ODOT Experience with Silica-Fume Concrete

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Two bridge-deck-overlay projects placed in 1984 and 1987 are the basis for Ohio's specifications on the use of silica fume; they are reviewed along with a full-depth silica-fume structure placed in 1987. Data on mixing, placing, curing, compressive and flexural strengths, resistance to freezing and thawing, and permeability are presented. An assessment of these results shows that Ohio's 15 percent by mass of cement silica-fume requirement could be reduced, retaining high compressive and flexural strengths, good resistance to freezing and thawing, and favorable permeability characteristics. At present silica-fume-modified concrete appears to be a satisfactory and cost-competitive method of extending the life of bridge decks.

The Ohio Department of Transportation (ODOT) has a problem with deteriorating structures due mainly to the damage caused by deicers. In its search for a solution, ODOT has tried various remedies over the years. Epoxy-coated steel has been used in the upper layer of reinforcement for more than 10 yr; and in the summer of 1987, ODOT started using coated bars in all layers of reinforcing steel for additional corrosion protection. Another approach is the use of bridge-deck overlays with and without sealers. The sealers studied included silanes and epoxies. Dense concrete using high-range water-reducing admixtures; polymer-modified concrete; latex-modified concrete; and most recently, silica-fume-modified concrete have been evaluated.

OBJECTIVE AND SCOPE

Three cases are discussed: structure 1 (ODOT bridge ASD 511-1621), structure 2 (ODOT bridge FRA 33-0131), and structure 3 (ODOT bridge MAD 161-0151).

Structure 1—Background Information

ODOT's first silica-fume project was an overlay, 120 ft long and 32 ft wide, placed on October 18, 1984, on a slab bridge on State Route 511 near Ashland, Ohio. The department had previously used latex-modified concrete overlays, and a latex-modified concrete overlay was proposed for this structure. The contractor approached ODOT proposing the substitution of silica fume for latex, and it was decided to use silica fume on only one lane. A grout was spread ahead of placement and not allowed to dry before placement of the overlay. The grout consisted of the paste remaining after the coarse aggregate was removed from the silica-fume concrete mixture. An air-detraining admixture was used to remove any incidental air found in the mixture. (This information is from Mark Luther Elkem Chemicals, Inc., unpublished data.)

The concrete was mixed in a volumetric batching mobile mixer. The silica fume was added by pumping directly into the mobile mixing chamber from the transport truck (*1*). The silica-fume concrete was stable with no clumping during batching and mixing.

Petrographic examination of the silica-fume concrete was conducted for the silica-fume supplier, and the ODOT laboratory ran an examination in accordance with ASTM C 457 using the modified point-count method.

	Private Consultant Results	*ODOT Results*
Air content, hardened concrete, %	4.7	5.5
Specific surface of the air void system, in.^{2} per in.^{3}	162	168
Spacing factor, $\bar{L}$, in.	0.032	0.030

This structure has been under observation since placement. Two cracks were discovered in the July 1987 visit. Upon coring, it was discovered that both were in a variable depth placement area with an overlay depth of 3–3.5 in. The cracks measured 0.03 in. wide, about 16 in. long, and 1–1.5 in. deep. The deck was checked for delaminations, and none were discovered.

The other lane of the deck, which is latex-modified concrete, was also checked for delaminations; none were discovered, but several cracks were found. As with the silica-fume overlay, these cracks, in variable depth overlay areas, did not extend through the entire depth of the overlay and measured 0.03 in. wide, about 16 in. long, and 1–1.5 in. deep.

The silica-fume concrete was slightly darker in color than the latex-modified concrete. Two different curing methods were used. The color of the concrete is uniform within each lane.

Structure 2—Background Information

ODOT's second silica-fume overlay was placed on April 22 and May 5, 1987, on a bridge 27 ft long and 32 ft wide on Avery Road over U. S. Route 33 in Dublin, Ohio. In preparation for the project, a test slab was placed on April 16, 1987. On the test slab the finishers experienced problems where the surface became sticky and the tining tool tended to drag aggregate with it.

