High-Performance Silica Fume (Microsilica)–Modified Cementitious Repair Materials

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Basic information about silica fume (microsilica), portland cement–based materials containing silica fume, and the use of these materials in the repair of structures is reviewed in this paper. Information is presented about high-performance (strength in excess of 20,000 psi) repair materials containing silica fume. Various applications are discussed, including those involving grout, underwater concrete, shotcrete, and concrete repairs.

This paper accomplishes two goals. The first is to present basic silica fume (microsilica) information and to introduce repair materials containing silica fume (SF). The second is to describe high-performance materials containing SF that usually achieve compressive strength around or in excess of 20,000 psi and that are suitable for many repair applications.

SILICA FUME BASICS

Also referred to as microsilica and as condensed silica fume, SF is the solid material collected from the exhaust gases of submerged electric arc furnaces during the production of silicon or silicon alloys. Before the mid-1970s nearly all SF was discharged into the atmosphere. After environmental concerns necessitated collecting and disposing SF in landfills, it became economically justified to use it in various applications.

SF particles are typically spherical, average about 0.15 micron in diameter, have a specific gravity of 2.2, and are gray in color. Usually, the particles are collected as a dry powder. The powder, which has a bulk density between 5 and 27 pcf, may be added as is to concrete. To improve handling characteristics and to make it more economical to ship, it may be either slurried with water or densified.

In the United States, SF is usually added to portland cement (PC) concrete in the range of 3.8 to 21 percent by weight of cement. Applications employing SF to improve corrosion protection of reinforcing steel tend to use 3.8 to 10 percent dosages. High-strength applications often use dosages between 7 and 21 percent and the 7½ to 20 percent dosage range covers most grout, chemical resistance, abrasion, abrasion-erosion, and cavitation resistance applications. In PC concrete, SF improves cohesion of the fresh concrete, and it enhances many of the hardened properties, like compressive strength, bond strength, abrasion resistance, abrasion-erosion resistance, cavitation resistance, permeability (reduced), frost resistance, and resistance to many chemical solutions.

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It is beyond the scope of this paper to more fully describe SF and SF concrete. These topics have been treated in numerous publications (*1–6*). By mid-1989 over 700 articles about materials containing SF had been published.

SF-BASED REPAIR MATERIALS

To facilitate the discussion about repair materials containing SF, these materials are grouped into the general categories presented in Figure 1. The high-performance (compressive strength exceeding 20,000 psi) materials are the primary focus of this paper. The lower-strength repair materials containing SF are discussed first, presented by category.

Grout

Grouts containing SF have been employed by various state departments of transportation to improve the bond between base concrete and repair overlays (*7,8*). These SF bonding grouts have also been used during parking garage restoration work to improve the bond between overlays or patches and the base concrete. SF grouts used in these applications tend to employ a SF-to-cement ratio by weight between 7½ and 15 percent. In some cases water-reducing admixtures are used, and many of the grout formulations contain fine aggregate. SF grout is noticeably more cohesive (less segregation and bleeding) than plain PC grout. SF grout has been used in anchor applications.

Various proprietary bagged grout and patch products containing SF are commercially available. The SF is added to improve bond, increase strength, and reduce permeability.

Underwater Concrete

The cohesiveness of mixtures containing SF makes them suitable for underwater applications. Several successful underwater repairs of dams have been completed. The first such repair in the United States occurred in the summer of 1988 when 2,300 cubic yards (cy) of a maximum 1-in. coarse aggregate concrete containing 48 pcy of SF was placed in the Dashields Lock & Dam, Milepost 13.3, on the Ohio River. That same year, 127 cy of concrete containing about 93 pcy of SF and ¾-in. maximum-sized coarse aggregate was placed in the Point Marion Lock & Dam No. 8 on the Monongahela River.

