Silica-Fume (Microsilica) Concrete in Bridges in the United States

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This paper reviews silica-fume-concrete (SFC) use in bridges in the United States. Although the focus is on bridge-deck overlays, other bridge-related applications are discussed, including full-depth decks, approach slabs, and piles. The reasons for using SFC include providing a chloride barrier, developing high early strength, achieving high ultimate strength, obtaining abrasion resistance, and improving bond strength. The concretes, representing silica-fume dosages between 5 and 15.5 percent, were placed successfully, although some difficulties were encountered. These dificulties, along with their solutions, are discussed. One silica-fume-concrete feature that required particular attention was the need to take measures to prevent plastic shrinkage cracking. An attempt is made to characterize the performances of the concretes, which are generally acceptable and encouraging. Further experimental work with silica-fume concrete is being done, and the material is now being specified in bridges.

Silica-fume concrete (SFC) has been used in bridges outside the United States since the 1970s (*1*); in some countries it is commonly specified to provide generally improved durability. Silica-fume concrete has been used with increasing frequency in bridge decks and associated structures in the United States since 1983, and this work is reviewed herein.

Many articles have described silica fume (SF) and its effect on portland cement concrete (*2–4*). Briefly, silica fume—a term often used interchangeably with the term microsilica—is collected from exhaust gases during the production of silicon or ferro-silicon alloys. Most SFs contain at least 85 percent amorphous silicon dioxide (SiO_2) and have a specific surface above 20 m^2/g. Silica fume is a highly reactive pozzolan that refines the portland cement paste pore structure. Usually, addition of SF to concrete significantly reduces permeability and improves many of the more significant concrete properties.

Silica-fume dosages used in bridges commonly lie at 5–15.5 percent, expressed as an addition by weight of the cement. Most of the bridge-related projects to date have used SF supplied from wet (sometimes called slurry-type) SF-based admixtures. Commercially available formulations of these wet SF admixtures usually contain, by weight, 45–50 percent SF, 47.5–51 percent water, and 2–4 percent other components, which may include chemical water-reducing admixtures (WRA) and/or high-range water-reducing admixtures (HRWRA). The dry SF-based admixtures typically contain at least 85 percent SF.

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BRIDGE-DECK OVERLAYS

The experiences of owners that have investigated using SFC as a bridge-deck-overlay material are presented here. The slab-type placements shared many similar operations: preparing the base to a moist-surface condition; applying bonding grout (for overlays); consolidating with internal vibration; screeding, and in the case of roller screeds, further closing the surface with a drag pan and a wet burlap drag; floating; applying a tine surface texture; and curing by immediately covering with wet burlap and plastic. This series of operations is designated by the phrase "in the standard manner" in this paper, and exceptions to this procedure are noted.

Ohio Department of Transportation

The Ohio Department of Transportation (ODOT) placed an experimental 15.5 percent SFC overlay in October 1984 during rehabilitation of Bridge No. ASD–511 along State Route 511 about 2 mi north of Ashland. It is believed that this placement represents the first of its kind in the United States. Silica fume concrete was investigated as a potential alternative to latex-modified concrete (LMC) (*5*). One lane of this bridge received an LMC overlay, and 15.4 yd^3 of SFC were placed on the other lane. The minimum overlay depth was 1.5 in., and the average depth was 2.3 in. The non-air-entrained concrete (Table 1) was supplied from a mobile mixer, with the wet SF-based admixture being pumped from drums. After a trial run, concrete was placed in the standard manner using mortar from the concrete for bonding grout and using a roller screed of the type commonly used to place LMC. A portion of the lane was covered with curing compound, and the remaining part was covered with wet burlap and plastic. After 2 days, the burlap and plastic were removed; and the lane was opened to traffic on the fourth day. An ODOT inspection at 1 week showed a blemish-free surface.

Rapid freezing-and-thawing results were poor (Table 1) because, as expected, the air-void spacing factor was high. The spacing factor was nearly four times greater than the 0.008-in. figure commonly associated with achieving good frost resistance, and the specific surface, at 168/in., was lower than the minimum 600/in. figure that is clearly acceptable. A bridge inspection by the author in July 1985, though, found no cracks; and it revealed generally blemish-free surfaces in both lanes. An ODOT inspection during July 1987 again found the concrete to be performing satisfactorily even though several cracks were seen in the LMC lane, and two were observed in the SFC lane. The largest crack was 16 in. long, 0.03 in. wide,