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At the time of project placement, a bonding grout consisting of equal parts of portland cement and sand was broomed onto the cleaned scarified surface just before the overlay placement and was not allowed to dry before overlay placement.

On this structure, the concrete was central-mixed and delivered to the project in truck mixers. Because of the finishing problem with the test slab, ODOT was prepared to allow a finishing aid, but it was not used on the April 22 placement since finishing on that day went smoothly. On May 5, a finishing aid was used. To date there is no difference in the appearance of the two surfaces.

Structure 3—Background Information

ODOT's third placement was a full-depth deck placed at night, started at 3:30 a.m. and finished at 7:00 a.m. on August 14, 1987. The structure, on Route 161 near Plain City, Ohio, is 123 ft long × 34 ft wide.

The concrete was central-mixed and delivered to the project in truck mixers. A concrete pump was used. Test results given in Table 1 indicate little variance in the concrete temperature, air content, slump, and yield.

The finishers on this project complained of finishing problems, and a finishing aid was used on the first few feet of the surface.

TABLE 1 ODOT'S THIRD SILICA-FUME PROJECT, FULL-DEPTH AIR CONTENT AND SLUMP FOR THE 21 LOADS DELIVERED

TRUCK NUMBER	TIME A.M.	ASTM C 231 AIR CONTENT, %	ASTM C 143 SLUMP, IN.
1	3:30	8.3	6
2	3:40	8.3	6 3/4
3	4:00	7.6	7 1/4
4	4:15	7.8	7
5	4:20	7.5	6
6	4:30	8.1	5 3/4
7	4:37	9.4	7 1/2
8	4:47	7.7	5 1/4
9	5:05	8.2	6 1/4
10	5:10	8.4	7 1/2
11	5:15	8.3	6 1/4
12	5:25	8.8	7 1/4
13	5:30	7.9	8
14	5:40	9.4	7 1/4
15	5:43	9.0	6 3/4
16	5:52	8.2	6 3/4
17	6:04	7.8	8 1/4
18	6:10	8.8	7 1/4
19	6:14	9.3	8
20	6:20	7.7	7 1/4
21	6:30	8.7	7 1/4

DATA COLLECTION

ODOT testing personnel were present at each of the three silica-fume deck placements and test-slab placements to perform concrete control tests such as slump and air content on the freshly mixed concrete. Cylinders and beams were also made on which compressive strengths, flexural strengths, examination by ASTM C 457, and tests for resistance to freezing and thawing were later made.

Test Slabs

In an attempt to familiarize the participants with silica-fume concrete and to give ODOT a chance to collect pertinent data, a test slab was specified as a separate pay item on each of the three silica-fume placement projects (*2*). On each project, the slab was placed a few days before the structure placement to allow a chance to correct any discovered deficiencies.

Deck Preparation

Structures 1 and 2

Both overlay decks were prepared in the same manner. Sound surface was removed to a depth of 0.25 in. by scarifying. Deeper areas of loose and unsound concrete were removed as needed to reach a solid concrete surface. The surface was then cleaned by abrasive blasting, followed by an air blast immediately before the overlay placement (*2*). A grout was applied to the clean and scarified surface just ahead of the overlay placement (*2*).

Structure 3

The full-depth deck was placed according to standard construction practices.

Finishing

All three structures were screeded in the same manner. The concrete was distributed using a finishing machine with a screw-type auger distribution system and a foller followed by a vibrating pan. The surface was finished by hand as needed and textured transversely with a tining tool (*1*, *2*).

Curing

Structure 1 (Silica-Fume Lane)

The northern half of the overlay was covered by a single layer of wet burlap with a layer of polyethylene film placed over the burlap. This covering remained for 2 days before it was removed and the deck was allowed to air-dry cure 2 more days before being opened to traffic. The southern half of the overlay was sprayed with white chlorinated rubber-membrane-forming curing compound.

