

MINERAL ADMIXTURES



Compilation 22

American Concrete Institute

Mineral Admixtures

ACI Compilation 22

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Editors Note: The term "microsilica" as used above and elsewhere in this compilation can be considered interchangeable with "silica fume." See "Cement and Concrete Terminology," ACI Publication SP-19.

Preface

ACI Compilations combine material previously published in Institute periodicals to provide compact and ready reference on specific topics. The Material in a compilation does not necessarily represent the opinion of an ACI technical committee — only the opinions of the individual authors. However, the information presented here is considered to be a valuable resource for readers interested in the subject.

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Silica Fume in Concrete

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High Strength Concrete

On The Cover: Roller compacted concrete with Class F fly ash was the primary material used to replace a failed dam in southwestern Utah. The completed dam is 75 ft high and will eventually impound over 40,000 acres. (Photo courtesy of Harry Roof, Western Ash Co., Denver, Colo.)



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Admixtures — What's New on the Market

by John M. Scanlon

Concrete technology is changing rapidly. Industrial research has for the past 20 years taken the lead in developing new innovative materials, that, when used to their fullest potential, greatly enhance the properties of hydraulic cement concrete. Concrete is no longer a mixture of one, two, and three shovels of cement, sand, and coarse aggregate, respectively. It has matured. It is ready to lead us into the 21st century.

Many changes have resulted from the development of technology in new mineral admixtures (pozzolans) and chemical admixtures. The cement industry has finally discovered that not everyone desires to use a finely ground Type I/II combination, even though such cements may be more economical to manufacture, transport, and store. Concrete producers have become more sophisticated in their knowledge of concrete properties and the manufacture of concretes having various qualities.

About 15 years ago, mineral and chemical admixture companies had to produce admixtures that could be used successfully with whichever hydraulic cement happened to be available to the concrete producer. Now the knowledgeable concrete producer is requiring hydraulic cement that will permit his mineral and chemical admixtures to react the most efficiently.

The American Concrete Institute Committee 116 publication SP-19, "Cement and Concrete Terminology," defines concrete as "a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate; in portland-cement concrete, the binder is a mixture of portland cement and water."¹ It does not say that concrete will weigh 144 pounds per cubic foot (2306 kg/m³) or have a compressive strength of 3000 psi (21 MPa). It does not say that concrete will have an initial setting time of six hours

or a final setting time of nine hours. It does not say that the concrete must freeze below 32 F (0 C) or, for that matter, boil at 212 F (100 C). It does not say that the concrete shall have a modulus of elasticity of 3.0×10^6 psi. The point is, the industry has traditionally been placing additional requirements on hydraulic cement concrete so that the composite material will do what's required by the user and attain the particular hardened properties that are desired by the engineer or owner of the structure in question.

Based on the needs of the contractor in constructing concrete structures and the designer's requirements for specific hardened concrete properties, standard practices, sampling procedures, test methods, and specifications have been established to assist in ensuring that the concrete develops the desired properties. These standards have responded to the needs of the concrete industry for decades, but now technology demands more. Now the users and owners are demanding greater capabilities from their concrete. They need concrete that can:

- Gain strength, without freezing, down to and below 20 F (–7 C).
- Remain workable for hours or days without hardening, and then set on demand.
- Remain cohesive while being dropped through water, without the use of a tremie.
- Attain a modulus of elasticity of 7500 ksi (51 GPa) at age 28 days.
- Attain a strength of 20,000 psi (138 MPa) at age 56 days.
- Provide positive protection of embedded metals from corrosion.

Chemical admixtures²

Freeze protection admixture

ACI Technical Committee Report 306R-88, "Cold Weather Concreting," recommends that concrete placed in sections of 12 in. (300 mm) or less be placed at a temperature of at least 50 F (10 C) and be maintained at 50 F (10 C)

for the duration of the protection period.³ Such requirements actually cause many contractors to curtail concrete construction, especially when ambient temperatures fall below freezing. Only dedicated contractors, knowledgeable in cold weather construction, attempt concrete construction below 20 F (–7 C). In addition, ACI 306R recommends that a 12 in. (300 mm) section of concrete placed above ground, and containing 500 lb/yd³ (296 kg/m³) of cement, be protected with insulation having a thermal resistance (*R*) rating of 6 hr·ft²·F/Btu when the ambient temperature is expected to drop to 20 F (–7 C).

Curtailling concrete operations during low ambient temperatures is expensive and may not be cost-effective. Freeze-protection admixtures have been developed that can be used to prevent the concrete from freezing, down to an ambient temperature of approximately 20 F (–7 C), without insulation. In addition, these innovative freeze-protection admixtures comply with all requirements of ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete,"⁴ for Type C accelerating, and for Type E water-reducing and accelerating admixtures. Typical test results are presented in Table 1.

The data in Table 2 illustrate that this admixture does not promote corrosion of steel in concrete, even at a dosage of 120 fl oz/cwt (78 cm³/kg) of cement.

Freeze-protection admixtures have been used in construction for approximately five winters with no known incidents of concrete freezing. Many specifiers are now requiring its use, so concrete construction will most likely continue throughout the winter months.

The parking garage of the Chrysler Technical Center, Detroit, Michigan, required 40,000 yd³ (30,600 m³) of concrete to be placed all year around. A

Table 1 — Freeze-protection admixture laboratory evaluation results (ASTM C 494 requirements).

Parameter	Type C accelerator	Type E water reducing and accelerating	Freeze-protection admixture
Water content (maximum % of control)	—	95	90.8
Time of setting (hr:min) Initial	at least 1:00 earlier and not more than 3:30 earlier at least 1:00 earlier		2:02 earlier
Final			2:27 earlier
Compressive strength, (minimum % of control)			
3-day	125	125	136
7-day	100	110	126
28-day	100	100	116
6-month	90	100	119
1-year	90	100	121
Flexural strength, (minimum % of control)			
3-day	110	110	128
7-day	100	100	109
28-day	90	100	103
Length change (% increase over control)	0.010 max.	0.010	0.008
Relative durability factor (minimum)	80	80	96

Table 2 — Time-to-corrosion test results.

Mix ID	w/c	Admixture dosage (fl oz/cwt)	NaSCN concentration* (% by weight of cement)	Average time-to-corrosion (weeks)
1	0.57	0 [†]	—	1.5
2	0.57	20	0.045	5
3	0.55	60	0.135	11
4	0.52	90	0.203	7
5	0.52	120	0.271	12

*Thiocyanate ion (SCN⁻) is 71.6% of NaSCN
[†]Control

freeze-protection admixture served as an all-temperature accelerator, in addition to protecting the concrete during the winter. In the summer, at ambient temperatures of 80 to 90 F (27 to 32 C), 5 fl oz/cwt (3 cm³/kg) of the freeze-protection admixture was used for the concrete to attain high early strength. All of this concrete attained compressive strengths exceeding 5,000 psi (34.5 MPa).

A 40 percent cost savings was realized in using a freeze-protection admixture on the Corning Glass Works, State College, Pennsylvania. At a dosage of 90 fl oz/cwt (59 cm³/kg), the admixture was used to protect the concrete from freezing and permit the slabs to be finished within 4 hours at ambient temperatures around 20 F (−7 C).

This particular freeze-protection admixture contains sodium thiocyanate

(NaSCN). Its effects on corrosion of steel in concrete when used at different dosages was evaluated by using the Southern Climate Accelerated Test Method.⁵ The results of this long-term test are shown in Table 2.

Extended set control admixture system

Conventional retarding and accelerating admixtures have been in use for many years. These admixtures are used to retard or accelerate the setting time of concrete by a few hours. According to ASTM C 494, the set alteration is limited to a minimum of 1 hour and a maximum of 3½ hours, whether it is retardation or acceleration.

Attempts have been made to extend the setting time of concrete beyond the typical retardation times achieved with conventional retarding admixtures.³ Al-

though the setting times were lengthened in these attempts, the workability of the concrete was compromised because of the inability to control the extended time of retardation. Recent developments in admixture technology have produced a two-part chemical system that, in effect, extends the setting time of concrete indefinitely. This is done by essentially stopping hydration of the cement, then stimulating resumption of hydration whenever it is desired, without loss of workability. The chemical that stops cement hydration will be referred to as the stabilizer and the reinitiator as an activator. The American Concrete Institute presently refers to these admixtures as "extended set-control admixtures."

Although the extended set-control admixture was primarily developed to reduce wasted concrete and wash water, additional innovative uses have been developed, such as:

- Extending cementitious grout workability from about 2 hours to 36 hours.
- Implementing long hauls of concrete, resulting in increased workability and reduced concrete temperature.
- Preventing cold joints in concrete caused by delayed delivery of concrete.

Anti-washout admixture

Experience has shown that the cost of dewatering hydraulic structures to place concrete averages about 50 percent of the construction cost. Therefore, the ability to place concrete without dewatering would result in significant savings. The primary procedure of placing concrete underwater has been by use of a tremie. This procedure is relatively slow, and maintaining embedment of the tremie in the fresh concrete is tedious but critical. If water gets into the tremie, cement is washed from the tremie concrete, resulting in cement-deficient layers of concrete in the placement. Many such weak areas go undetected during construction because detecting them requires unusually close inspection.

During the early 1980s, admixtures were developed that dramatically prevented cement from being removed from the concrete when falling through water. This concrete has excellent cohesion and can either be used by dropping directly through water, or as tremie concrete that assures the elimination of cement-deficient layers. The most successful of these anti-washout admixtures are composed primarily of derivatives of cellulose and water-reducing chemicals.

Washout and abrasion tests

The effects of the anti-washout admixture on setting time, on relative resistance to washout, and on underwater abrasion have been evaluated. The test program included evaluation of the effects of concrete temperature and the presence of fly ash. The washout test was conducted according to the procedure described in Appendix A of Technical Report REMR-CS-18, "Evaluation of Concrete Mixtures for Use in Underwater Repairs," U.S. Army Engineer Waterways Experiment Station. The underwater abrasion tests were conducted according to Corps of Engineers CRD-C 63-80,⁶ which was the basis for ASTM C 1138-89, "Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)."