TABLE 1 CONCRETE PROPORTIONS FOR ODOT, KyDOH, AND NYSDOT OVERLAYS

State Agency	ODOT		KyDOH		NYSDOT	
Year	1984	1987	1985	1985	1984	1985, 1986
Bridge	Ashland	Avery Rd.	Three Rivers Power Plant	N/A	N/A	The Syracuse Project
Trial, Overlay, or Lab	Overlay	Overlay	1st Overlay	Lab	Lab	Overlays
Silica Fume Dose[a] (%)	15.5	15.0	15.5	15.5	13.9	14.0
Cement, Type 1 (lb/cu yd)[b]	658[c]	698[c]	658[c]	658[c]	694[h]	680[h]
W/(C+SF)[b]	0.35	0.34	0.33	0.33	0.31	0.30±
Slump (in.)	4.0-11.0[d]	6.5-8.0	7.0-8.5	10	7.5	6.5-8.0
Air Content, Fresh (%)	5.2	9.1-9.8	8.5	8.8	2.2	5.0-9.0
Strength: (psi)						
Compressive	6880	6060-6380	10800	8190 @ 7d	11000	9000 @ 7d
Flexural	940	990-1080				
Hardened Air system	ODOT W.Dolch[e]	ODOT	P.D. Cady[e]	KyDOH		
Air Content (%)	5.5 4.7	--	6.71	9.02		
Specific Surface (1/in.)	168 162	620	525	623		
Spacing Factor (in.)	0.030 0.032	0.004	0.0083	0.0052		
Freezing and Thawing						
Durability Factor:						
@ 300 cycles	5.5[f]	97.5-103.1	85[fg]			
@ 352 cycles			60-70[fg]	95		
Weight Loss[i] (%)		0.03-0.05			0.55	0
Chloride Content at all depths[j] (%)					0	

Note a: SF dose is expressed as a percentage, by weight, added to the cement. Note b: W/(C+SF) - water-to-(cement plus silica fume), by weight. Note c: 3/8-in. limestone. Note d: Slump was varied deliberately. Note e: W. Dolch is a professor of Civil Engineering at Purdue University. P. D. Cady is a professor of Civil Engineering at Pennsylvania State University. Note f: ASTM C666, procedure B. Note g: Limestone had a history of D-cracking in concrete. Note h: 1/2-in. limestone. Note i: 25 cycles at one cycle per day in a 10% sodium chloride solution. Note j: 3% and 10% sodium chloride solutions, 95-day ponding.

and about 1.25 in. deep (cored). Chain dragging indicated good bond.

A second SFC overlay was placed on the two-lane Avery Road Bridge over Route 33, near Dublin. This time the concrete (Table 1) was air-entrained to improve frost resistance. Subsequent to placing a trial slab, the southbound lane was constructed in April 1987, and the northbound lane was cast in May. The concrete was truck-mixed prior to the 45-min trip to the job site where it was discharged without further slump adjustment. Concrete was placed in the standard manner using a cement-sand bonding grout and a roller screed. The placement proceeded smoothly. The finish was acceptable, and at 3 mo no cracks were seen. Rapid freezing-and-thawing tests were acceptable, and the hardened concrete air-void tests revealed the presence of a traditionally acceptable air-void system.

ODOT is expanding the use of SFC overlays. Approximately 120 yd^3 of air-entrained 15-percent SFC was placed in a full-depth application in August 1987 for the Plain City Bridge on Route 161 in Madison County. Again, rapid freezing-and-thawing tests were acceptable. Durability factors ranged between 95.5 and 101.1, the spacing factor was 0.008 in., and the specific surface was 550/in. The Route 422 extension project in Cleveland (ODOT Project No. 462) will require approximately 500 yd^3 of SFC in 10 bridges. For each bridge, one lane will receive an SFC overlay, and one lane will receive a high-density overlay. This work was planned for spring of 1988. Also, two other ODOT bridge deck overlays are currently being bid in Barnesville, Ohio.

University of Cincinnati

During May 1986 the University of Cincinnati placed overlays on two pedestrian walkways using about 25 yd^3 of 5-percent SFC. Also, one 65-ft-long three-span full-depth pedestrian bridge was cast. These placements were successful, and the university subsequently constructed a parking garage with SFC.

Kentucky Department of Highways

On the evening of May 30 and the morning of May 31, 1985, a 15.5 percent SFC (Table 1) minimum 1.25-in.-thick overlay was placed by the Kentucky Department of Highways (KyDOH). The three-span structure (Bridge No. 1120–44) services an access road to the Three Rivers Power Plant near Seebree. At least one loaded coal truck per minute travels toward the plant on what is now the SFC lane. Concrete was produced in a mobile mixer, and the wet SF- based admixture was supplied from drums. On May 30, concrete was placed in the standard manner using mortar from the concrete for bonding grout and using a roller screed initially. The roller screed was in disrepair, and the initial overlay surface closure was unacceptable. Bull-floating improved the surface, and a fine-broom texture was applied. Due to various delays some plastic shrinkage cracks developed in the segment over the second pier before the concrete was covered with wet burlap and plastic. Only two spans were placed on May 30. On May 31 a reciprocating beam vibrator—the type commonly used for high-density concrete—was used for the third span with excellent results. In addition to the finishing equipment change, the fine aggregate-to-aggregate percentage was increased from 50 on May 30 to 55 on May 31.

Durability factors as defined by ASTM C666, procedure B (Table 1) for the overlay concrete were around 85 at 300 cycles; but after 352 cycles, performance dropped off. The air-void spacing factor was 0.0083 in., which just exceeded the traditionally acceptable 0.008-in. maximum figure. It was noted that the limestone was known to cause D-cracking in concrete. Subsequent laboratory tests (Table 1) with a different coarse aggregate and batching in a drum mixer produced durable SFC, having a durability factor over 95 at 352 cycles. This concrete, incidentally, showed a spacing factor of 0.0052 in.