TABLE 2 BATCH WEIGHTS FOR ODOT'S FIRST THREE SILICA FUME PROJECTS

	COARSE AGGREGATE NO.8 LIMESTONE, LB.	FINE AGGREGATE NATURAL SAND, LB.	PORTLAND CEMENT TYPE 1, LB.	SILICA FUME SLURRY, LB.	WATER, LB.
STRUCTURE #1	1361	1537	658	227 A	147
STRUCTURE #2	1417	1308	698	210 B	81
	27 OZS. OF AIR ENTRAINER				
	275 OZS. OF HRWR				
STRUCTURE #3	1475	1392	700	210 B	40
	24.5 OZS. OF AIR ENTRAINER				
	290 OZS. OF HRWR				

A 45% SILICA-FUME & 51% WATER - THE OTHER 4% IS MADE UP OF VARIOUS ADMIXTURES SUCH AS WATER REDUCERS AND HRWR. (INFORMATION FROM ELKEM CORPORATION INC.)

B 48% SILICA-FUME & 50% WATER - THE OTHER 2% IS MADE UP OF VARIOUS ADMIXTURES SUCH AS WATER REDUCERS AND HRWR. (INFORMATION FROM SIKA CORPORATION INC.)

Structures 2 and 3

As soon as the tining operation was completed, the finished overlay surfaces were covered with a single layer of wet burlap. The fresh overlay surface received a wet burlap cure for 3 days, during which the burlap was kept wet by continuous application of water through soaker hoses under a polyethylene sheet.

Mixture Proportions

The first overlay contained 658 lb of cement/yd^3 as had been specified for the latex-modified concrete. Then 227 lb of silica-fume slurry was added to approximate 15 percent by mass of the cement. Mixtures for the three structures are given in Table 2.

LABORATORY INVESTIGATION VARYING SILICA-FUME CONTENT

Shortly after the first overlay placement, ODOT's laboratory ran permeability tests on cylinders made from concrete mixtures of varying silica-fume content (*3*). The testing was performed according to the procedure found in FHWA report RD 81/119 (AASHTO T 227), and these results (Table 3) are then depicted graphically (Figure 1).

From this graph it can be seen that permeability decreases as silica-fume content increases. Based on these test results, ODOT chose to retain a 15 percent by mass silica-fume content requirement and require 700 lb of cement (*2*).

This concrete functioned well and was retained for ODOT's third placement.

The possibility of reducing ODOT's silica-fume content to 10 percent is discussed later in this paper (Analysis of Data—Rapid Permeability).

PLACEMENT CONDITIONS

Table 4 shows that the silica-fume projects were placed at various temperatures and humidities ranging from 62°F to 86°F. The temperature differentials between concrete and deck caused no significant adverse effects. Complaints of finishing problems existed on both high- and low-humidity days. There was virtually no wind on any of the placement days. In spite of the temperature differentials and finishing complaints, no cracking during curing was observed.

ANALYSIS OF DATA

Slump

Average slump test results performed in accordance with ASTM C 143 were the following:

	Test Slab	*Bridge Deck*	
Structure 1	6.9 in.	8.3 in.	
		4/22	5/5
Structure 2	6.0 in.	7.5 in.	7.4 in.
Structure 3	7.0 in.	6.5 in.	

TABLE 3 RAPID PERMEABILITY TEST RESULTS VARYING SILICA FUME CONTENT AND CEMENT CONTENT WITH AND WITHOUT FLY ASH AND HRWR

SAMPLE SERIES	SILICA-FUME CONTENT, %	FLY ASH	HRWR	CHARGE, COULOMBS	TIME, MIN.	CEMENT, LB.
275	2.5	NO	NO	12137	360	700
270	2.5	YES	NO	9711	360	560
265	2.5	YES	NO	9294	360	450
260	2.5	YES	NO	10582	360	380
280	5	NO	YES	3827	360	700
281	5	YES	YES	3201	360	560
283	5	YES	YES	4059	360	450
283	5	YES	YES	3631	360	380
285	6.75	YES	YES	851	360	560
286	6.75	YES	YES	2987	360	450
287	6.75	YES	YES	3080	360	380
284	6.75	NO	YES	392	360	700
289	10	YES	YES	328	360	560
290	10	YES	YES	941	360	450
291	10	YES	YES	1796	360	380
288	10	NO	YES	136	360	700
293	15	NO	YES	187	360	560
294	15	YES	YES	256	360	450
295	15	YES	YES	362	360	380
292	15	NO	YES	78	360	700

NOTE: Permeability tests performed according to procedure found in FHWA Report RD 81/119.