Freeze-thaw tests

The U.S. Bureau of Reclamation in Denver, Colorado, has conducted tests on concrete for the Coachella Canal In-Place Lining Project, containing the anti-washout admixture and Type II cement, with no air-entraining admixture.* The concrete contained 4.5 percent total air, but no air void parameters were determined. The results from tests on 3 x 6 in. (76 x 152 mm) cylinders, which went through freezing and thawing cycles at a rate of 3 per 24 hours, took 559 cycles to reach a 25 percent weight loss. The acceptable result is anything greater than 500 cycles before reaching the 25 percent loss.

Sulfate resistance

Sulfate expansion tests were also performed, using 3 x 6 in. (72 x 152 mm) cylinders. The test procedure involved soaking of the test cylinders in a 2 percent sodium sulfate solution at room temperature for 16 hours, followed by air drying at 130 F (54 C) for 8 hours. This cycle was repeated until 0.5 percent expansion was achieved.

The test results indicate that after 600 cycles, considered to be equivalent to 16 to 20 years of service life, the expansion of concrete treated with the admixture is at 0.29 percent. The 0.5 percent expansion limit was never reached.

Corrosion inhibiting admixtures

Following the vast increase in highway construction starting in the late 1950s, and continuing to this day, much of the infrastructure has been found to be decaying due to corrosion of embedded

Table 3 — Chloride permeability based on charge passed.

Charge passed (coulombs)	Chloride permeability	Typical of
4000	High	High water-cement ratio (>0.6) Conventional PCC
2000 — 4000	Moderate	Moderate water-cement ratio (0.4 to 0.5) Conventional PCC
1000 — 2000	Low	Low water-cement ratio (<0.4) Conventional PCC
100 — 1000	Very Low	Latex modified concrete Internally sealed concrete
100	Negligible	Polymer impregnated concrete Polymer concrete

Table 4 — Concrete properties.

Mix proportions					Hardened concrete	
Mix ID	Portland cement	Silica fume	Fly ash	w/c	28-day compressive strength (psi)	28-day chloride permeability (coulombs)
1	497	—	74	0.52	4060	8356
5	497	37	—	0.52	5278	2201
17	507	38	152	0.52	5829	1112
4	505	76	75	0.52	6902	579
14	610	—	—	0.43	5699	4192
8	612	—	153	0.43	6221	3777
3	603	15	—	0.43	5612	4880
2	605	38	75	0.43	7439	456
7	605	38	76	0.43	7149	1035
12	610	38	76	0.43	7279	610
16	600	75	—	0.43	7265	301
9	608	76	152	0.43	8715	203
13	708	—	76	0.37	7265	2441
11	708	15	151	0.37	8294	1081
10	700	37	—	0.37	7120	816
15	703	38	150	0.37	8149	416
6	706	76	76	0.37	9077	283

metals in concrete. This is not only an American problem, it is a problem for all countries with concrete exposed to saline solutions of any sort, and especially for concrete treated with chlorides to remove ice and snow.

The first attempt at a solution to these corrosion problems was to reduce the water-cement ratio of the concrete and to increase the concrete cover over reinforcing steel. These measures primarily just slightly increased the time-to-corrosion and were not a permanent solution to the problem. Responding to this problem, the Federal Highway Administration developed a rapid test method for determining the apparent chloride permeability of various concretes. This method is described in the

report, FHWA /RD-81/119, "Rapid Determination of Chloride Permeability of Concrete," and is commonly referred to as the AASHTO T 277 test method. Table 3 shows the five chloride permeability categories that were created.⁷

Corrosion inhibitors, such as calcium nitrite, have been reported to delay the initiation of corrosion and control the rate of corrosion by stabilizing the passivating layer of iron oxide film on the embedded metal. These liquid admixtures have been around since the mid 1970s and have been successfully used in combination with condensed silica fume. Using data from research and field evaluations, the manufacturer of the calcium nitrite corrosion inhibitor has developed a system for predicting

*Bureau of Reclamation Tests on Anti-Washout Admixtures. Personal communication from James Pierce.

the service life of concrete containing various quantities of calcium nitrite, including various quantities of condensed silica fume. This service life is attained by varying the dosage rate of calcium nitrite.

Another manufacturer recently began marketing a liquid corrosion inhibitor which, unlike calcium nitrite, does not involve reactivity with chlorides and consequently can be used in a fixed dosage, and will not accelerate the time of setting.

Both of these admixtures are important developments. Their introduction has had a significant impact in extending the time-to-corrosion. Along with other mineral admixtures, they may improve the quality of our infrastructure for a long time.

Mineral admixtures

Ground granulated blast-furnace slag

Ground granulated blast-furnace slag (GGBS) has been used as a cementitious material since the 18th century. GGBS is a mineral admixture that is currently being interground with portland cement to form portland blast-furnace slag cement (a blended cement). It is also batched separately at the concrete batch plant. Batching separately from the cement has two advantages: each material (cement, GGBS) is ground to its own optimum fineness; and the proportions of each ingredient can be varied. Such convenience provides more versatility to the concrete producer in developing specialty concretes. The quantity of GGBS used in comparison to the total cementitious materials (GGBS and portland cement) normally varies from 25 to 70 percent by mass. The following benefits are reported to be derived by using GGBS in concrete:

- Reduces temperature in mass concrete
- Greatly reduces permeability
- Improves sulfate resistance
- Reduces potential expansion due to alkali-aggregate reaction

Fly ash

Fly ash is "the finely divided residue resulting from the combustion of ground or powdered coal which is transported from the firebox through the boiler by flue gases" (ACI 116). Fly ash has been around for many years. It is generally classified as Class F or Class C. Class F is usually produced by burning anthracite or bituminous coal, and Class C is normally produced by burning sub-bituminous coal or lignite.

Fly ash provides many benefits in concrete, some of which are:

- Improved workability
- Reduced bleeding (which could be beneficial or not)
- Improved long-term strength
- Generally reduced generation of heat (Class C)
- Reduced permeability

Many benefits accrue from using fly ash in concrete. It is the author's opinion that unless there is an extraordinary reason that it shouldn't be used, all concrete should contain fly ash. Most 21st century concrete will most likely contain fly ash either as a blended cement or batched at the mixing plant. Many people in the concrete industry feel very strongly that concrete containing fly ash and a small quantity of condensed silica fume would have equal corrosion resistance to concrete containing larger quantities of condensed silica fume only as a mineral admixture. Extracting some data from Reference 7, we can see in Table 4 the effects fly ash, in combination with a small dosage of condensed silica fume, has on the 28-day chloride permeability of concrete.

In evaluating the test results in Table 4, the best results appear to have been obtained when condensed silica fume and fly ash were used together. Also, considering the cost of the various mixtures, obviously the use of fly ash with reduced quantities of condensed silica fume becomes the most cost-effective for equally low chloride permeabilities.

Conclusions

- Concrete can now be placed in freezing weather without freezing, gain strength rapidly, and remain durable by using a freeze-protection admixture.
- Concrete can be stopped from hydrating, then used when needed, by using an extended-set control admixture.
- Underwater structures can now be constructed and attain high quality without dewatering by using an anti-washout admixture.
- The use of both mineral and chemical admixtures can greatly increase the ability of concrete to resist the corrosion of embedded metals.
- Fly ash is a major contributing partner in developing cost-effective, corrosion-resistant concrete.
- Greater efforts need to be made to transfer such technology, so that more rapid implementation can occur.
- These innovations in chemical admixtures for use in concrete should greatly extend civil engineering capabilities

by reducing wasted concrete and washwater from mixing trucks, allowing placement of concrete at relatively low (20 F [-7 C]) temperature, and placing concrete under water without the use of a tremie. Such capabilities reduce concrete construction costs, and the placement of concrete year around with reduced insulation during the winter.

• Innovations in mineral admixtures should provide the capability of obtaining exceptionally high strengths and moduli of elasticity, plus greater abilities to produce more impervious and corrosion-resistant concrete.

• Concrete technology is expanding rapidly. When further innovation is needed, an admixture will most likely be developed to respond to that need.

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Selected for reader interest by the editors.

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Properties of Shrinkage-Compensating Silica-Fume Concrete Made with Type K Cement

by Ziad Bayasi and Rabih Abif Maher

Within the need for rehabilitation of the aging infrastructure, repair and restoration of concrete pavements and bridges has a high priority. This situation is expected to continue into the future. An important consideration of any concrete repair project is the selection of proper repair material.^{1,2} Among the important items to focus on in this selection are:

- Differential volume changes of the repair and original surface materials (substrate).
- Bond strength between the substrate and the repair material.
- Rapid strength development.
- High strength and durability.

This article describes an experimental investigation of the material properties of fresh and hardened shrinkage-compensating silica-fume concrete made with Type K cement. Those properties that pertain to repair applications are emphasized.

Shrinkage-compensating silica-fume concrete made with ASTM C 845 Type K cement has important properties for repair applications. Use of shrinkage-compensating concrete can help reducing shrinkage (or even generate expansion),^{3,4} and it has been documented that adding silica fume to concrete decreases permeability, increases strength, enhances abrasion resistance, improves durability, and accelerates strength development at early ages.^{5,6}

Shrinkage-compensating concrete basically differs from conventional concrete in two properties: workability and expansivity. Fresh Type K shrinkage-compensating concrete has a relatively high water demand compared to conventional concrete. The extra water is needed for the chemical reaction that generates expansion. Fig. 1 compares the dimensional change of shrinkage-

compensating concrete with that of ASTM C 150 Type I portland cement concrete. The degree of expansion of shrinkage-compensating concrete is strongly linked to the efficiency and duration of curing, which is responsible for supplying the necessary water for the expansive reaction.^{3,4}

Adding silica fume to conventional concrete reduces workability, decreases air content, significantly reduces permeability, and increases compressive strength (Fig. 2, 3, 4, 5). Silica fume also enhances flexural strength and accelerates early-age strength development.^{5,6}

Experimental program

The silica fume used in this investigation contained 96.5 percent of SiO₂ and had an average particle size of 1.5 microns (6×10^{-5} in.).⁸ An ASTM C 494 Type F naphthalene formaldehyde sulfonate-based high-range water-reducing admixture was used because of its reported effectiveness in silica-fume concrete.^{9,10} Aggregates were a natural river sand and a pea gravel, (maximum size $\frac{3}{8}$ in. [9 mm]).