The bridge was inspected regularly. At 4 mo, no changes were seen. At 9 mo, a few cracks were seen in the May 31 concrete near the second pier, and more were seen there after 2 yr. Although the cracking was disappointing, the overlay appeared to be functioning well as a chloride barrier. There were no spalls or delaminations, and the original surface texture was still visible, indicating high wear resistance. It was noted that there were no cracks seen in the outbound lane that was made with high-density concrete. There was interest in placing future overlays with a higher air content to improve frost resistance.

New York State Department of Transportation

Beginning in February 1984, the New York State Department of Transportation (NYSDOT) studied in the laboratory a non-air-entrained 13.9-percent SFC (Table 1) and concluded that the SF-based admixture could enhance strength and decrease water and chloride permeability of concrete. Silica-fume concrete was considered to be a potential alternative to LMC and high-density concrete. By June 1985, several 2-in. minimum thickness experimental air-entrained SFC overlays were scheduled into bridge repair work on the east side of Syracuse (Project No. D251436) along with more than a dozen LMC overlays.

During 1985 two bridges received SFC. One was a 4.5-yd^3 base repair (Bridge No. BIN 1093550), and the other was an overlay (Bridge No. BIN 1093562). Wet SF-based admixture, added first to the truck mixers, was dispensed from a 6,000-gal-capacity mobile dispenser. Typically the 6-yd^3 loads (Table 1) were mixed 100 revolutions before being discharged at about 25 min, often after slump adjustment. Concrete was placed in the standard manner using a vibratory screed for the base repair, which worked well, and using a roller screed for all other placements. There were cases of poor surface closure and plastic shrinkage cracking with both SFC and LMC when the roller screed was used. The SFC, though, did show good workability retention. Also, the grooves that were saw-cut into all the SFC overlays were made without raveling or spalling.

Silica fume concrete placements in 1986 proceeded smoothly. The previously experienced plastic shrinkage cracking was eliminated because these overlays were cast in the evenings when evaporation rates were lower and more favorable for placement. Additionally, proper adjustment of the roller screed, increased consolidation, absence of delays, and a higher fine aggregate-to-aggregate ratio served to improve results. After further trial batch work, the northbound east lane of bridge number BIN 1093562 was placed on May 14. On June 24, the one-lane exit ramp from Route I–690 eastbound to Route I–481 northbound (Bridge No. B191093520) was placed. A small portion of BIN 1093562 was cast on July 15, and the last placement under this contract (Bridge No. 1093520), on August 2, used 21 yd^3 of SFC with no problems. Typically, the concrete was cured under wet burlap for 1 day, then the burlap was removed and the concrete was cured under plastic for 3 more days.

An NYSDOT inspection in 1987 showed that one lane of the BIN 1093520 overpass was unblemished and the other lane showed reflection cracks. There was a question about whether the affected lane received adequate curing. Visual inspection indicated wear resistance better than normally seen, and no scaling or popouts were observed. Freezing-and-thawing tests on cores from the last SFC placement showed only insignificant weight loss (Table 1). The NYSDOT construction report for the Syracuse overlays (*6*) concluded that SF overlay concrete can be handled and finished, and the material appears to be a viable alternate to LMC and low slump concrete. The report encouraged the use of SFC in future overlays.

NYSDOT is considering SFC as an alternate overlay material, and further SFC bridge deck work is being planned. NYSDOT specifications now require initiation of curing within 5 min if the theoretical evaporation rate according to Figure 2.1.5 of ACI 305R–77 exceeds 0.05 lb/ft^2/hr. Focus is on precautions to eliminate plastic shrinkage cracking.

Tennessee Department of Transportation

In June 1986, the Tennessee Department of Transportation (TDOT) began using 11.2-percent SFC (Table 2) in a minimum 4-in.-deep repair of the 1,228-ft-long Landon B. Hassler Memorial Bridge (Bridge No. 69–SR42–3–27), located where State Route 42 crosses the Obey River. Silica-fume concrete was included as an add-on material that was expected to achieve 4,500 psi within 3 days. On remarkably short notice, a 6000-gal-capacity mobile dispenser was set up at the concrete plant, located 40 min from the job. There was no trial batch. Typically, no slump adjustments were necessary. The truck-mixed concrete was placed in the standard manner using a vibratory tandem wooden screed, bull-floating, water-misting to prevent plastic shrinkage cracking, and wet-burlap (no plastic cover) curing. The approach spans also received overlays which were full depth in places.

The concrete was uniform and exhibited good workability retention. Although the concrete was somewhat sticky, the desired finish was achieved. The SFC developed 5,220 psi at 3 days. The surface was acceptable even though after 10 days transverse cracks were seen on about 5-ft intervals—roughly the same as in the adjacent conventional concrete lane, and apparently a common occurrence. A 6-mo inspection revealed no changes in the surface. The TDOT considered SFC to be an acceptable material for use in high early strength applications.