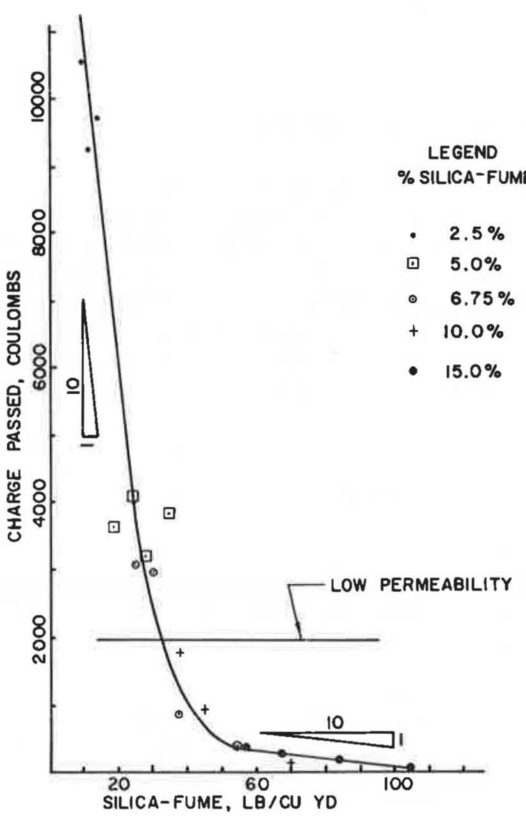

FIGURE 1 Chloride permeability vs. silica-fume content using an HRWR.

The slump was fairly constant on all three structures, although it varied more with the mobile mixer than with the truck mixer.

Compressive and Flexural Strengths

Tables 5 and 6 give compressive and flexural strengths. These results are higher than would be expected with plain structural concrete. Strength was gained rapidly. The 1-day compressive strengths for structures 1 and 2 averaged 3,390 psi and 3,620 psi respectively and rose to 6,880 psi and 6,220 psi at 28 days. The flexural strengths ranged from 490 psi and 560 psi average at 1 day to 940 psi and 1,035 psi average at 28 days. The compressive strengths for structure 3 were considerably higher at 6,240 psi at 1 day and 8,020 psi at 28 days. The flexural strengths started at 750 psi for 1 day and rose to 1,170 psi at 28 days. The test slab 28-day strengths were even higher at 8,810 psi compressive and 1,320 psi flexural.

Compressive strength increased with the increase in silica-fume content. Figure 2 compares compressive strengths attained varying silica-fume content.

The test-slab strengths were higher than those from the actual deck placements. This is to be expected as placement conditions were easier to control on a small test slab.

The higher strength of structure 3 was most likely achieved because of its low water-cement ratio (0.33). Table 2 shows that a large amount of a high-range water reducer (HRWR) was used, significantly reducing the amount of mixing water. However, there appeared to be a sufficient amount of water

TABLE 4 CONDITIONS FOR ODOT'S FIRST THREE SILICA-FUME PLACEMENTS

	AIR TEMP	DECK TEMP	CONCRETE TEMP	HUMIDITY	WIND	TIME PLACED
STRUCTURE #1 TEST SLAB	66°F	73°F	70°F	55%	0	9:30 AM
STRUCTURE #1 OVERLAY PLACEMENT OCTOBER 18, 1984	45°F TO 71.5°F	40°F TO 61°F	61.9°F TO 67.9°F	94% TO 75%	0	9:00 AM TO 11:00 AM
STRUCTURE #2 OVERLAY PLACEMENT APRIL 22, 1987	70°F	--- A	77.2°F	67%	0 TO 15 MPH GUST	9:00 AM TO 12:00 PM
STRUCTURE #2 OVERLAY PLACEMENT MAY 5, 1987	47°F TO 59°F	42°F TO 51°F	70.7°F TO 74.9°F	---	2 TO 10 MPH	8:00 AM TO 11:00 PM
STRUCTURE #3 PLACEMENT (FULL DEPTH) AUGUST 14, 1987	71°F	70°F	84°F TO 86°F	82% TO 85%	0	3:30 AM TO 7:00 AM

A DATA NOT AVAILABLE.

available for hydration. The HRWR worked well in conjunction with the silica fume.