Three mixes were tested (Table 1). The concrete was mixed in a laboratory drum mixer and consolidated by external vibration using a vibrating table. Slump was measured in accordance with ASTM C 143, and air content using the pressure method in accordance with ASTM C 231. After placement, the specimens were kept in their molds and covered with plastic sheets for 24 hours. The specimens were cured at 72 F (22 C) and 100 percent relative humidity for 7 days, then exposed to the laboratory environment (70 to 75 F [21 to 24 C]) and about 30 percent relative humidity until testing at 35 days.

The dimensional change of the expansive silica-fume concrete dur-

ing both fresh and hardened states was measured using two steel plates embedded in 3 x 3 x 10 in. (76 x 76 x 254 mm) concrete beams cast in flexible wooden molds (Fig. 6). Three beams were made for each mix. The plates were inserted during concrete vibration and the distance between them was measured immediately after placement and later during the curing period at ages of 1, 2, 3, 4, 5, 6, and 7 days using a micrometer. The average dimensional change of the three beams was considered to be representative of the pertinent mix. The flexible wooden molds were used so that expansion would be minimally restrained.

Measurement of expansion starting from the point of placement could help shed light on the behavior of silica fume in Type K concrete. Furthermore, as reported below, this method resulted in expansion values higher than those usually obtained for Type K concrete, since it measures the expansion in fresh and hardened states combined.

Compressive strength was measured in accordance with ASTM C 39 using three 6 x 12 in. (150 x 300 mm) cylinders. Flexural strength was measured in accordance with ASTM C 78 using three 4 x 4 x 14 in. (100 x 100 x 350 mm) beams loaded at $\frac{1}{3}$ points over a span of 12 in. (300 mm). Rapid chloride permeability was measured in accordance with AASHTO T 277; two 4 x 8 in. (100 x 200 mm) cylinders were made from each mix and one 2 in. (50 mm) thick slice was sawed from the midheight of each specimen for the permeability test. Permeable void volume fraction was measured in accordance with ASTM C 642 using the remaining sections of the permeability specimens.

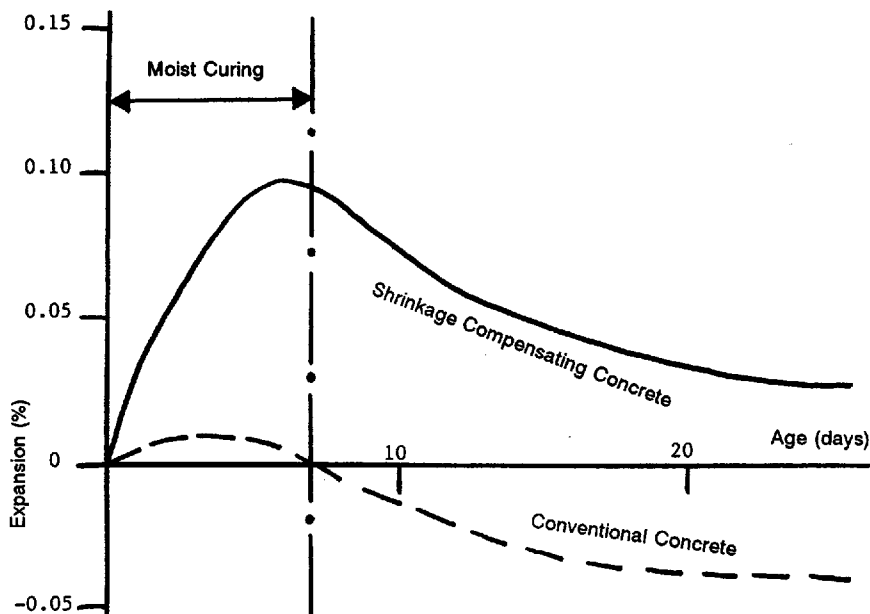


Fig. 1 — Dimensional changes of shrinkage-compensating Type K and Type I portland cement concretes.

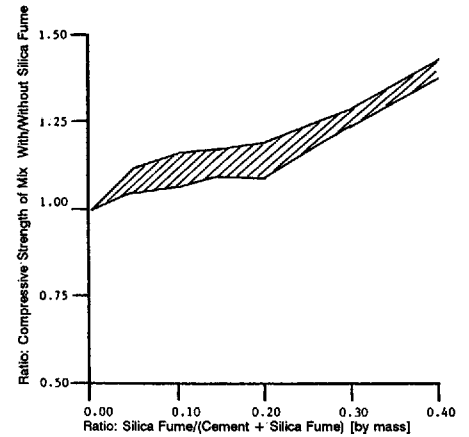


Fig. 5 — Effect of silica fume on the compressive strength of concrete.

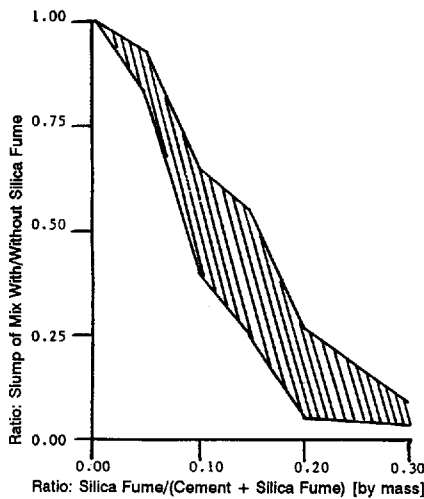


Fig. 2 — Effect of silica fume-binder ratio on the workability of concrete.

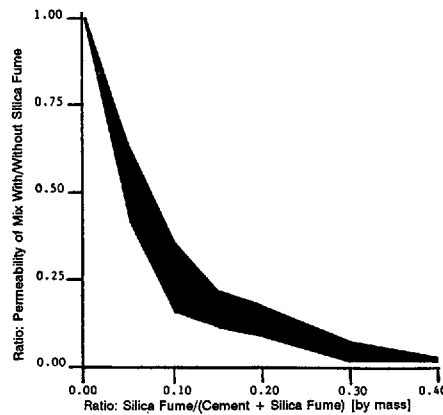


Fig. 4 — Effect of silica fume on the permeability of hardened concrete.

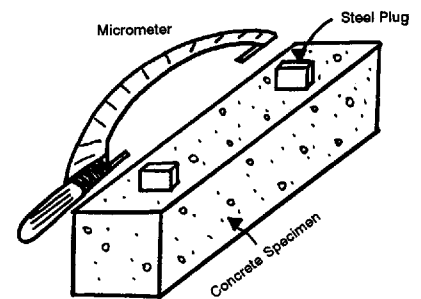


Fig. 6 — Method of measurement of expansion of silica-fume shrinkage-compensating concrete.

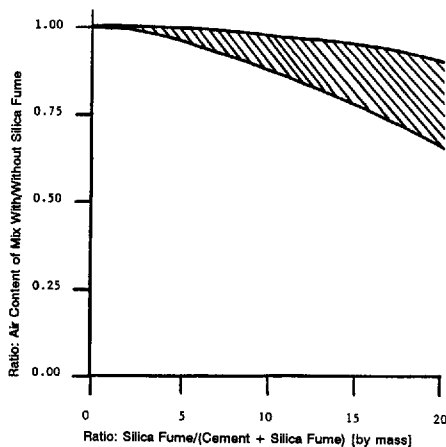


Fig. 3 — Effect of silica fume on air content of fresh concrete.

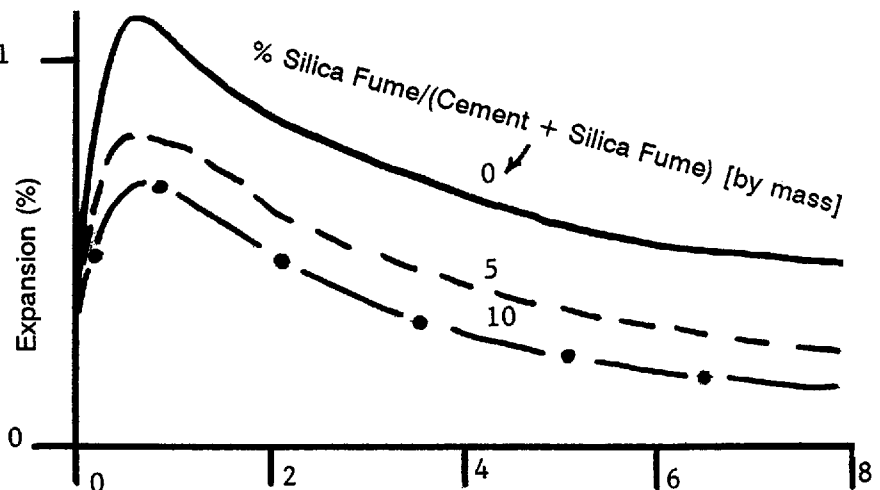


Fig. 7 — Effect of silica fume on expansion of shrinkage-compensating concrete during early age.

Table 1 — Mix Proportions.

Mix No.	1	2	3
*Percent silica fume	0	5	10
Water	307 lb/yd ³		
Cement + silica fume	748 lb/yd ³		
Coarse aggregate	1495 lb/yd ³		
Fine aggregate	1495 lb/yd ³		
Superplasticizer	88 fl oz/yd ³		
*Percent of Type K cement + silica fume			

Results

Test results for slump, air content, compressive strength, flexural strength, rapid chloride permeability, and permeable voids are shown in Table 2. Silica fume reduced the slump (workability) of the shrinkage-compensating concrete, and this reduction increased with increasing silica fume content. Due to their low workabilities, the air contents of mixes 2 and 3 were higher than mix 1, which did not contain silica fume. Silica fume increased the compressive and flexural strengths of the shrinkage-compensating concrete. Permeability of shrinkage-compensating concrete was dramatically reduced by the addition of silica fume; this reduction was more substantial than when silica fume is used in conventional concrete.^{5,6} The percentage volume of permeable voids was also reduced by the inclusion of silica fume.

Shrinkage test results (Fig. 7) indicate that silica fume may actually reduce the expansion of shrinkage-compensating concrete. More test data are needed to substantiate this conclusion.

Conclusions

The most important conclusions that can be made from the results this experimental research are:

- Silica fume reduces the slump (workability) of shrinkage-compensating concrete made with Type K cement.
- Silica fume significantly improve the strength of shrinkage-

Table 2: Test Results of Shrinkage Compensating Silica Fume Concrete.