A second SFC overlay is scheduled for late fall of 1987 for

TABLE 2 CONCRETE PROPORTIONS FOR TDOT, MiDOT, AND MeDOT OVERLAYS

State Agency		TDOT	MiDOT	MeDOT		
Year		1986	1986	1986		1987
Bridge		Landon B. Hassler Memorial	Fontenac	Passadumkeag & Dresden		Ohio St.
Silica Fume Dose	(%)	11.25	10.0	7.2	7.2	10.0
Cement	(lb/cu yd)	620[ab]	658[a]	658[a]	658[d]	635[d]
W/(C+SF)		>0.34	0.39	0.40	0.35-0.37	0.50
Slump	(in.)	5	5.25[c]	4.25-7.50	3.5-4.75	6.0
Air content, fresh	(%)	6	5.3[c]	5.9-7.8	6.5-5.9	6.5
Compressive strength	(psi)					
@ 3 days		5220	4740			
@ 7 days		6550 @ 5d	6450	4110-5180	5440-6610	6260
@ 28 days			7840	5540-6730	5870-7160	
Flexural Strength	(psi)					
@ 7 days			1180			
@ 28 days			1230	980	1170	
Modulus of Elasticity	(psi)		5,200,000			
Rapid chloride charge passed	(coulombs)					
Dryiing shrinkage:	(%)					
@ 28 days			0. 35			
@ 6 months			0.53			
Rapid chloride (charge passed)	(coulombs)			548[e]		

Note a: Type 1. Note b: 1-in. limestone. Note c: Mean of all results. Note d: Type 2.

Note e: Tested at 148 days. Charge passed level for 658 lb/cu yd of cement, w/c = 0.35, 4880 psi @ 28 days conventional concrete placed on the same deck was 5060 coulombs @ 148 days.

the Broad Street Bridge over I-40 near Nashville. This 4.5-in. overlay will be placed on the 203-ft-long by 76-ft-wide deck on weekends, one lane per weekend. Again, the SFC is being used primarily to achieve high early strength and thereby minimize the time that lanes are closed to traffic.

Michigan Department of Transportation

The State of Michigan Department of Transportation (MiDOT) began SFC laboratory tests in May 1985 (*7*). This work suggested that a 658 lb/yd^3 of cement mixture with 10-percent SF could develop "very low" AASHTO T277 rapid chloride permeability (RCP) (*8*), which was comparable to the 658 lb/yd^3 LMC mixture currently used. MiDOT considered SFC to be a potential economically competitive alternate to LMC for bridge decks.

By late June 1986, two four-span bridges—Fontenac Ave. Bridge and Mt. Elliott Ave. Bridge (Bridge Nos. S12 and S10, respectively, of contract number 82024), both over I-94 in Detroit—received experimental thin-bonded overlays. The overlays were 2 in. thick, although in some places the repair was full depth. Wet SF-based admixture was dispensed from a remote-controlled 6,000-gal-capacity mobile dispenser to a central mixer. After a 15-min trip to the job, concrete (Table 2) was placed in the standard manner using a cement-sand bonding grout and a roller screed. During the first placement, the fine aggregate content was increased to improve surface closure. Workability retention was good, and surface closure was acceptable, although it could have been better.

No plastic shrinkage cracking was experienced. The hardened concrete surfaces showed no spalls or popouts, and they were blemish free with the exception of some tight cracks that appeared within 2 weeks. These cracks were generally rectangular, and both thick and thin depth areas were affected. It should be mentioned that in Michigan low slump high-density placements some years earlier showed heavy cracking (*7*), and local LMC overlays generally showed little cracking. An initial MiDOT report (*9*) indicated that at 6 mo the average SFC shrinkage was 0.53 percent, whereas LMC from the Ferry Avenue Bridge nearby was 0.41 percent. Rapid chloride permeability tests on both job cylinders and cores from the overlays revealed that the SFC consistently achieved RCP results near the low end of the "very low" range (this included one core with a full-depth crack), and the LMC specimens showed results near the upper end of the "very low" range. The 90-day 3 percent sodium chloride solution ponding tests found no chlorides at the 1.5-in. depth for SFC, whereas LMC showed 0.3 lb/yd^3 at the same depth.

MiDOT is continuing laboratory study of SFC, and another experimental bridge deck overlay placement is being planned.

MiDOT is also investigating the use of a dry densified SF-based admixture for making SFC for bridge deck overlays.