Figure 3 also shows the effects of HRWR on silica-fume concrete (*3*). Addition of the HRWR, as expected, increased compressive strengths even more.

Fifteen percent was the highest silica-fume content investigated. It was felt that more than 15 percent silica fume would cause workability problems.

Resistance to Freezing and Thawing and Air Content

The air content of 5.2 percent (Table 7) on structure 1 appeared adequate, but the durability factor was very low at 5.5 (Table 8) and not much better for the test slab at 11.5. ODOT considers a durability factor of 80 and above as good.

The other air-void-system values (Table 7) indicate that the air-void system was not as good as the 5.2-percent air content suggested. The specific surface of the air-void system (α) of frost-resistant concrete should be at least 500–800 in.^{2}/in.^{3}. Structure 1 had an α of 168 in.^{2}/in.^{3}. The spacing factor (L) should be 0.008 in. or less. Structure 1 had an L of 0.03 in. It was not realized that air would be a problem, and no attempt had been made to control the air on structure 1. No air-entraining admixture was used, therefore a poor air-void system should have been expected.

The rapid permeability results (see silica-fume projects in Table 9) were very good. An average of only 670 coulombs

TABLE 5 COMPRESSIVE STRENGTH TEST RESULTS FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

	AGE	TEST SLAB, PSI	BRIDGE DECK, PSI	
STRUCTURE #1	1 DAY	4790	3390	
	3 DAY	5830	4650	
	7 DAY	6620	6060	
	28 DAY	8750	6880	
			4/22*	5/5*
STRUCTURE #2	1 DAY	3970	3550	3690
	3 DAY	5360	4870	4680
	7 DAY	5710	5940	5450
	28 DAY	6370	6060	6380
STRUCTURE #3	1 DAY	7700	6240	
	3 DAY	8370	7000	
	7 DAY	7900	7440	
	28 DAY	8810	8020	

*Lane 1 was placed on 4/22 and lane 2 on 5/5

NOTE: Performed in accordance with ASTM Method C 39.

TABLE 6 FLEXURAL STRENGTH TEST RESULTS FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

	AGE	TEST SLAB, PSI	BRIDGE DECK, PSI	
STRUCTURE #1	1 DAY	700	490	
	3 DAY	960	660	
	7 DAY	1060	800	
	28 DAY	1230	940	
			4/22	5/5
STRUCTURE #2	1 DAY	490	600	515
	3 DAY	730	740	730
	7 DAY	930	900	860
	28 DAY	1020	990	1080
STRUCTURE #3	1 DAY	795	750	
	3 DAY	1000	930	
	7 DAY	1055	955	
	28 DAY	1320	1170	

NOTE: Performed in accordance with ASTM Method C 78.