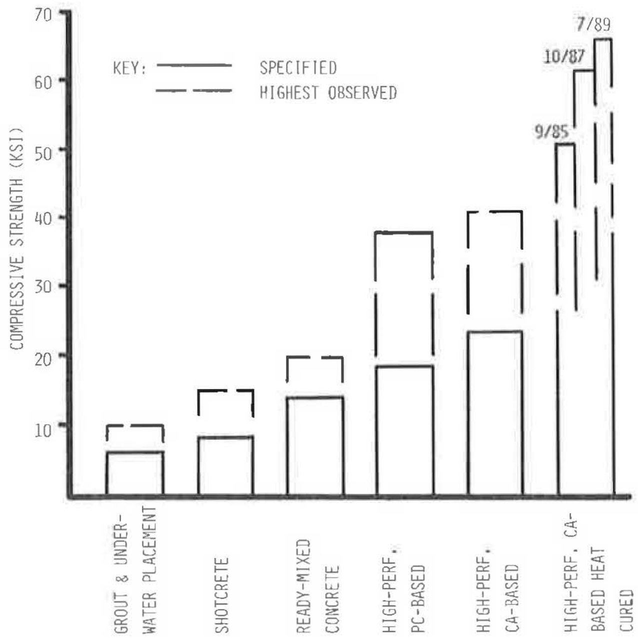

FIGURE 1 Strengths of SF concretes.

A smaller volume of similar SF concrete was used during a repair at the London Locks on the Kanawha River in West Virginia. The water-to-cementitious materials (W/C) ratio of these concretes varied between 0.34 and 0.40, and the concretes achieved 28-day strengths between 8,000 and 10,000 psi.

One project in England used an SF grout in a tremie placement in which the coarse aggregate was preplaced.

Shotcrete

SF shotcrete, both dry process and wet process, is used worldwide, and in some countries it is used extensively. For example, over 90 percent of the shotcrete used in Norway contains SF. Although most of the shotcrete work is in new construction, SF shotcrete has been commonly used as a repair material (*9,10*).

Reasons for choosing SF shotcrete include reduced rebound (hence reduced materials and clean-up costs), thicker placements, better bond, and improved durability. Usually SF dosages for shotcrete lie between 7½ and 10 percent, but dosages as high as 15 percent have been used. Strengths exceeding 15,000 psi were reported for trial work associated with the 1983 Bureau of Mines repair in Lake Lynn, Pennsylvania (*11*).

SF Concrete

Although research investigating the properties of SF concrete (concrete containing SF) began almost 40 years ago, and SF concrete has been used intermittently since the mid-1960s in Japan, SF has been commercially available for manufacturing concrete only since the mid-1970s in Norway and since the early 1980s in the United States. SF concrete is now routinely used for repair work in many countries and continents, including North and South America, Europe, Iceland, and Australia.

SF concrete has been used for repairs in many applications, and some of these are listed in Table 1 along with the SF dosages and several W/C ratios typically employed. Perhaps the largest volume of SF concrete is employed in repair applications to protect steel from corrosion. Decks of many parking garages and bridges have been either partially or completely replaced with SF concrete for this reason. Also, approach slabs, traffic barriers, sidewalks, and other portions of bridges have been replaced with SF concrete (*7*).

Some bridges, such as the over 1,200-ft-long Landon B. Hassler Memorial Bridge in Tennessee, used the high-early-strength property of SF concrete to enable rapid opening of structures to traffic. Portions of pavements in Norway have been replaced with SF concrete, and these have already significantly outlasted other pavements exposed to similar steel-studded tire loadings. In another abrasion-resistant application, an approach lane to a weighing platform at the New Enterprise Stone and Lime Company, Roaring Spring, Pennsylvania, has already survived more than three times longer than concrete previously in use.

Refractory Concrete

A relatively large volume of calcium aluminate (CA)–based SF concrete is used in the repair of refractories. SF often replaces some or all of the CA cement. Refractory SF concrete for repair work is usually chosen because it is more durable than many other refractory concretes.