Maine Department of Transportation

The Maine Department of Transportation (MeDOT) investigated using SFC wearing courses as an alternative to LMC, primarily to achieve good bond and to act as a chloride barrier. Two bridges were selected for experimental work during the latter half of 1986. The two-lane bridges—Passadumkeag (Bridge No. 264950-0-990), located where State Route 2 crosses the Passadumkeag River, and the Dresden (Bridge No. 334), spanning the Eastern River—received 2.5-in.-thick minimum design wearing surfaces. The SF-based admixtures, added first to the truck mixers, were transferred from pre-weighed drums. The 7.2 percent SFC (Table 2) was mixed 100 revolutions at the plant, driven 20 mi to the job, and mixed at least 20 revolutions just before discharge, sometimes after on-site water addition. Concrete was placed in the standard manner using a cement-sand bonding grout, a vibratory tandem wooden screed, and bull-floating. The concrete was wet-burlap-cured for seven days, and the lane was opened within 9 days. The concrete was uniform, achieved the desired properties, and was easy to place and finish. No cracks or delaminations were observed. AASHTO T277 RCP tests on SFC specimens from the Dresden Bridge showed that the charge passed level was improved (reduced) by a factor of 10 relative to that of the conventional concrete that was also placed in the deck. MeDOT placed a minimum 3-in.-thick wearing surface during the summer of 1987 on the two-lane Ohio St. Bridge over I-95 in Bangor. Approximately 100 yd^3 of 10 percent SFC (Table 2) were placed as previously described. The first MeDOT contract job using SFC will be a minimum 2-in.-thick overlay for the Sandy River Bridge in Farmington. Specifications currently being written for this project will call for a maximum water-to-cement-plus-SF ratio of 0.40, and will require at least 65 lb/yd^3 of a wet SF-based admixture.

Virginia Department of Transportation

In 1984 the Virginia Department of Transportation (VDOT) conducted SFC laboratory work (*10*) and concluded that 5 percent SFC having a water-to-cement ratio of 0.40 or lower would be suitable for overlays as thin as 1.25 in. The SFC provided satisfactory strength, low permeability, a 90-day ponding chloride content at the 0.25–0.75-in. depth that was half the level of the control concrete, and satisfactory rapid freezing-and-thawing durability even though a high air-void spacing was observed (attributed to use of HRWRA).

In May 1987, a four-span bridge near Winchester received the first VDOT SFC overlay—a minimum 1.25-in.-thick placement in the traffic lane using both 7- and 10-percent SFC (Table 3). Three weeks later the passing lane was placed. The wet SF-based admixture was added to the truck mixers at the plant along with HRWRA, and in two of the seven truckloads additional HRWRA was added at the job. The time from batching to discharge was about 35 min. Concrete was placed in the standard manner using mortar from the concrete for the bonding grout and using a roller screed. Portions of the decks were covered with wet burlap and plastic, and other areas received a curing compound only. The hardened concrete surface was acceptable. Only one foot-long crack was seen, associated with a joint where the overlay depth changed abruptly. Also, a zone that was poorly consolidated with the internal vibrator soon delaminated and was replaced. Air contents in the fresh concrete were generally low, and, as expected, some of the air-void spacing factors were high. Although the rapid freezing-and-thawing results were mixed, those concretes having air contents within the specification performed satisfactorily. Future VDOT SFC overlay placements are expected.

TABLE 3 CONCRETE PROPORTIONS AND PROPERTIES FOR VDOT OVERLAY

		Traffic Lane May 13, 1987		Passing Lane June 6, 1987	
Silica fume dose	(%)	7.0	10.0	7.0	10.0
Cement, type 2[a]	(lb/cu yd)	658	658	658	658
Slump[b]	(in.)		1-1/2 - 7 1/2		
Air content: fresh concrete	(%)	3.7	5.2	4.5	6.0
Compressive strength:	(psi)				
@ 28 hrs.		4340	5880	3730	5370
@ 7 days		6850	6770	6090	6100
@ 28 days		9180	7800	7890	6950
Flexural strength psi @ 28 days			760 - 960		
Hardened concrete air void system:					
Air content[c]	(%)	5.2	5.8	6.5	7.2
Specific surface	(1/in.)	539	582	489	455
Spacing factor	(in.)	0.0088	0.0077	0.0085	0.0082
Durability factor[d]		33	60	79	80

Note a: Coarse aggregate was a nominal 3/8-in. stone. Estimated fine aggregate-to-aggregate ratio was 0.45. Maximum water-to-cementitious materials ratio was 0.40. Note b: Specified slump was 6 in. ± 2 in. Note c: Coarse void content was around 1%. Note d: ASTM C666, procedure A, modified with addition of 2% sodium chloride.

Illinois Department of Transportation

In 1987 the Illinois Department of Transportation (IlDOT) used 11.1-percent SFC in minimum 3-in.-thick overlays near Stauton (in March), which carries Route 4 over I–55, and in Mascoutah on the Silver Creek Bridge (in June). Concrete (Table 4) was placed in the standard manner using a 15-percent SF-modified bonding grout, a reciprocating beam vibrator, a fresno-float, a longitudinal astroturf drag, and a transversely tined surface texture. At Stauton, the SFC was covered with wet burlap and plastic for 4 days; and at Mascoutah, curing compound was used. The SFC was somewhat easier to place and finish than high-density concrete. The ready-mixed concrete was also cheaper than alternate concretes that required mobile mixers. The first Route 4 bridge inspection, made at 3 mo, revealed about four short transverse cracks and a few still-shorter ones near the drains, but these were not considered significant. It was noted that an adjacent high-density deck placed in October 1986 showed seven transverse cracks that were on 6–8-ft centers.