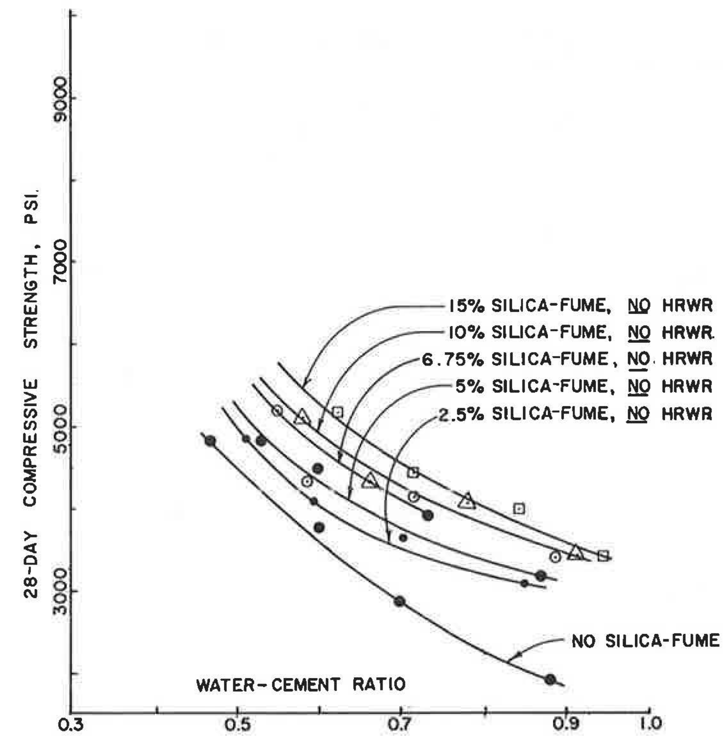

FIGURE 2 Compressive strength vs. water-cement ratio without using an HRWR.

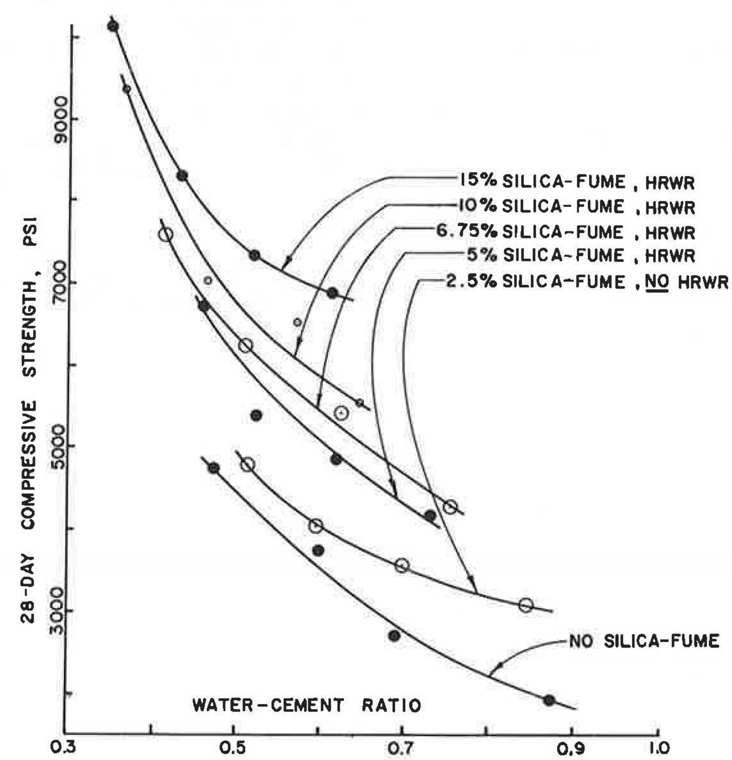

FIGURE 3 Compressive strength vs. water-cement ratio using an HRWR.

TABLE 7 PLASTIC AND HARDENED AIR-TEST RESULTS FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

		TEST SLAB	BRIDGE DECK	
STRUCTURE #1	AIR CONTENT OF UNHARDENED CONCRETE, %	4.2	5.2	
	AIR CONTENT OF HARDENED CONCRETE, %	7.1	5.5	
	SPECIFIC SURFACE, SQ.IN. PER CU.IN.	200	168	
	SPACING FACTOR, IN.	0.01	0.03	
			4/22	5/5
STRUCTUE #2	AIR CONTENT OF UNHARDENED CONCRETE, %	9.2	9.1	9.8
	AIR CONTENT OF HARDENED CONCRETE, %	10.8	10.7	--- A
	SPECIFIC SURFACE, SQ.IN. PER CU.IN.	533	620	---
	SPACING FACTOR, IN.	0.013	.004	---
STRUCTURE #3	AIR CONTENT OF UNHARDENED CONCRETE, %	6.7	8.1	
	AIR CONTENT OF HARDENED CONCRETE, %	---	5.8	
	SPECIFIC SURFACE, SQ.IN. PER CU.IN.	---	550	
	SPACING FACTOR, IN.	---	.008	

A DATA NOT AVAILABLE.