Mix No.	1	2	3
Slump (in.)	6	1	0.5
Air content (%)	3.2	4.5	4.9
Compressive strength (psi)	6130	6720	6840
Flexural strength (psi)	570	760	670
Permeability (coulombs)	6587	350	442
Permeable voids volume (%)	13.0	10.4	9.9

compensating concrete made with Type K cement.

- Silica fume dramatically decreases the rapid chloride permeability of shrinkage-compensating concrete made with Type K cement.
- Silica fume may reduce the expansion of shrinkage-compensating concrete made with Type K cement.
- With its expansivity, superior strength, and impermeability, silica-fume shrinkage-compensating concrete made with Type K cement can be considered a suitable repair material for highways and bridges.

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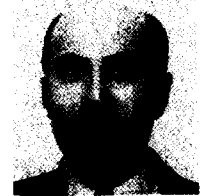
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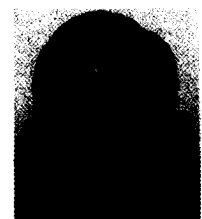
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High-Strength Silica Fume Concrete — Chicago Style

by Guy Detwiler

Material Service Corporation has developed and commercially marketed high strength silica fume concrete (HSSFC) in the Chicago area. This concrete, with design strengths ranging from 10,000 psi (70 MPa) to 14,000 psi (97 MPa), has been successfully supplied to over a dozen high-rise projects. Currently, preparations are being made to commercially market concrete with a design strength of 16,000 psi (110 MPa). Continuing optimization of the mix design has resulted in full scale test placements of concretes with compressive strengths surpassing 20,000 psi (140 MPa).

Many years pass between the time when we are able to achieve the next higher strength level and the time when the concrete is made commercially available. First, a testing program must be conducted to establish the engineering properties of the higher strength concrete. Second, and just as important, the mix design must be refined to make it "user friendly." The concrete producer must be able to batch consistent concrete. Slump loss during delivery must be minimized. The concrete must be placeable and it should set in a reasonable amount of time.

We are going to focus not on attaining strength, but on optimizing non-engineering properties of the HSSFC while maintaining strength and economy. The concrete mix design is continually refined to enhance constructability. All modifications of the mix design described in this article occurred in production concrete placed in high-rise buildings in downtown Chicago. This has been an ongoing process directed toward development of HSSFC that meets the needs of the entire construction team.

Performance concrete

Our HSSFC developed for use in Chicago's high-rise buildings has been marketed as a performance concrete. This concept involves an end product approach to the mix design. The engineer specifies the required engineering properties, usually compressive strength and modulus of elasticity, but does not enforce specifications related to the mix design.

A typical performance concrete mix design submittal does not include proportioning information. A statement on the submittal reads "Materials and proportions for this mix design are proprietary and will be adjusted to insure performance as specified." A statistical evaluation verifying the ability of the concrete to meet the design criteria is included with the submittal.

The performance concept allows for adjustment of the mix design during the course of a project. This creates a substantial advantage when compared to a prescription mix that essentially locks in a specific set of materials and proportions. HSSFC is a complex system of materials that performs most effectively when adjusted for varying ambient conditions, batching methods, placing methods, types of placements, stripping requirements, and delivery times. No one mix design is optimal for all circumstances.

This approach also allows the concrete producer to adjust the mix to compensate for variable raw materials, a change of raw material source, or the use of a backup batch plant. It is unrealistic to expect all raw materials to remain consistent and available over a long period of time. Unexpected mechanical difficulties may arise that would require the use of an alternative

batch plant with a different set of raw materials. Different types of materials and mix adjustments are used to custom design the concrete for varying batching, delivery, and placing conditions while maintaining the required engineering properties.

The use of HSSFC in high-rise construction is driven primarily by the economic benefits of column cost optimization. The higher cost of HSSFC is more than offset by a reduction of the amount of reinforcing steel and volume of concrete required. The performance concrete concept yields further economic benefits to both the contractor and the owner. The contractor receives concrete designed specifically for each placement. This lowers in-place costs and accelerates the construction cycle. Benefits to the owner may include a lower cost building and earlier occupancy.

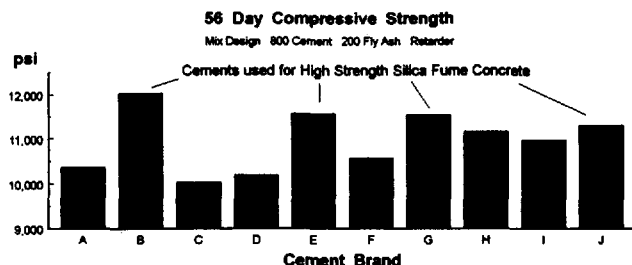
Materials

The materials in the mix affect various properties of HSSFC. Cement, fly ash, and aggregate are normally used in the same proportions regardless of design strength or placement requirements. This is considered the base mix design. Silica fume, water, high-range water-reducing admixture (HRWRA), retarder, and non-chloride accelerator are incorporated into the mix in varying amounts to control particular performance aspects of the concrete.

All of our HSSFC mixes use the same coarse and fine aggregate. The optimized coarse aggregate content remains constant for all mixes and the fine aggregate content varies only to control yield. An increase in the amount of material in the aggregate passing the No. 200 sieve usually reduces compressive

Table 1 — Effect of silica fume form and method of addition on compressive strength

Silica fume form	Slurry	Densified
Air content, percent	1.7	3.7
Unit weight, pcf	153.5	149.6
56 Day strength, psi	17,490	14,400
Method of addition:		
Slurry was added to water weigh box with batch water and charged with materials into central mixer.		
Densified was added from bags to the truck mixer after all other materials are thoroughly mixed.		
Design strength, psi		14,000
Silica fume content, lb/yd ³		100

**Fig. 1 — Compressive strength of concrete made with various cements available in the Chicago area.**

strength. If this occurs, an increase in the silica fume content or a decrease in the water-cementitious materials ratio will insure that the required level of strength is maintained.

Cement content typically remains constant, even though the cement's source can have a dramatic effect on concrete strength. The cements that are used in HSSFC are those that produce the highest strengths in concrete without silica fume (Fig. 1). Of the ten cements available in our market, we consider four of them usable in HSSFC. A change in cement brand may require an adjustment in the silica fume content or the w/c ratio to maintain the required level of strength.

To achieve high strengths in concrete not containing silica fume, Blick et al¹ reported that fly ash (or an alternative pozzolan) must be used. However, when the mix contains silica fume, fly ash becomes an optional instead of a necessary component of the concrete. The most important advantage that fly ash has to offer HSSFC is its ability to reduce the cement content. Not only does a cement reduction have economic benefits, but it will also result in improved thermal properties by reducing the temperature increase of the concrete.² Our optimization process has resulted in a standard cement and fly ash content for HSSFC that provides the cost effective strength required and generates less heat.

Our HSSFC has silica fume contents ranging from 3 percent to 18 percent by weight of cement. Adjusting the silica fume content is the principal method of controlling the strength of the concrete. As design strength increases, the silica fume content of the concrete is increased. A change in any of the concrete's raw material sources, raw

material quality, or production methods may affect the compressive strength of the concrete. The desired strength level is maintained by an adjustment in the silica fume content.

The other variable used to control strength is the water content of the concrete. As design strength and silica fume content increase, the water content and resulting water-cementitious materials ratio decrease. Water-cementitious materials ratios range from 0.30 for concrete with a design strength of 10,000 psi (70 MPa) down to 0.21 for concrete with a design strength of 16,000 psi (110 MPa). As the water content decreases and the HRWRA demand increases, the concrete becomes more difficult to control. The rate of slump loss increases, the set time is retarded, and the mix becomes very sticky.

Each pound of silica fume used in the mix increases the water demand of the concrete by approximately one pound. Using the desired low water content, the concrete has no slump before the addition of an ASTM C 494 Type F HRWRA. The HRWRA demand increases dramatically as the silica fume content increases and the water content decreases. The dosage of HRWRA may vary from less than 100 to more than 500 oz/yd³ (3.9 to 19.3 L/m³) depending on the water and silica fume content of the mix and the desired slump at point of placement. All of our HSSFC is produced by adding HRWRA to a no-slump mixture.

The decision to use a Type F instead of a Type G HRWRA is a result of the variable dosage requirements of HSSFC. Independent control of retardation and water reduction is essential to achieve the proper balance between slump loss and setting time. Low dos-

ages of a Type G HRWRA may provide an insufficient amount of retarder to control slump loss while high dosages of a Type G HRWRA will minimize slump loss but may cause excessive retardation of the concrete.

An ASTM C 494 Type D water reducing retarder is used in all of our HSSFC. The retarder serves two important functions in addition to retarding initial set. It is by far the most cost-effective strength producer in the concrete. It is also very effective for reducing the rate of slump loss during delivery and placement. As the dosage of retarder is increased, slump loss decreases. The benefits of slump retention must be weighed against the amount of retardation that is tolerable.

Some of the unwanted retardation resulting from the use of retarders may be offset by addition of a non-chloride ASTM C 494 Type C or E accelerator. The dosage of this admixture must be balanced with the dosages of HRWRA and retarder to provide a decrease in setting time without excessive slump loss or a decrease in compressive strength.

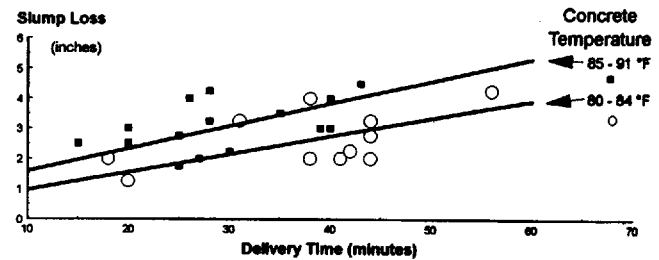
Batching and mixing

Batching and mixing methods used to produce HSSFC can have a large impact on strength and consistency. Development of the following procedures have allowed for the production of consistently high quality concrete. Although many alternative methods are available, these have provided excellent results and have proven to be cost effective over years of use.