HIGH-PERFORMANCE SF-BASED MATERIALS

PC-Based Mortar/Concrete

The SF materials previously discussed—grout, underwater concrete, shotcrete, and concrete—are high performance in the sense that strength and the other properties mentioned are usually significantly improved relative to non-SF reference mixtures. The remainder of this paper focuses upon materials that are high performance in the sense that strength exceeds 20,000 psi.

History

During the late 1970s, high-performance PC-based SF materials were developed in Denmark. By 1982 some of these materials had been patented and were being provided to users in Europe and North America. These materials have been used to repair concrete exposed to very severe environmental conditions.

Materials and Packaging

High-performance PC-based SF materials are typically packaged in 50-lb bags, which are used in whole-bag increments and usually contain all the mortar or concrete ingredients

TABLE 1 REPAIR CONCRETES CONTAINING SILICA FUME

Portland Cement-Based Repair Application	Silica fume dosage range commonly seen (% added by weight of cement)	W/(C + SF)[1]
Abrasion (industrial floors, loading docks, pavements)	7% - 15%	≤0.45
Abrasion/erosion (stilling basins, spillways, sidewalls, baffles, river liners)	14% - 18%	<0.35, and in some cases <0.30
Cement replacement (low heat of hydration pier repair)	10%	<0.40
Chemical resistance (vats, floors, channels, slabs)	10% - 20%	≤0.40
Corrosion protection of steel, primarily due to low permeability and increased electrical resistivity (parking garages, bridges, piles)	3.8% - 10%	≤0.40
High early strength (bridges)	11% - 15%	≤0.45
Lightweight concrete (parking decks)	7½%	≤0.40
Marine environment (piers, docks, piles)	5% - 15%	≤0.45

Note 1: W/(C + SF) = water-to-(cement plus silica fume)

except water. Rarely, additional high-range water-reducing admixture (HRWR) might be added. Although the aggregate size and mineral composition may vary from one specific product to another, one of the more popular products uses ¼-in. maximum size calcined bauxite aggregate. A special PC cement is used to develop very high strengths. None of 26 other cements achieved equivalent strength. SF for these products is undensified and comes from the production of silicon. The amorphous SiO_2 content of such SF is above 90 percent. A large dose of dry HRWR is used to obtain W/C ratios below 0.24 with slump exceeding 8 in. Steel fibers may be added to the concrete for applications requiring enhanced toughness. Most commonly, ¾- or 1-in.-long fibers are supplied. Proportions of these products have been published (*12*).

Concrete Mixing

The concrete is typically produced at the repair site in ½- to 1½ cubic foot (cf) batches using either horizontal axis mortar mixers or pan mixers. After the bag contents have been emptied into the mixer along with the amount of water recommended by the supplier, the concrete is mixed for 10 min. Next steel fibers are added, if required, and the concrete is mixed an additional 5 min. In cases needing increased workability, additional HRWR is added.

Properties of Fresh Concrete

The fresh properties are usually as follows for the described material: slump = 8 to 10 in.; air content = 3.3 percent; unit weight = 170 pcf; initial time of setting at 70°F is just under 1 day (the setting of these concretes tends to be retarded, which may be attributed to very high admixture content). The concrete is highly cohesive.

Placement and Curing

As with all overlay or patchwork, careful preparation of the base concrete is important. Preferred results are obtained when the base is meticulously clean and in a saturated surface-dry condition. The material should be consolidated using mechanical equipment. Best results for flatwork occur when a vibratory screed is used. In most cases, surface texturing and curing should begin immediately. Extended wet curing (for at least 3 days), preferably using wet burlap covered with plastic, is recommended.