In June 1987, the IlDOT placed approximately 15 yd^3 of 11.2 percent SFC in an abrasion-resistant overlay for the approach lane of the two-lane Wood River Bridge, located along State Route 3 in East Alton. The overlay thickness ranged between 1.5 in. and 4 in. The concrete was truck-mixed, using a bagged densified SF-based admixture that was added first to the mixers. The placements were successful. In this case, SFC was used instead of LMC primarily because of the simplicity of production.

City of Milwaukee, Wisconsin

The city of Milwaukee placed 36 yd^3 of 10-percent SFC overlay on the 60th and Hampton Bridge during 1987. Reportedly, the placement was successful, although detailed information is not yet available.

Pennsylvania Department of Transportation

During May 1984, the Pennsylvania Department of Transportation (PaDOT) began testing a non-air-entrained 14.8-percent SFC that was made with a wet SF-based admixture (Table 4). A product evaluation report from August 1984 (*11*) was favorable. The rapid freezing-and-thawing results were excellent even though the air content was only 3.8 percent. Negligible RCP was reported. The SF-based admixture was approved for use as an experimental overlay material. An overlay is being planned.

Indiana Department of Highways

The Indiana Department of Highways (IDOH) conducted a laboratory evaluation of SFCs (*12*) that achieved air contents

TABLE 4 IlDOT, PaDOT, IDOH, VDOT, AND OHIO TURNPIKE COMMISSION CONCRETE PROPORTIONS AND PROPERTIES

State Agency		IlDOT	PaDOT	IDOH	VDOT	Ohio Turnpike Commission
Year		1987	1984	1984	1986	1985
Concrete Description		March field trial	Lab	Lab	Lab	I-77 overpass Placement[b]
Silica fume dose	(%)	11.1	14.8	15.2	4.5-12.5	6.8
Cement	(lb/cu yd)	630[a]	700	700[a]	660-705	658
W/(C+SF)		0.35	0.33	0.31	0.40-0.41	0.43
Slump	(in.)	6	6.5	4-6.5	2.0-4.75	4.25
Air content of fresh concrete	(%)	7.5-8.1	3.8	3.6-5.0	6.6-10.5	6.0
Compressive strength	(psi)					
@ 1 day					3280-5140	2180
@ 3 days				7340	5130-7580	
@ 7 days			8740	9930	5800-9400	6310
@ 28 days			10920	11880	7400-11720	8170
Flexural strength	(psi)					
@ 1 day						350
@ 3 days						600
@ 28 days			2080	1310		
Hardened concrete system						
Air content	(%)			3.6-5.6		
Specific surface	(1/in.)			276-336		
Spacing factor	(in.)			0.017-0.018		
AASHTO T277-831 charge passed	(coulombs)	539[c]	0			
ASTM C666[d]						
Durability factor			106.8	91.0-94.1	101.5-107.5	
Bond strength performance indicator @ 28 days[e]	(%)			101		

Note a: 3/8-inch limestone. Note b: 1.5 lb/cu yd polypropylene fibers were added. Note c: Test age was 49 days. n=3. Note d. VDOT and PaDOT use procedure A with VDOT using a 2% sodium chloride solution and VAOT using a 3% solution. VAOT results are for 500 cycles. IDOH used procedure B. Note e: The bond strength performance indicator expresses the ratio of the flexural strength of a reference base concrete-test concrete composite (joined vertically near the center of the beam) divided by the flexural strength of the base concrete.

significantly below the desired levels. The SFCs developed high ultimate strength, high early strength, and good bond (Table 4). Durability factors were acceptable (in the 90s), and the material appeared to limit the depth of chloride penetration to around 0.5 in. In July 1985, field tests were recommended.

Vermont Agency of Transportation

A Vermont Agency of Tranportation (VAOT) laboratory investigation preliminary report dated December 1986 (*13*) indicated that significant strength increases were seen in air-entrained 4.5-percent and 13.8-percent SFC (Table 4) relative to those of reference concretes. The SFCs also showed acceptable frost resistance. The durability factors consistently exceeded 100 at 500 cycles. Most encouraging was the observation that the SFCs were significantly better than the reference concretes in regard to screening chloride ions from the top inch portions of ponding test specimens. An experimental field placement was recommended, and VAOT has scheduled an SFC bridge overlay during 1988.

State of Washington Department of Transportation

The Washington State Department of Transportation has plans to place experimental SFC nominal 1.5-in.-thick bridge deck overlays on two structures. One bridge is north of Seattle, and the other is in the Spokane vicinity. Ready-mixed concrete will be used.

APPLICATIONS OTHER THAN OVERLAYS

Although great attention has been given to bridge deck overlays, SFC has been used in several other bridge-related applications. Work identified in other (non-overlay) applications is summarized as follows.