Our HSSFC has been developed primarily with the slurried form of silica fume. The slurried form was initially selected due to its availability in the mid

Table 2 — Effect of HRWRA on slump loss and compressive strength

	Control	HRWRA	HRWRA
	Batch B-1	Batch B-2	Batch B-3
No. of tests	25	16	13
Avg. slump loss, in.	3.4	2.0	2.5
Avg. time, min	36	31	34
Avg. temperature, F	83	84	84
Compressive strength, psi			
Avg. 7 day	9850	10,120	9920
Avg. 28 day	13,210	13,360	13,070
Avg. 56 day	14,670	14,780	14,330
Design strength	15,000 psi		
Average slump loss from batch time to discharge. Average time is from initial to final slump test.			

**Fig. 2 — Slump loss as a function of delivery time and concrete temperature.**

1980s. In addition, we are reluctant to dedicate the cement bin that is required to handle the large quantities of the densified form of silica fume.

The slurried silica fume is contained in an insulated 9000 gal (34,000 dm³) tank with a dual recirculation and agitation system. Two in. (50 mm) diaphragm pumps rated at 120 gpm (32 dm³/min) move slurry through 2 in. (50 mm) lines directly into the water weigh box located 70 ft (21 m) above. A magnetic flow meter is used to reduce wear from the highly abrasive slurry. The system is back-flushed with water each night to prevent gelling of the slurry in the lines.

After weighing of the slurry is completed, the remaining water (batch water minus water contributed from the slurry) is weighed into the water weigh box along with the retarder and, if required, the non-chloride accelerator. Mixing of the slurry with the water and admixtures provides for additional dispersion of the silica fume.

No build up of silica fume on the interior of the water weigh box occurs as evidenced by the ability of the load cell to zero the computer at the end of the batch cycle. However, the water temperature probe in the water weigh box once malfunctioned due to silica fume build up on the sensor. A splash guard was installed and the problem has not recurred.

The weighed materials are charged into a central mixer using a standard charging sequence:

- Two-thirds of the material in the water weigh box
- Start aggregates
- Start cement and fly ash

- End cement and fly ash
- End aggregates
- Final 1/3 of material in the water weigh box.

This results in a no-slump mixture. After a 30 second pre-mix, a measured amount of HRWRA is charged into the no-slump material in the mixer.

An ammeter is attached to the mixer motor and a chart is made relating the current reading to slump. After addition of the HRWRA, mixing continues until the meter reading stabilizes. A stable reading indicates the HRWRA is thoroughly mixed into the concrete. If the meter reading corresponds to a slump that is less than desired, additional HRWRA is charged into the mixer and the above process is repeated until the desired slump (meter reading) is achieved.

The concrete is then discharged into a ready-mixed concrete truck. The truck drum is emptied of all wash water before receiving the load and drivers are instructed not to add water. Due to the complexities of batching and mixing high strength silica fume concrete, the total batch time is approximately five minutes as compared to two minutes for normal concrete.

Densified silica fume in 50 lb (23 kg) bags is warehoused for use in case slurry equipment malfunctions. In that event, the concrete without silica fume is mixed in the central mixer, discharged into the truck drum, and the bagged material is then added to the truck and thoroughly mixed. The mixing time is increased beyond that recommended by ASTM C 94 when using high amounts of silica fume.

This method of silica fume addition,

using our materials and batching sequence, has increased the entrapped air content of the HSSFC by 2 to 3 percent. A strength loss of up to 15 percent has been experienced (Table 1). To compensate for the strength loss due to the entrapped air when using the densified form, an increased amount of silica fume is incorporated into the concrete.

Production quality control

Every day the first load for each strength level of HSSFC is sampled at the batch plant. A visual inspection of the concrete is conducted to insure that it has the proper appearance. The distinctly different appearance of HSSFC enables easy identification of improperly batched loads. Upon arrival at the project, each load of concrete must pass a visual inspection by our technician before it is placed. Any load not having the proper appearance is rejected.

Physical tests conducted at the plant include slump, temperature, unit weight, yield, air content, and casting of compressive strength cylinders. Unit weight is a particularly important test. Low unit weight usually indicates that the concrete has an air content or water content higher than desired. In either case, the strength of the concrete will probably be lower than expected. Concrete with a lower than expected unit weight is not delivered to the project and an investigation is conducted to identify the cause of the problem.

Slump loss

HSSFC experiences a significantly higher rate of slump loss than does normal strength concrete. This is primarily

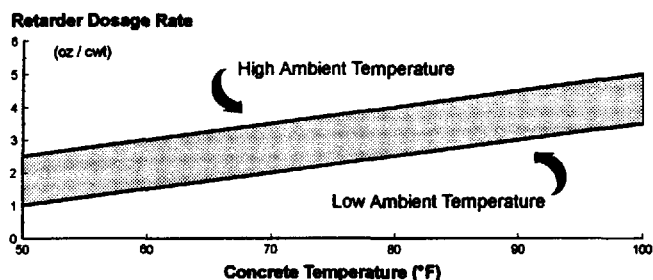


Fig. 3 — Retarder dosage range for varying concrete and ambient temperatures.

Table 3 — Effect of non-chloride accelerator on setting time

Accelerator dosage	Setting time (hours)	56-Day strength (psi)
none	12	14,130
16 oz/cwt	15	14,280
32 oz/cwt	11	14,140
Design strength		12,000 psi

due to the high dosage of HRWRA added to the concrete at the batch plant. The combination of the proper amount of retarder with the HRWRA minimizes slump loss without adversely affecting other properties such as setting time and strength development.

Three HRWRA were compared to evaluate their effect on slump loss of HSSFC. The testing was conducted during summer months when an increased rate of slump loss is experienced due to high ambient and concrete temperatures. No other adjustments to the mix designs occurred during the period of testing. The types of HRWRA included a naphthalene-melamine blend and two formulations of naphthalene, all meeting the requirements of ASTM C 494 Type F. All three HRWRA produced similar compressive strength and slump losses (Table 2).

Slump loss was examined as a function of concrete temperature and delivery time. No adjustments were made to the mix design during the period of testing and the retarder dosage rate was kept constant. As expected, the rate of slump loss increases as concrete temperature and delivery time increase (Fig. 2).

Addition of an ASTM C 494 Type D water reducing retarding admixture greatly improves the ability of the HSSFC to resist slump loss. Low ambient and concrete temperatures require lower addition rates of retarder to control slump loss. As concrete and ambient temperatures increase, the dosage of retarder is carefully increased to control slump loss without excessively retarding the concrete (Fig. 3). This system has provided for an acceptable amount

of slump loss (3 in. [75 mm] in 30 minutes) while maintaining a reasonable setting time. This has been used for concrete with temperatures from less than 60 F (16 C) to more than 100 F (38 C) that was placed in ambient conditions ranging from below freezing to more than 100 F (38 C).

Regardless of precautions taken to minimize slump loss, it is often necessary or desirable to increase the slump of the HSSFC at the site using a second addition of HRWRA. All projects using HSSFC have HRWRA available at the site for this purpose. Mechanical difficulties or extended dumping time may require multiple site additions of HRWRA to maintain the necessary workability. HSSFC has been re-dosed on the site with HRWRA up to three times with minimal effect on compressive strength. However, setting time is extended as the total dosage of HRWRA increases.

Placement

In Chicago, HSSFC is most commonly placed using a crane and two buckets. While one bucket of concrete is hoisted and placed, the second bucket is on the ground being filled. Concrete pumps have also been successfully used to place HSSFC in columns, beams, shear walls, and column mushrooms.

Delays in placement that result in the HSSFC remaining motionless in a bucket or pump line will greatly increase the rate of slump loss. This is particularly evident in low to moderate slump concrete where a 15 minute period of time without movement typically results in a slump loss of 3 to 4 inches (75 to 100 mm). For the same

reason, concrete in the truck drum should be agitated if it is not being discharged.

Our performance mix design submittal states that "slump will be consistent with placement requirements." The slump of HSSFC is related to the dosage of the HRWRA, not the water content of the mix. Before the addition of the HRWRA, the HSSFC has no slump. As a result, the slump test does not yield useful information regarding the relative consistency of concrete production or the water-cementitious materials ratio of the concrete. For these reasons, we contend that slump testing is essentially irrelevant. We request that project specifications remove all references to slump testing and allowable slump ranges for HSSFC.

Columns, core walls, and grade beams can be placed and consolidated much more efficiently using a high slump HSSFC. For these applications, contractors prefer flowable concrete with a slump over 8 in. (200 mm). This high-slump concrete is not appropriate for up-turned beams or for column mushrooms in slab placements. For these applications, a slump of less than 4 in. (100 mm) prevents the HSSFC from flowing into adjacent areas of the slab where lower strength concrete should be placed.

Coordination between the concrete producer and the contractor is important to insure that the HSSFC arrives at the site with the appropriate consistency. However, if the concrete arrives with a slump higher than desired, the truck drum is stopped for 10 to 15 minutes to allow the concrete to lose slump. If the concrete arrives with a slump lower

than desired, additional HRWRA is added to increase the slump.

Some engineers and testing agencies have expressed concern regarding the potential segregation of very high slump HSSFC. One such situation occurred when placement of an 11 in. (280 mm) slump load was reported. Cores were obtained from the column in question and no segregation was reported. The compressive strength of cylinders cast from that load were similar to those obtained from lower slump loads.

It is extremely difficult, if not impossible, to attain a reasonably flat, steel troweled finish with HSSFC. Essentially no bleed water appears, creating a spongy surface prone to plastic shrinkage cracking. Fortunately, most of this type of concrete is placed in areas that do not require finishing of the surface. One exception is the concrete used in the column mushroom areas of slabs. HSSFC used for these applications should be placed and floated, and an evaporation retardant, fog mist, or curing compound should be used to prevent plastic shrinkage cracking.

Setting time

The use of very high dosages of HRWRA that are required to produce workability and addition of sufficient retarder to limit slump loss have made control of the setting time of HSSFC difficult. Actually, of more concern to the contractor is the time at which the forms may be removed. Although the HSSFC is retarded, once it sets, heat is generated, strength gain occurs very rapidly, and forms are removed.

Our first commercial production of HSSFC contained a fixed dosage of retarder that resulted in setting times of 20 to 48 hours, depending on ambient and concrete temperatures. Moreno³ reported that some column and core wall surface defects occurred when forms were removed before sufficient strength was developed. Subsequently, a tarp was placed on the core wall and it was heated to 100 F (38 C) to allow for earlier form removal.

Optimization of the mix design led to the use of variable dosages of retarder as discussed earlier. By using a dosage of retarder that is appropriate for the concrete and ambient temperatures,

HSSFC setting time is reduced to 16 to 20 hours while maintaining an acceptable amount of slump loss. This approach allows for form removal the day after placement.