Properties of Hardened Concrete

Table 2 presents the properties of hardened concrete. Compressive strengths exceeding 20,000 psi at 28 days are typical. At later ages a small strength gain is observed (Figure 2). The highest strength reported for this material was 38,000 psi (*12*), and the author has achieved 28,000 psi. To achieve 28,000 psi, a small amount of dolomite coarse aggregate (ASTM C 33 No. 67 grading) had been added to the concrete. In another instance, 30 percent by weight gravel (ASTM C 33 No. 8 grading) at SSD moisture condition was added to the basic

TABLE 2 HARDENED PROPERTIES OF HIGH-PERFORMANCE PC-BASED CONCRETE CONTAINING SILICA FUME

Property	Result	Associated Compressive Strength
Compressive strength (n=6)		
@ 7 days	17,670 psi	
@ 28 days	21,110 psi	
Flexural strength (single point)		
@ 28 days (n=2)	2,690 psi	22,070 psi
Static modulus of	8,000,000 psi	24,000 psi
elasticity (16).	7,690,000 psi[1]	22,350 psi[1]
Poisson's ratio[1]	0.21	22,350 psi
Splitting tensile strength[1]	1,436 psi	22,350 psi
Direct tensile strength[1]	900 psi	22,350 psi
Double shear strength[1]	5,340 psi	22,350 psi
ASTM C666 procedure A, durability factor (n=2)		
Without air entrainment (3.3% air)	100[2]	20,000 psi[3]
With 12.0% air[3]	100[2]	11,660 psi[3]
AASHTO T277-83 Rapid Chloride Permeability	Very low	
Charge passed @ 42 days (n=3)	102 Columbs	18,140 psi

Note 1: Unpublished work conducted during 1984 by the Concrete Structures Bureau Laboratory, United States Bureau of reclamation, Denver, Colorado.

Note 2: No steel fibers used. All other mixtures used steel fibers.

Note 3: Air content was made high deliberately to determine the effect upon frost resistance. Associated strength of non-air-entrained prisms was nominally 20,000 psi.

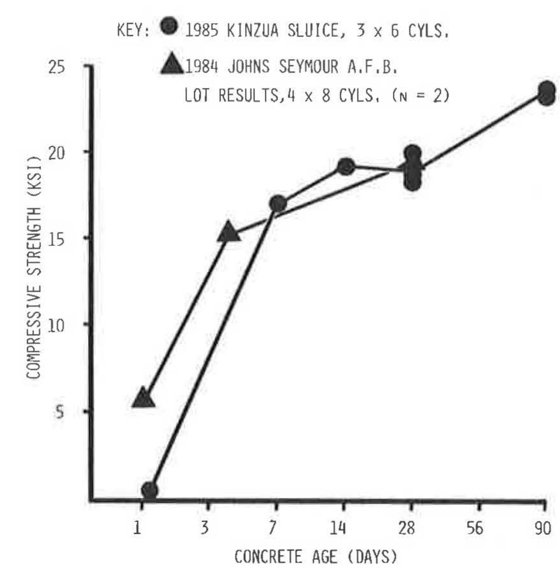

FIGURE 2 Two examples of strength development, high-performance PC-based SF-concrete.

product. Workability was improved in this case with only a small strength reduction, which was 20,060 psi (n = 4) for the modified mixture and 21,520 psi (n = 9 on three batches) for the initial mixture.

Flexural strengths higher than those of PC concrete have been observed. The mathematical expression for the flexural strength results shown in Table 2 may be expressed as follows: flexural strength = 18 (compressive strength)$^{1/2}$. Constants as high as 20 have been seen in mixtures in which steel fibers had been added. The factor for the dolomite-modified mixture was 20.1.

The results for static modulus of elasticity (E) are around 8 million psi. The ACI predictor equations for E somewhat overestimate the observed E by ½ to 3 million psi. Although at very high strength levels, this is also true for other PC concretes (*13,14*).

Poisson's ratio for the subject concrete, at 0.21, was the same as that found for the reference concrete.

The material shows clearly acceptable resistance to cycles of freezing and thawing even when air-entraining admixtures are not added.