Full-Depth Bridge-Related Applications

In October 1985, the Ohio Turnpike Commission used 6.8-percent SFC (Table 4) in an approach slab at the west end of the westbound lane of an I–77 overpass. Silica-fume-based admixture was pumped from drums into truck mixers, added first along with polypropylene fibers. After a 35-min trip to the job, the concrete was pumped to the slab, leveled with an adjustable vibratory screed, and bull-floated and darbied. Although surface texturing and curing were delayed, the fibers prevented plastic shrinkage cracking. No differences were seen between this placement and previous conventional concrete placements. However, the impressive high early strength development of the SFC was noted.

The new Delaware River Gap Bridge along I–80, operated by the Delaware River Joint Toll Commission, has specified approximately 5,000 yd^3 of SFC in a full-depth deck to provide a chloride barrier. Initial placements began in late 1987. Traffic lane construction was scheduled to begin in April 1988. The specifications require the SFC to achieve RCP charge passed levels no greater than 750 coulombs. A maximum water-to-cement ratio of 0.40 is specified along with a cement content between 635 and 705 lbs/yd^3. Only wet SF-based admixtures will be allowed, and a wet burlap cure is specified.

During the summer of 1986, roughly 1,000 yd^3 of 5.8-percent SFC were used on an experimental basis throughout the Vondale Road Bridge, which is owned by Jefferson County, Alabama. Dry undensified SF was dispensed from a silo into a central mixer. The results were favorable. In October 1987, placement of 4,800 yd^3 of a similar SFC began for the Blue Lake Bridge, located in Birmingham. The SFC was used throughout the structure to improve generally the concrete performance.

Bridge-Related Marine Applications

The Florida Department of Transportation (FDOT) began laboratory testing of SFC in November 1984. Initial tests with 14.9-percent SFC using local aggregates developed around 10,000 psi and showed low shrinkage and good corrosion protection properties. Fourteen prestressed piles were cast during early 1987 using a 10-percent SFC. The results showed that SFC can be placed with the same degree of effort as conventional concrete, and corrosion tests revealed that the SFC was significantly better than the typically specified concrete. There were plans to use SFC in a bridge by the end of 1988 (*14*).

On May 19, 1987, the Massachusetts Bay Transit Authority (MBTA) used about 24 yd^3 of 15.8-percent SFC to achieve high early strength for an urgent railroad bridge repair in Sandwich, Massachusetts. A 5,000-psi 3-day strength was specified for two pile caps that were partially submerged in sea water during high tide. Achieving good workability and bond strength was important. The job was 45 min from the concrete plant, and there was no time for a trial batch. Fortunately, the concrete (wet SF-based admixture was supplied from drums) performed as desired. Workability retention was excellent, and the concrete was pumped. Although temperatures were unseasonably low (evening air temperatures in the low 40s, and water temperatures in the 50s) the concrete achieved nearly 6,000 psi within 3 days, and the structure opened on schedule.

The Texas Department of Transportation (TxDOT) is evaluating the use of SFC to achieve better corrosion protection for bridges in marine environments and to reduce the size of some precast elements by achieving high strength. Some test piles have recently been cast.

The Alabama Highway Department (AHD) has specified about 8,100 yd^3 of 11.1-percent SFC in precast piles for the Perdido Pass Bridge, located near Mobile. Up to another 6,871 yd^3 of cast-in-place SFC has been specified for portions of the substructure. The SFC is being used to improve corrosion protection of the steel and to increase abrasion resistance of the submerged concrete.

The MeDOT is currently using SFC in the piles for the Fairbanks Bridge located near Farmington. Again, SFC is expected to improve corrosion protection of the reinforcing steel.

Miscellaneous Bridge-Related Applications

The Elk River Bridge, in Charleston, West Virginia, where the Elk River enters the Kanawha River, was repaired in the summer of 1985. The sidewalks and monolithically cast-in-place traffic barriers were made with no problems using truck-mixed 7-percent SFC. Wet SF-based admixture was pumped to the truck mixers from a 2,000-gal tank. The traffic barrier forms could usually be removed within 1.5 hr, then the concrete was covered with curing compound. Inspection in July 1987 showed no significant changes in the concrete surfaces.

During 1986 the Pennsylvania Turnpike Commission used truck-mixed 12-percent SFC in parapet walls and traffic barriers associated with two bridges, primarily to achieve better frost resistance.

The IlDOT has specified SF in bonding grout since 1986 for various types of overlays (*15*). A 15-percent SF dose is also specified for use in grouts for partial patches.

Perhaps the first bridge-related placement of SFC in the United States took place on January 6, 1983. An approach lane to a weighing platform at a quarry near Roaring Springs, Pennsylvania, used 2.75-in.-thick 11-percent SFC overlays to improve abrasion resistance and to develop high early strength. The 2 yd^3 of concrete were central-mixed. The concrete was hand-screeded; bull-floated; and cured under burlap, straw, and plastic. Nearly every truck leaving the quarry traverses the weighing platform, often decelerating and accelerating over the debris-covered approach lanes. The SFC has performed very well—significantly outlasting previously tried wearing surfaces, which typically lasted only 2 yr. In 1987, at least one other weighing platform received a wear-resistant SFC surface.