Due to scheduling demands, a large high-rise project required column and core wall forms to be removed at an age of 14 to 16 hours after placement. Therefore, the setting time of the HSSFC had to be reduced to approximately 12 hours for the contractor to remain on schedule. Use of a non-chloride accelerating admixture decreased the setting time of the concrete to the necessary range without significantly increasing slump loss or reducing 56 day compressive strength (Table 3).

Further optimization of the mix design has decreased the setting time of HSSFC to approximately 8 hours. This has been accomplished by testing various raw materials to find those combinations that produce the quickest set. A compatibility study including over 400 mixes pointed to specific combinations of materials that set significantly faster than the combinations that we were using. Again, this has been accomplished while maintaining the required engineering properties.

Several methods have been developed to determine when forms may be safely removed. Maturity meters have been used when a specific stripping strength has been required. Some contractors have placed a thermometer in the concrete in the forms. After a noticeable rise in temperature occurs, the HSSFC has set and forms are removed. Other contractors use a less scientific but equally effective method. If the forms feel warm to the touch, set has occurred and the forms are removed.

Burg⁴ has reported that the peak internal temperature of our HSSFC typically occurs at an age of 24 to 48 hours from time of placement. Thermal cracking is most likely to occur if forms are removed when the internal concrete temperature is near its maximum. Forms are typically removed well before the peak temperature is reached and essentially no thermal cracking has been reported. In cold weather conditions, forms have been released but left in place for a few hours before being completely removed. This system ap-

pears to prevent thermal shock of the columns and shear walls and reduces the possibility of thermal cracking.

Conclusions

The successful development of HSSFC is dependent on more than the ability to achieve the required strength. The concrete must be designed to tolerate a wide variety of production, delivery, placement, and ambient conditions to insure that this material is economically viable.

The performance design concept allows for the fine tuning of the mix design in actual field conditions. The base mix design is the foundation of a family of similar concrete mixes whose compressive strength is controlled by varying the silica fume and water content. By adjusting the HRWRA, retarder, and non-chloride accelerator dosages, the placeability, slump loss, and setting time can be optimized for varying conditions while maintaining the required engineering properties.

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Selected for reader interest by the editors.

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Long-Term Behavior of Silica Fume Concrete

M. Lessard, S. L. Sarkar, D. W. Ksinsik, and P. C. Aïtcin

The experimental sidewalk constructed in autumn 1980 in the SKW silicon plant in Bécancour in Quebec province, Canada represents one of the first reported field applications of silica fume concrete in North America. The 11 sidewalk sections each have a different cement content, and silica fume additions ranged from 10 to 20 percent in addition to the cement content [195 to 405 kg/m³ (330 to 680 lb/yd³)]. One segment that contained only 140 kg/m³ cement and as much as 56 kg/m³ (95 lb/yd³, or 40 percent) silica fume had to be replaced after five years of service life due to severe deterioration, although it yielded a high compressive strength [40 MPa (5800 psi)] after one winter. The first results of this experiment were reported elsewhere.¹

A series of seven concrete testing programs undertaken at regular intervals over the last 10 years included compressive strength tests on a number of core cylinders. Additionally, the microstructural characteristics of four concrete sections, each containing 10 percent silica fume, were studied after one winter exposure.¹ The bubble-spacing factor was determined after three years.

In the present testing program (1990), the compressive strength, bubble-spacing factor, chloride-ion permeability, and the microstructural characteristics were reevaluated after 10 years. Three 95 mm (3.7 in.) diameter cores were used for the strength tests.

The experimental sidewalk has been continually exposed to the extremely severe climatic conditions that prevail in Quebec province [annual temperatures range from 30 C in summer to -30 C in winter (86

to -22 F)] over the last 10 years. In addition to this, deicing salts are generously applied to the sidewalk surface every winter, together with occasional hot water spray. A 30-Mg (33-ton) loader is used on the sidewalk for snow removal as well, and because the sidewalk is not reinforced, this resulted in the prompt appearance of surface cracks in some sections.

Sidewalk construction

The sidewalk was constructed as follows:

1. A nonsilica-fume ready-mix concrete prepared by a local manufacturer was transported in trucks to the job site 45 minutes away.

2. The nonsilica-fume concrete mix was tested for slump loss and air content upon arrival at the construction site before a calculated amount of silica fume was added directly to the mix from a bin by means of a rather primitive weighing scale.

3. The concrete was then remixed for 5 to 10 minutes while water was added simultaneously to obtain a slump of 90 to 120 mm (3.5 to 4.7 in.). The dispersion of these ultrafine particles was deemed satisfactory when a homogeneous color was observed.

Since the concept of using superplasticizer, or high-range water-reducing admixture, had not fully evolved 10 years ago, these mixes contained no superplasticizer, and their slumps were controlled by adding water. Because it was not possible to control the amount of water, these concretes contain a high water-cement ratio.

4. The concrete was then directed to the actual jobsite, where it was retested for slump and air content. However, the desired air content of

6 percent could not be obtained due to difficulties encountered adding the silica fume in the concrete mixer. These difficulties included time lag in transportation, time required for proper introduction of silica fume, a very low density material, and placing the mix 2 hours after the initial mixing.

Visual inspection

Table 1 gives the cement content and corresponding thickness of the sidewalk sections tested. Surface cracking determined from visual inspection indicates that the number of cracks is directly related to the section thickness. However, this is normal for nonreinforced concrete that regularly bears a 30-Mg (33-ton) load during winter.

Test Results

The results obtained for the 10 years testing period are given in Tables 1 through 3.

Air content and bubble-spacing factor

The air contents presented in Table 2 range from 2.1 to 8.3 percent, and the bubble-spacing factor $\bar{L}$ between 220 and 490 μ m.

Comparing the 3-year and 10-year $\bar{L}$ values reveals no significant difference in D-260 and E-200 concretes, but there is a greater difference in A-315 and B-405. This difference, which is within the acceptable range, can be attributed to the mix homogeneity factor, which was extremely difficult to control when placing the concrete.

Chloride-ion permeability

Table 2 shows that, regarding chloride-ion permeability, there are two distinct families of concrete. One is A-315 and B-405, with extremely

Table 1 — Visual characteristics of sidewalk after 10 years

Concrete	Cement, kg/m ³	Thickness, mm	Visual observation
A-315	315	125	Very few cracks
B-405	405	85	Cracked
D-260	260	70	Heavily cracked
E-200	200	90	A few cracks

Table 2 — Air content, bubble spacing, and chloride-ion permeability results

Concrete	1983		1990		Chloride ions, Coulombs
	Air content, percent	$\bar{L}$, μ m	Air content, percent	$\bar{L}$, μ m	
A-315	4.2	270	5.5	370	450
B-405	2.1	380	4.0	490	425
D-260	6.1	350	4.3	340	1250
E-200	7.4	220	8.3	240	1550

* ASTM C457 Procedure A, "Modified Point Counting Method," 1982.
 † AASHTO Standard T277-831, "Rapid Determination of the Chloride Permeability of Concrete," 1983. Average of two measurements.

Table 3 — Compressive strength at different ages

Concrete	Compressive strength, MPa*						
	After 1st winter	After 2nd winter	Before 3rd winter	After 3rd winter	After 4th winter	After 7th winter	After 10th winter†
A-315	69.8	68.3	57.5	56.6	55.4	64.3	76.6
B-405	80.3	72.4	69.9	73.6	65.2	63.7	88.1
D-260	56.8	51.5	50.3	46.4	46.2	48.9	68.4
E-200	45.6	38.5	43.9	38.5	37.3	37.8	47.3

*Average of 3 values.
 †Length: diameter ratio: less than 1.

low chloride permeability (450 and 425 coulombs, respectively). The other — D-260 and E-200 — exhibits somewhat higher permeability (1250 and 1550 coulombs, respectively). The results obtained for A-315 and B-405 are in accordance with the findings of Perraton, Aitcin, and Vezina² and Aitcin and Laplante.³

According to Whiting,⁴ a very low chloride-ion permeability (as in concretes A-315 and B-405) is obtained in latex concrete, whereas the permeability of D-260 and E-200 corresponds to concrete with w/c lower than 0.40, although the initial nonsilica-fume concrete mix had a high w/c , and water also was added later to the mix to introduce the silica fume. However, the chloride-ion permeability of all four sections is much lower than that of a nonsilica-fume concrete with a high w/c .

Compressive strength

At the end of the 10-winter exposure, the compressive strength of the four concretes varied from 47 to 88 MPa (6800 to 12,800 psi) (Table 3), and is directly proportional to

the cement content. Interestingly, the compressive strength in each case increases at age 10: 9 percent for A-315 and B-405, 17 percent for D-260, and 4 percent for E-200. A certain degree of variation in strength values was recorded for each section over the 10-year period as well.

Several factors, or a combination thereof, can explain the variation in strength values over the years. One is the low length/diameter ratio (less than 1) of some of the cores used for testing. Alternatively, variations can arise from minor differences in experimental conditions, since it is difficult to control all the testing parameters precisely over a long period of time. Lack of homogeneity of the mixes due to the difficulty in placing these concretes (stated earlier) may also have been a factor.

Additionally, the suggested correction factor of 0.87 used for cores with length/diameter ratios smaller than 1 may not represent the true correction factor. According to ASTM C 39-86, this factor was established for concrete with compressive strengths between 13.8 and

41.4 MPa, whereas the present series of concretes has compressive strengths greater than 41.4 MPa.

Microstructure at age 10

The objective of microstructural characterization of these concretes by SEM/EDXA, XRDA, and optical microscopy was to determine if any deterioration had taken place over a period of 10 years. Thus, the state of the aggregates also had to be carefully examined.

Petrographic examination of aggregates and concrete

Petrographic examination of thin sections under a transmitted light polarizing microscope revealed that the concrete comprises 95 percent limestone as coarse aggregates, the remainder being clayey gravel.

Because the limestone is mostly composed of extremely fine, often cryptocrystalline, anhedral calcite (Fig. 1), the characteristic calcite cleavage was rarely observed. A small quantity of medium subhedral to anhedral calcite crystals is present, but these crystals do not show any disjoining with their finer counterparts.⁵ Medium-size anhedral quartz crystals, though not profuse, are associated mostly with the calcite. Graphic intergrowth of β -quartz and feldspar was observed in some parts, but a reddish tint was more common, giving the rock a ferruginous appearance.