NOTE: Performed in accordance with ASTM Methods, C 231 and C 457, modified point-count method, respectively.

was recorded. ODOT has found normal concretes to exhibit 9,000–12,000 coulombs. ODOT considers any values under 2,000 as low.

Because the rapid permeability results were favorable on structure 1, the poor durability factors were attributed to a poor air-void system and not considered characteristic of silica-fume concrete.

Despite poor durability factors, structure 1 is sound. No delaminations have been discovered, and only two cracks were found, neither of which penetrated the full depth.

Structures 2 and 3 both have very good durability factors at 99.5, 97.5, and 101.1.

The air-void characteristics also were much better than those of structure 1. Structure 2 exhibited a specific surface of 620

TABLE 8 RESISTANCE TO FREEZING AND THAWING FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

	TEST RESULT	TEST SLAB	BRIDGE DECK	
STRUCTURE #1	LOSS IN MASS, %	-1.678	-1.054	
	EXPANSION, %	0.779	1.123	
	DURABILITY FACTOR	11.5	5.5	
			4/22	5/5
STRUCTURE #2	LOSS IN MASS, %	-.030	-0.050	-.045
	EXPANSION, %	.028	.019	.013
	DURABILITY FACTOR	103.1	99.5	97.5
STRUCTURE #3	LOSS IN MASS, %	-.031	-.022	
	EXPANSION, %	.022	.020	
	DURABILITY FACTOR	95.5	101.1	

NOTE: Performed in accordance with ASTM C 666 Method B.

TABLE 9 RAPID PERMEABILITY TEST RESULTS ON VARIOUS BRIDGE OVERLAYS IN OHIO AT 28 DAYS

LOCALE	OVERLAY TYPE	AVG. CHARGE PASSED, COULOMBS
FRA-270	POLYMER (X) 3/4"	33
MRW-229	EPOXY 1/4"	56
FRA-16	EPOXY 1/4"	77
FRA-270	POLYMER (X) 3/4"	270
ROS-207	EPOXY 1/4"	292
DEL-23	L.M.C. & H.M.W.M.	388
FRA-33	*SILICA FUME	522
MAD-161	*SILICA FUME (FULL DEPTH)	608
ASD-511	*SILICA FUME HALF DECK	670
FRA-270	POLYMER (Y) 3/4"	798
TUS-77	H.M.W.M.	837
ERI-250	L.M.C. 1 1/4"	869
ALL-30C	EPOXY 1/4"	934
ASD-511	L.M.C. HALF DECK	1267
WAS-73	S.D.C. 2 3/4"	1389
MAR-529	SILANE SEALER	1525
SUM-271	L.M.C. 1 1/4"	2072
WAY-30	SUPERPLASTICIZED CLASS 'S'	2264
BRO-221	SHRINK COMP. HALF DECK N.B.	2268
PIC-104	SILANE-SEALER N. 1/2	2751
RIC-97	SUPERPLASTICIZED CLASS 'S'	2806
PIC-104	SILANE SEALER S. 1/2	2849
FAI-22	S.D.C. 1 3/4"	2986
MUS-208	SILANE SEALER	3344
LIC-37	S.D.C. 1 3/4"	3438
MRW-314	CLASS 'S' DECK 9"	3969
CLI-68	SILANE SEALER	4223
MAR-746	SILANE SEALER	6116
BRO-221	CLASS 'S' HALF DECK S.B.	9015
DEL-229	SILANE SEALER	9039

L.M.C.=LATEX-MODIFIED CONCRETE   H.M.W.M.=HIGH MOLECULAR WEIGHT METHACRYLATE

S.D.C=DENSE CONCRETE WITH HRWR   CLASS'S'=ODOT'S STANDARD SUPERSTRUCTURE CONCRETE

in.^{2}/in.^{3} and spacing factor of 0.004 in., both characteristic of a good air-void system. Structure 3 exhibited a specific surface of 550 in.^{2}/in.^{3} and a spacing factor of 0.008 in. These results are not as good as those of structure 2, but they are still values characteristic of a good air-void system. Such results indicate that an air-entraining admixture is necessary.