The AASHTO T 277 rapid chloride permeability (RCP) result shown in Table 2 typifies those historically observed. The RCP shown in Table 2 is at the low end of the very low range.

The abrasion resistance results (Table 3) for the concrete were significantly better than those for the reference concretes. The favorable performance of the SF concretes in the field, however, suggests that the revolving disk-type abrasion tests understate the performance of very high-strength concretes (*15*). Comparative sandblasting testing has also indicated that the abrasion of the SF concrete is significantly higher than that of other concretes (*15*). Still another type of abrasion test was conducted in 1984 at the Waterways Experiment Station, Vicksburg, Mississippi, on the material that was ultimately supplied to a runway repair project. In this test a weight was dropped on a 1-in.-diameter steel cable under which panels of the steel-fiber-reinforced, high-performance PC-based material were placed. In these previously unreported tests, the SF material performed well even after sustaining 5,000 blows. The abrasion-erosion resistance results shown in Table 3 indicate that this property is over 14 times better than in conventional PC concrete.

The cavitation results, also shown in Table 3, indicate that having demonstrated a 99-fold improvement relative to the reference concrete, high-performance PC-based SF material may provide better cavitation protection than other PC-based materials.

Tests exposing the high-performance PC-based SF material to various chemical solutions—usually acids—were conducted, and it was found to outperform reference PC concrete (*15*). It is recommended, however, that if a chemically resistant repair material is needed, the concretes be evaluated first by testing them in the chemical solutions.

Concretes exceeding 10,000 psi have shown creep and shrinkage values less than those of lower-strength concretes (*12,14*). SF concretes have shown similar creep as PC concrete of comparable strength, although somewhat less shrinkage has been observed (*14*).

On the basis of the fresh and hardened properties of the high-performance PC-based SF material, it is believed that there are many transportation applications in which these materials can be used, like pavement patchwork and overlays in areas exposed to severe abrasion. Examples of projects that have used this material are described next.

TABLE 3 HARDENED PROPERTIES RESULTS FOR ABRASION, ABRASION-EROSION, AND CAVITATION TESTS

Property	Result: For High-Performance SF Concrete	Result: For Reference Concrete	Associated Compressive Strength
Abrasion			
° ASTM C779, procedure A, revolving disks, 60 min., mean depth of wear at 42 days. (n=3)	0.028 in.		19,330 psi
		0.038 in.	6,000 psi
° DIN 52-108 (German wear test) mean mass loss on saw-cut from slabs. (n=2)	0.74%		19,330 psi
		1.43%	6,000 psi
Abrasion/Erosion[1]	0.5%		24,000 psi
° CRD 63-80 volume loss of 12-inch-diameter specimens exposed to revolving steel balls in water for 72 hours (16).		>7%[2]	≤6,000 psi[2]
Cavitation[3]			
° Eight-hour exposure to venturi-type cavitation apparatus, subjecting nominal 4.5 by 4.2 by 12-in. prisms to an upstream pressure of 60 psi and a maximum water velocity of 70 ft/sec.			
Weight loss (n=2)	1.6 grams		22,354 psi
		131.5 grams	8,090 psi
Volume loss (n=2)	0.035 in.		22,354 psi
		3.485 in.	8,090 psi
Capacity of cavitation resistance relative to control	99X		23,354 psi
		1X	8,090 psi

Note 1: From reference 16.

Note 2: Concrete manufactured without specialty or hard aggregate commonly shows losses in excess of 7%.

Note 3: Unreported work conducted during 1984 by Concrete Structures Bureau Laboratory, United States Bureau of Reclamation, Denver, Colorado.

Examples of Projects

During November 1982 a small repair was demonstrated at the Dashields Lock & Dam on the Ohio River. Approximately

9 cf of concrete was placed in a nominal 3-in.-thick overlay in an area of existing deterioration. The high-performance material, which did not contain steel fibers, was screeded and finished with a steel trowel. An inspection in 1988 revealed that there was no evidence of deterioration of the overlay, although the adjacent concrete had deteriorated severely.