The fine aggregate is composed of quartz and feldspar, the latter with its characteristic twinning feature. The feldspar does not exhibit any mineral alteration, nor does the quartz have a high extinction angle that can make it a potential candidate for alkali-aggregate reaction.⁶

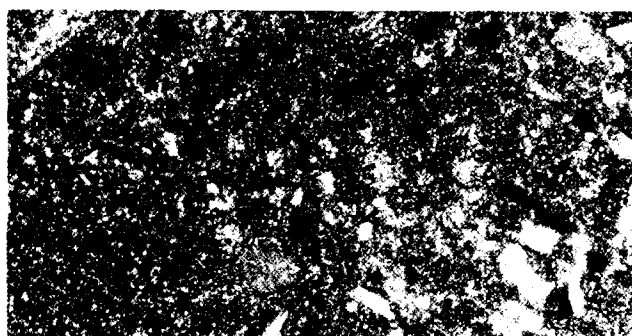


Fig. 1 — Extremely fine textured limestone comprising anhydrous calcite in coarse aggregate.

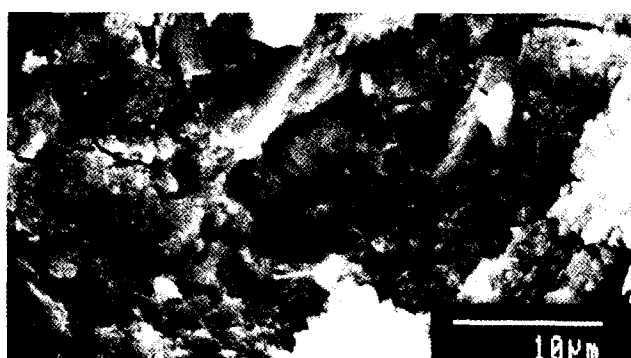


Fig. 3 — Fissures in the hydrated cement paste of B-405 concrete.



Fig. 2 — Fine fissures in the hydrated cement paste of the B-405 concrete.

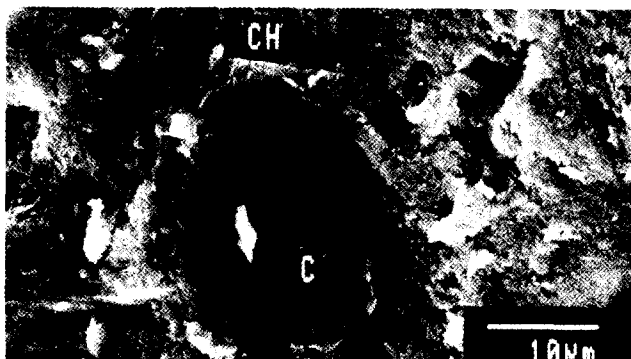


Fig. 4 — Partly hydrated cement grains in B-405 concrete.

No reaction rims have appeared to suggest alkali-aggregate reaction, and inter- and intragranular fissures are rare in these aggregates. In general, there is no evidence of the disruptive action of repeated exposure to freeze-thaw conditions upon the aggregates.⁷

The hydrated cement paste (HCP) of the B-405 concrete, contains a number of fine fissures (Fig. 2), as contrasted to the HCPs of the other three concretes.

SEM/EDX analysis

Based upon the frequency of microfissures, determined qualitatively from optical microscopy that follows the order: B-405 > D-260 > A-315 > E-200, SEM/EDXA examination of the two extreme cases, B-405 and E-200, was carried out.

The microfissures in B-405 were also clearly visible under the SEM (Fig. 3). Though less than 1 μm wide, they are frequent in the paste. Partly hydrated cement grains are still present (Fig. 4). Hexagonal plates of AFm phase also occur in abundance, either in the larger

pores (Fig. 5) or in the paste. Except for the presence of microfissures, the HCP has retained its density (Fig. 6) and is composed of amorphous C-S-H gel with low Ca/Si, which is characteristic of pastes containing silica fume. Stacked-type CH crystals, though not perfect morphologically, are also visible (Fig. 7). Some oriented CH crystals have developed in parts of the paste-aggregate interface (Fig. 8).

In contrast to B-405, the CH appearing at the E-200 concrete paste-aggregate interface is much more granular in nature, smaller in size, and less oriented, (Fig. 9), i.e., its degree of crystallinity is lower than that of B-405. The interface is strong, with no visible signs of debonding. CH crystals of similar morphology as B-405. The interface is strong, with no visible signs of debonding. CH crystals of similar morphology as B-405 are also present in the paste. Some large unreacted silica fume particles remain in the paste (Fig. 10); however, in place of AFm, this concrete displays an abundance of AFt (Fig. 11). There is evidence of hollow-

shell hydration with ill-crystallized chloroaluminate in the center (Fig. 12), but partly reacted cement grains are much less frequent in this concrete.

XRDA

Confirmation of chloroaluminate in E-200 concrete was obtained by XRDA. The quantity of AFm was also found to be highest in B-405.

Analysis of CH generated as a function of cement content in these concretes was performed using the integrated intensity of CH peaks at 18.10 and 34.08 deg 2θ. Fig. 13 clearly shows that an increase in cement volume from 200 to 315 kg/cm³ (337 to 530 lb/yd³) gives rise to higher CH, irrespective of the $w/c + s$, which decreases from 0.80 to 0.52. Interestingly enough, a lesser quantity of CH is generated at 400 kg/cm³ (675 lb/yd³) cement content, or the B-405 concrete.

Discussion of concrete microstructure

None of these concretes can be designated as low $w/c + s$, which explains the appreciable quantity of



Fig. 5 — Hexagonal AFm plates in a large pore.

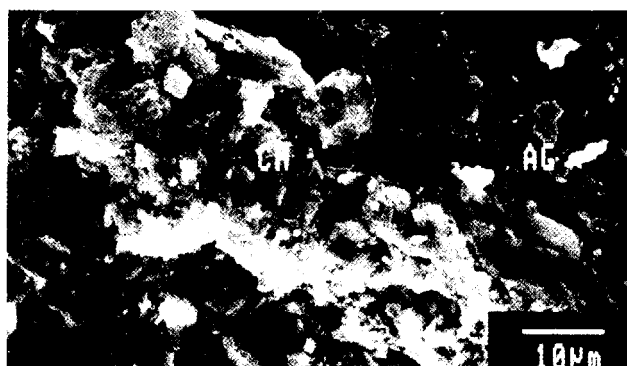


Fig. 9 — Granular and smaller CH crystals at the paste-aggregate interface of E-200 concrete.

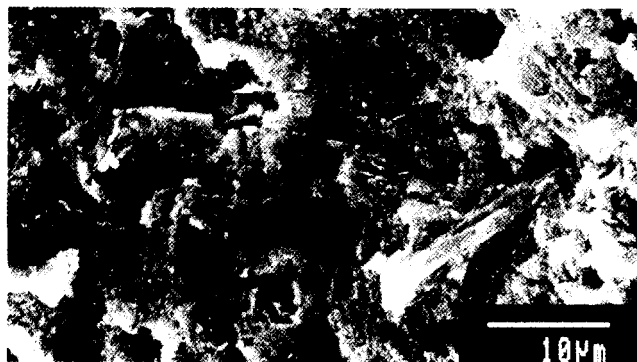


Fig. 6 — Dense paste composed of amorphous C-S-H gel.

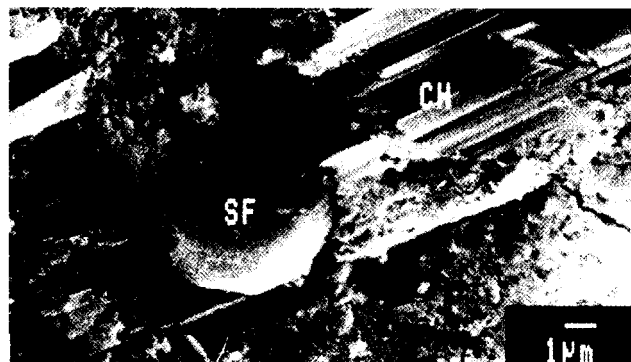


Fig. 10 — Large unreacted silica fume particle.

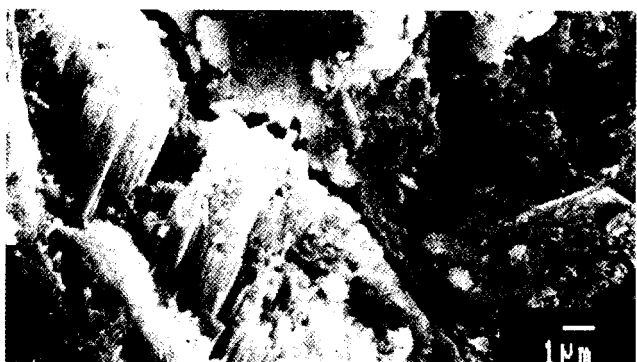


Fig. 7 — Stacked type of CH crystals in the paste of B-405 concrete.



Fig. 11 — AFt needles in a vacant space.



Fig. 8 — Oriented CH crystals in parts of the paste-aggregate interface.

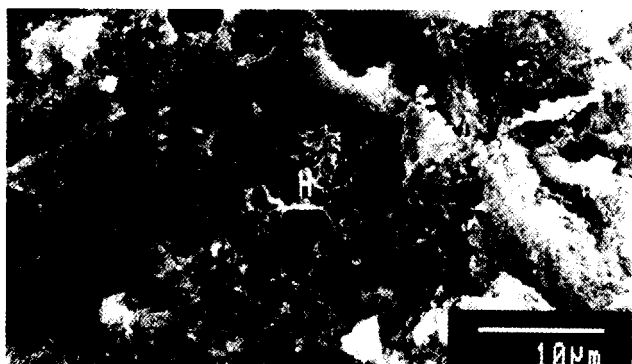


Fig. 12 — Hollow-shell hydration with chloroaluminate in the center.