DISCUSSION OF RESULTS

Several SF dosages were used—from 5 percent (University of Cincinnati) to 15.5 percent (KyDOT). A sound approach is to use the lowest SF dose that will still provide the desired concrete performance while maintaining a comfortable margin of safety. For example, the VDOT used 7- and 10-percent doses in the field when laboratory investigations suggested that a 5-percent dose coupled with a water-to-cementitious materials ratio below 0.40 would work.

Most of the jobs were small (the quarry job was only 2 yd^3), and many were supplied with wet SF-based admixtures supplied from drums. In some cases, the drum volumes were sized to fit the load sizes (MeDOT, IlDOT). Mobile dispensers provided wet SF-based admixtures for several jobs (NYSDOT, TDOT, MiDOT), but unless a job is large enough to economically justify installing a mobile dispenser, or unless admixture is supplied from a plant with permanent dispensing capability, future wet SF-based admixture bridge work will probably use drummed material. Dry undensified SF was used successfully (AHD), although it is believed that transportation costs will limit the use of this form of the material to regions near SF sources. One placement (IlDOT) successfully used a dry-bagged densified SF-based admixture that was developed for small jobs. It is likely that dry densified products will play a more important role in future SFC bridge work, especially on small jobs.

Some of the earlier placements used mobile mixers (ODOT, KyDOH), but either central-mixed or truck-mixed concrete is now generally preferred. Ready-mixed concrete costs less than mobile-mixed concrete, and the good workability of the SFCs is maintained long enough to make ready-mixed concrete use feasible.

Many different types of screeds were used satisfactorily, but initial surface closure was most acceptable when vibratory screeds were used. Roller screeds worked well, too, but sometimes required the equipment to be adjusted and the aggregate proportions modified. Well-maintained equipment and experienced operators are as important to SFC work as they are to conventional concrete placements.

Clearly, SFC has been placed successfully in a variety of bridge-related applications. In all cases only off-the-shelf equipment was needed to batch, place, finish, and cure the concrete. Laboratory and field tests were often conducted, and they helped develop effective placement procedures and minimize construction problems. Although some jobs proceeded smoothly without trials (Ohio Turnpike Commission; TDOT; MBTA), most were preceded by trial work, which is recommended.

It is clear that plastic shrinkage cracking precautions must be taken, and more attention is now being paid to them. Although a few of the earlier placements experienced plastic shrinkage problems, these seem now to have been eliminated. Routine preventive measures include minimizing delays, beginning curing immediately, working with the weather to minimize the evaporation rate (e.g., evening placements by NYSDOT), and using polypropylene fibers (Ohio Turnpike Commission). Several of the structures were entirely crack free, and cracking was generally light. More extensive cracking could usually, but not always, be attributed to problems such as delayed curing, interrupted curing, or thermal effects. In the case where a 7-day continuous wet burlap cure was used (MeDOT), no cracking was observed. It is believed that immediately started and extended wet curing is an important factor in eliminating cracking.

Some of the earlier studies did not use air-entrained concrete, and although some of these freezing-and-thawing results were clearly acceptable (IDOH, PaDOT), others were only marginally acceptable or poor. Frost resistance field performance of the SFC has been acceptable as have been the available laboratory freezing-and-thawing results of the air-entrained concretes that showed void spacing factors under 0.008 in. The trend has been to use air-entrained SFC, and this practice is recommended strongly.

Although SFCs are noted for high strength, and there were cases where this was at least one of the motives for considering its use (TxDOT; Ohio Turnpike Commission), the most prevalent reason for using the material was to provide a chloride barrier. Various agencies (PaDOT, IDOT, MiDOT, MeDOT, VDOT, VAOT) reported good resistance to chloride intrusion; and as a chloride barrier, the SFC overlays appear to be performing well. Bond was good, and with the exception of one poorly consolidated zone (VDOT) no delaminations have been reported. In at least three instances (TDOT; MBTA; the quarry) SFC was used to achieve high early strength. In several cases SFC was used to provide abrasion resistance (the quarry, IlDOT, ADH), and among those placements old enough to assess fairly, good wear resistance has been reported (the quarry, KyDOH).

The performance of the various SFCs are now resulting in increasing interest in this relatively new construction material. For example, the volume of SFC used in bridge-related applications has steadily increased from year to year, as follows: 2 yd^3 in 1983, 15.4 yd^3 in 1984, about 270 yd^3 in 1985, at least 1,480 yd^3 in 1986, at least 3,500 yd^3 in 1987, and there are now contracts for about 23,000 yd^3 in 1988. The results have been encouraging enough either to merit further study of SFC on an experimental basis or to prompt specification of the material in new bridge construction.

CONCLUSIONS

- SFC at dosages between 5 and 15.5 percent can be manufactured, placed, finished, and cured using conventional equipment. Measures must be taken to prevent plastic shrinkage cracking.

- There are several motives for using SFC: to provide a chloride barrier, to develop high-early strength, to achieve high-ultimate strength, to provide abrasion resistance, and to improve bond strength. Expectations in regard to the original motives for using SFC appear to have been met.
- Interest in SFC is increasing, and SFC is now being specified in bridges.

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