In April 1985 about 9 cf of steel-fiber-reinforced concrete was placed in a cavitation damage repair in Sluice No. 4 at the Kinzua Dam in northwestern Pennsylvania. After batching, the concrete was lowered to a boat that transported it to the sluice. The concrete was then carried through the sluice about 130 ft to the repair location. The concrete was placed and internally consolidated. Inspection of the casting in 1988 revealed no evidence of damage. The compressive strength development curves for this concrete are shown in Figure 2.

Columns of high-strength concrete, specified to have a compressive strength of 12,000 psi, were cored and repaired with PC-based SF concrete in 1988. An upward-directed plastic elbow was attached to each horizontal hole. Then the concrete was placed, aided by an internal vibrator. On the following day, the elbows were removed, along with the remaining concrete, which was still weak enough to be easily trimmed. At 3 days, cylinders cast with the repair concrete exceeded 16,000 psi.

To obtain high resistance to abrasion, approximately 40 cf of high-performance material was placed under the arresting gear at the end of a runway at Seymour Johnson Air Force Base in October 1984. (See Figure 2.) Arresting cables, located at the end of runways, are about 1 in. in diameter, and are supported 2 to 3 in. above the runway. Aircraft engage the cables with a tail hook in an emergency. When the aircraft wheels pound the cable to the runway, the underlying concrete is damaged. The overlay, which was flush with the adjacent pavement, ranged between 2 and 5 in. deep and was about 3 ft wide. The runway was opened 48 hr after placement. The concrete performed well, outlasting other materials that had been tested or used previously. This concrete was subsequently employed in similar applications.

CA-Based Mortar/Concrete

CA-based materials containing SF were developed in the mid-1980s. These are manufactured, packaged, and batched similar to the way that PC-based SF materials are packaged and batched. The CA-based materials, however, use more SF in the formulations, and they develop higher strength than the PC-based materials. The CA-based materials also exhibit a faster setting time than the PC-based ones.

The CA-based materials have been used in applications where high abrasion resistance is required (like warehouse floors) and in repairs where materials will be exposed to heat.

Proprietary CA-Based Material with Special Curing

When the CA-based materials are exposed to a special curing process (after initial wet curing, the materials are dried and heated), the strength and heat resistance dramatically increase. Cubes 3 to 4 in. cast with the material have developed strength in excess of 65,000 psi. The progression of the strength records using this material is shown in Figure 1.

Repair applications that have used the specially cured materials include replacing parts of equipment where formerly steel parts were used. In addition, abrasion-resistant repair plates and shapes have been cast and used with success. In some cases, when a repair material will be exposed to high-temperature (over 1,000°F) environments, this material is used.

Price

The delivered price of SF currently available across North America ranges from around $0.20/lb for bulk material for large jobs to $0.50/lb for bagged formulated products used on small jobs. This means that the additional cost of SF to a cubic yard of concrete ranges from around $10/cy for large jobs with low dosage levels (see Table 1) to around $50/cy for small jobs at high dosage levels. Handling by the concrete suppliers increases the price.

The price of the high-performance (≥20,000 psi) PC-based bagged materials without coarse aggregate is often around $4,000/cy when used in small quantities. The price of the CA-based repair materials usually begins at $4,000/cy.

CONCLUSION

SF-modified concretes have been used successfully in a variety of repair applications. The strong bond strength, high compressive strength, low permeability, and good durability of silica fume grouts, mortars, and concretes make them appropriate repair materials.

High-performance PC-based materials containing SF have been used successfully in severe environments. These materials are suitable for repair work in cavitation, abrasion-erosion, abrasion, and some chemical environments.

Although high-performance CA-based materials containing SF have only recently become available, the high strength, heat resistance, and durability of these materials make them desirable for certain applications.

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