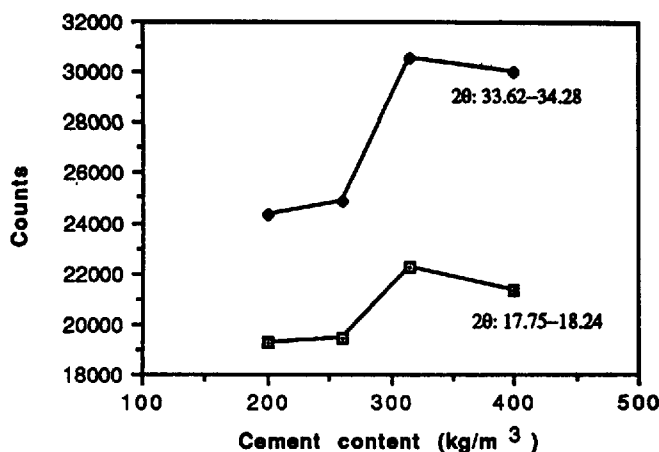


Fig. 13 — Plot of CH versus cement content (integrated intensity of CH peaks).

well-crystallized CH in these concretes, including the E-200 concrete with its relatively low cement content. An abundant supply of water led to the rapid hydration of cement grains and the simultaneous generation of CH, and the speed of CH evolution obviously exceeded its rate of consumption by silica fume. The trend of CH generation seen in Fig. 13 indicates it to be a function of cement content; it also suggests, but cannot confirm in the absence of $w/c + s$ data on B-405 concrete, that it is somewhat interdependent on the $w/c + s$.

Microscopic evidence of microfissures in B-405 concrete is a result of the high volume of cement used to make this concrete, which could have caused the shrinkage cracking. Also, no curing compound was applied to the concrete placed on the first day, although it was a part of the specification. Curing compound was applied as drying shrinkage cracks began to develop within the first 24 hours, but it proved to be too late. This also could have led to plastic shrinkage cracks due to a lack of bleed water. However, in the other sections curing compound was applied immediately after finishing of the surfaces. The presence of partly hydrated cement grains in this concrete can also be related to its high cement content.

The presence of chloroaluminate arises from the percolation of Cl^- ions from deicing salts.⁸ Although a precise explanation cannot be given at this stage as to why its occurrence is higher in the E-200 concrete, it is possible that its specific location in the field makes it more vulnerable to Cl^- ion permeation, i.e., either this section received a

greater application deicing salts or there is greater accumulation of salt where the E-200 concrete is located. This needs further investigation. Nonetheless, the appearance of AFt in this concrete can be explained in terms of the unstable nature of chloroaluminate that results in conversion to AFt.⁹ On the other hand, the formation of AFm in the B-405 concrete can be said to be a natural phenomenon, arising from the hydration of ASTM Type I/II cement.¹⁰

Conclusions

Although the compressive strength measurements exhibit some differences in values over the total testing period of 10 years, it is clear that compared to the 1-year values the strength of cores increases from 4 to 17 percent at 10 years. The chloride-ion permeability of two concrete sections (A-315 and B-405) is very low and comparable to latex concrete, whereas in the other two (D-260 and E-200) it is low in comparison to nonsilica fume concrete, despite its high $w/c + sf$.

The hydrated cement paste of these concretes, even after such a long field exposure under severe climatic conditions and regular deicing salt application, is relatively dense and unaffected, with the exception of the B-405 sample, which manifests an unusually high degree of microcracking.

When comparing the present microstructure with that at age 1 year,¹ it can be stated that mineralogical alteration has indeed occurred. For example, the B-405 concrete has developed AFm phase (not observed at 1 year), whereas E-200 shows evidence of AFt and chloroaluminate,

the latter mineral most likely formed due to the percolation of deicing salts, though this is not a cause for major concern.

The aggregates show no evidence of deterioration, and the paste-aggregate bonding is still strong. There is no evidence of cement components leaching out due to increased permeability. As a matter of fact, the permeability is still very low.

It can be said that these four field concretes in which silica fume was used are still in very stable condition, with satisfactory durability properties even after 10 years of service life in severe exposure conditions.

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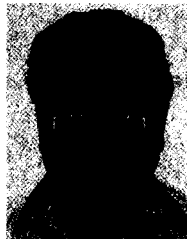
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Selected for reader interest by the editors.

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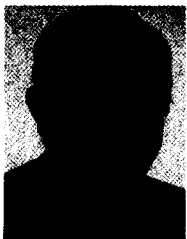
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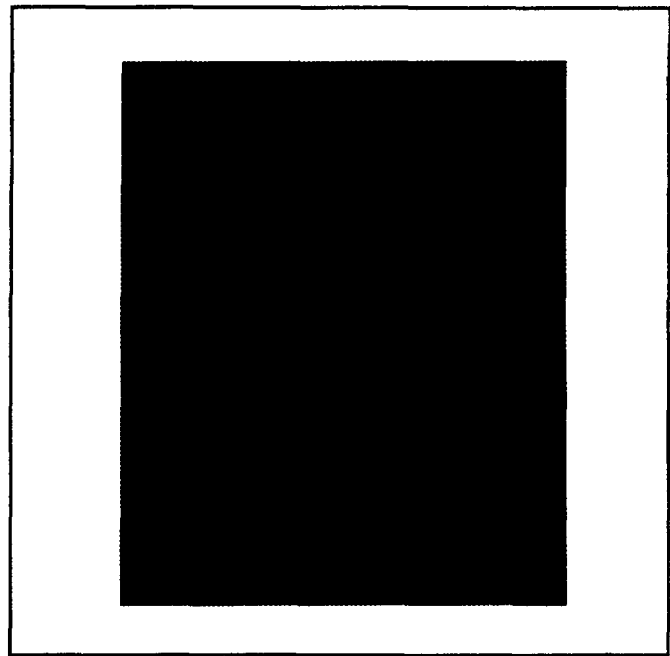
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Silica Fume Concrete in Melbourne, Australia

by Ian Burnett

During the latter part of the 1980s, construction in Melbourne, particularly in the central business district, was at an all time high. Much of the concrete was specialized, such as high strength concrete for pumping to 50 stories, general concrete for pumping to 55 stories, and shotcrete for site retention and other applications. Silica fume concrete (SFC) was being used in Australia — it had been produced in Tasmania since 1977, mainly for economic reasons — but it was not being used in Melbourne or anywhere else on the mainland.

At the Concrete Institute of Australia (CIA) Conference on Supplementary Cementing Materials in Sydney in 1988, the significant benefits and potential of SFC were clearly illustrated. This conference and the high level of construction activity in Melbourne provided the impetus to spur the development of SFC for a variety of applications, including:

- Shotcrete for site retention.

- High strength and very high strength concrete (HSC and VHSC).
- Pumped concrete for tall buildings.
- Increased resistance to aggressive ground waters.
- Tunnel linings.
- Vertical shotcrete walls.
- High rise pump blowback.
- Precast concrete piles.

SFC in Australia

The Readymix Group and Pioneer Concrete Services began producing SFC in Tasmania in 1977 using silica fume (SF) supplied by the Tasmanian Electro Metallurgical Company (TEMCO) at Bell Bay. This fume typically contains approximately 90 percent amorphous SiO_2 , 3 percent Fe_2O_3 , and 2.5 percent each of C and Al_2O_3 .

The TEMCO SF available from then until now has been uncondensed and has a density of 200 to 300 kg/m^3 (300 to 500 lb/yd^3). It's handling characteristics had been variable. It normally is transported

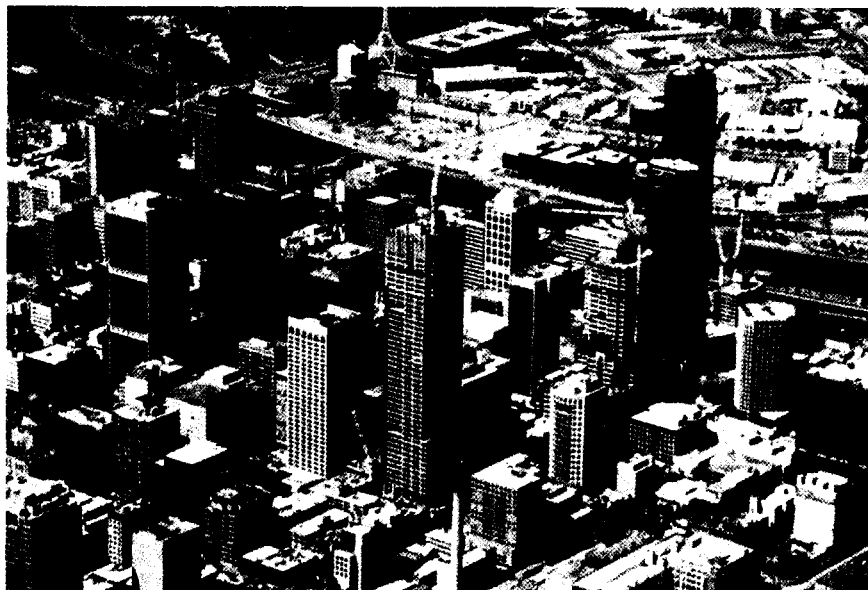
in bulk cement tankers and blown into conventional cement silos. Occasionally it takes some hours to unload the bulk cement tanker because the SF packs and contains a very small proportion of condensed moisture. Despite its handling difficulties, it has generally been of good quality and produces good quality concrete. In some instances it has been used in special applications, for example fiber-reinforced shotcrete in tunnelling by the Hydro Electric Commission.

On the Australian mainland, SFC production was extremely small and restricted to a very few applications until the late 1980s. In early 1990, Barrack Silica (now Microsilica Pty. Ltd.) in Western Australia began the collection and densification of SF. This SF was used in some of the work described in this article.

Potential of SFC

SFC has always had significant potential. The papers presented at the CIA Supplementary Cementing Materials Conference in Sydney in 1988, and the Trondheim, Norway, Conference in 1989, highlighted its numerous practical applications and benefits.

In the building boom in Melbourne in the latter half of the



The Melbourne central business district.

Table 1 — Condensed silica fume properties.

Chemical properties	
SiO_2	88% (min)
C	2.5% (max)
Fe_2O_3	2.2% (max)
Al_2O_3	2.2% (max)
Na_2O	1.8% (max)
K_2O	2.5% (max)
MgO	3.5% (max)
SO_3	1.5% (max)
Loss on ignition	3.5% (max)
Physical properties	
Specific surface	15 to 20 m^2/gm
Particle size	0.1 to 0.2 μm