential is formed between the concrete unit and the atmosphere. The cooler temperature of the concrete unit causes the steam to condense on its surface. When the temperature of the concrete unit and the chamber atmosphere are equal, steam ceases to condense on the unit's surface ..." During the cooling phase, the temperature differential is reversed, with a rapid evaporation potential developing at the unit surface. This condition can cause excessive surface evaporation and shrinkage. Preventive measures include maintaining a saturated surface or applying a curing compound during the cooling phase.

**Note:** An extensive bibliography and a producer survey on the subject of concrete containing silica fume are available through PCI Headquarters.