Rapid Permeability Tests

Rapid permeability tests were performed on the concrete used in the structures using the whiting procedure (*4*). Specimens are rated according to the number of coulombs passed.

Concrete Permeability	*Charge Passed (coulombs)*
High	Greater than 4,000
Moderate	2,000–4,000
Low	1,000–2,000
Very Low	100–1,000
Negligible	Less than 100

As shown in Table 9, ASD 511 (structure 1) passed 670 coulombs, FRA 33 (structure 2) passed 522 coulombs, and MAD 161 (structure 3) passed 608 coulombs.

The test results were similar for the three structures. The concrete used in structure 3 contained a large amount of HRWR and therefore a low water-cement ratio, but this did not affect the rapid permeability values, all of which were very low.

In Table 9, a relationship between the various overlays and sealers used on Ohio bridge decks is given. As can be seen, ODOT's silica-fume concrete rates favorably on this comparison chart.

It is also of interest to note Figure 1, which is a plot of rapid permeability results, taken from Table 3. Placing a horizontal line at 2,000 coulombs (considered low permeability), it can be seen that the required percentage of silica fume could be lowered and still produce favorable results. Even at 7–10 percent silica-fume content, a rating of low permeability is achieved.

Cost

The life expectancy of overlay projects exceeds 10 yr. The cost per square yard for any type of overlay varies, depending on the quantity to be furnished and the amount of variable depth involved. Listed below are some prices bid on projects to be placed in spring 1988. These projects are of similar characteristics. (These prices were obtained from Keith Keeran, ODOT's construction bureau, unpublished data.) The prices are per square yard placed.

County	*1.25 in.-Thick Silica-Fume-Modified Concrete*	*1.25 in.-Thick Latex-Modified Concrete*	*1.75 in.-Thick Dense Concrete with HRWR*
CUY	$26	$30	$23
FRA	$28	$29	$35

CONCLUSIONS

On the basis of field observations and data analysis, the following conclusions can be drawn:

- The addition of silica-fume to concrete makes it less permeable and therefore more resistant to chloride penetration. Permeability decreases as silica-fume content increases, and very low permeabilities are achievable.
- Compressive and flexural strengths increase with the addition of silica-fume to concrete.
- An experienced concrete supplier can produce a consistent and homogeneous mixture using silica fume.
- If proper curing is achieved, a crackfree overlay or deck can be obtained; a 72-hr. continuous water cure is advisable.
- A high silica-fume content can cause finishing problems; 15 percent silica fume by mass appears to be the maximum amount that should be used.
- The addition of silica fume had no detrimental effects on the air-void system.
- A possible tendency to cracking in variable thickness overlays was detected.
- A reliable bond can be achieved when overlaying a bridge deck if the old wearing surface is removed to sound concrete and a bonding grout is scrubbed into the surface. No delaminations have been discovered to date.
- Silica-fume-modified concrete can be mixed successfully in a mobile mixer or in a central mixer. Latex-modified concrete should be mixed in a mobile mixer.
- The cost of silica-fume-modified concrete placed as an overlay is similar to that of a latex-modified overlay.

RECOMMENDATIONS

On the basis of these conclusions, the following recommendations are made:

- Decrease ODOT's specified silica-fume content to 10 percent by mass of cement. This maintains favorable permeability characteristics, produces a more economical mix, and reduces the possibility of finishing problems.
- Use an air-entraining admixture. A proper air-void system can be achieved when the proper quantity of air-entraining admixture is used.
- Use an HRWR. Used in the proper quantity, it can help alleviate some finishing problems and increase compressive and flexural strength.
- Maintain the presently specified continuous water cure.
- Monitor the variable depth situations. Determine if stresses are created which promote cracking in these areas.
- Continue to monitor silica-fume overlays and other types of overlay systems, but the indication so far is that silica-fume-modified concrete forms a durable, highly impermeable surface using standard concrete mixing and finishing practices and readily available materials at moderate cost.

ACKNOWLEDGMENTS

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