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FINAL REPORT

# INVESTIGATION OF CONCRETE CONTAINING CONDENSED SILICA FUME

by

Celik Ozyildirim
Research scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways and Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

January 1986
VHTRC 86-R25

1934

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# ABSTRACT

The properties of hydraulic cement concretes containing silica fume were investigated to assess their suitability for use in overlays with a minimum thickness of 1 1/4 in. The properties studied were compressive and flexural strengths, bond strength, modulus of elasticity, permeability, freeze-thaw resistance, thermal expansion, and drying shrinkage. The characteristics of air voids in the hardened concrete were determined by petrographic examination. The study was conducted in two stages: the first to determine the mixture proportions that would yield satisfactorily high strengths and low permeabilities, and the second to conduct the main testing program. Silica fume from two sources was used. Concretes made with silica fume from either source at a water-cement ratio of 0.40 or lower and a replacement rate of 5% yielded the desirable properties. It is expected that concretes made with silica fume can provide a cost-effective protective system for bridge decks when placed in overlays with a minimum thickness of 1 1/4 in.

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ACKNOWLEDGEMENTS

Special thanks are expressed to Mike Burton, John Reisky de Dubnic, and Leroy Wilson for the preparation and testing of the specimens, and to Ms. H. Walker and Bobby Marshall for the linear traverse analysis.

Appreciation is also extended to Arlene Fewell for typing the report and to Harry Craft for reviewing it.

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## INTRODUCTION

Overlays of low permeability concrete placed at a minimum thickness of 1 1/4 in effectively protect bridge decks against the intrusion of corrosion-causing chlorides. However, presently proven products such as latex modified concrete are expensive, and less costly alternatives are desirable.

One possible alternative is the use of concrete made with condensed silica fume (SF) as an additive or a replacement for a portion of the portland cement. Research has demonstrated that SF concrete has a higher compressive strength than conventional concrete at ages of 3 days and beyond, a lower permeability, and increased resistance to alkali/aggregate reactions and aggressive fluids.(1,2,3,4) These desirable effects are attained because SF is a very efficient pozzolan that forms reaction products with the lime from hydrated cement to reduce the volume of large pores and capillaries normally found in the paste.(1)

The type of SF used in concrete is a by-product from the manufacture of silicon or ferro-silicon alloys. It has a minimum silica content of 85%,(1) mostly in the amorphous state. The particles, which are collected from the gases escaping from the furnace during the manufacturing process, are very fine spheres with a surface area of the order of 20,000 $m^2/kg$.(4) Most particles are smaller than 1 μm and the average diameter is about one-hundredth that of a grain of portland cement. At present, an ASTM subcommittee is considering a revision of ASTM C 618, the specification for pozzolans for use in concrete, to include silica fume. Appropriate chemical and physical requirements will be included.

The use of SF in concrete normally increases the water demand because of the extreme fineness of the material. However, this effect can be counteracted by the addition of a high range water reducer (HRWR) to achieve workability at the desired water/cement ratio (w/c). The HRWR also disperses the fine SF particles and adds to the uniformity of the mixture. The SF induces a proneness to plastic shrinkage; however, proper curing prevents damage from this phenomenon. When air entrainment is required for resistance to damage from cycles of freezing and thawing, increased amounts of the air-entraining agents are needed.(4)

The Ohio Department of Transportation has used concrete containing SF in a bridge deck overlay at a reported cost considerably below that for a latex modified concrete mixture.(5) It is also possible that this material would be useful for other applications where high strength and low permeability are needed. Thus, some of the properties and the cost of concrete made with SF as a part of the cementitious material were evaluated.

## OBJECTIVE

The objective of the study was to evaluate, under laboratory conditions, the properties of concretes utilizing SF in order to assess their suitability for use in thin overlays with a minimum thickness of 1 1/4 in.

## SCOPE

The study was conducted in the laboratory in two stages. In the initial stage, trial batches were prepared to obtain the mixture proportions for workable concretes with satisfactory strengths and low permeabilities. In the second stage, the main testing program was conducted. The properties studied were compressive and flexural strengths, bond strength between the regular base concrete and the overlays with and without SF, modulus of elasticity, permeability, freeze-thaw resistance, thermal expansion, and drying shrinkage. Petrographic examinations were used to determine the air void system.

## MATERIALS

Type II cements from the same plant were used in the mixtures batched for both the initial stage and the main testing program. Although cements from two shipments were used, their chemical composition and physical properties, shown in Table A-1 of the Appendix, were similar.

In the initial program silica fume from a single source, SF1, was used. In the main testing program fume from two sources, SF1 and SF2, was used. The chemical compositions given in Table A-2 show that the SF2 had a higher amount of silica and lower amount of iron oxide than did SF1. Both had a specific gravity of 2.3, and would comply with the requirements being considered for adoption by the ASTM.

The fine aggregate was a siliceous sand with a specific gravity of 2.59 and a fineness modulus of 2.90. The coarse aggregate was crushed granite gneiss with a specific gravity of 2.78 and a dry rodded unit weight of 103.2 $lb/ft^3$. The nominal maximum aggregate size was 1/2 in, except in the base concrete, for which it was 1 in. All the batches contained a commercially available vinsol resin for air entrainment and, except for the base concrete, a napthalene sulfonate formaldehyde condensate as an HRWR.

## MIXTURE PROPORTIONS

All the mixtures were proportioned in accordance with ACI 211.1 using an air content of 6.5%, except that 6.0% was used for the ones with SF in the initial phase of the study. The amounts of materials used in the initial phase are given in Table 1 and those for the main testing program in Table 2. The base concrete in Table 2 was used in tests for bond strength and permeability. For the main testing program all batches except the one for the base concrete were duplicated for assurance. The amount of coarse aggregate was 1,505 $lb/yd^3$ in all mixtures except for the base concrete, which was 1,839 $lb/yd^3$.

The ingredients were mixed in a pan-type mixer following the procedures of ASTM C 192. The SF was mixed with some of the mixing water into a slurry, which was introduced into the mixer after the cement. The HRWR was added prior to the final 2-minute mixing.

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TABLE 1

Mixtures for Initial Phase Tests

| Mixture | Batch | Cement + SF, lb/yd$^3$ | w/c | FA,lb/yd$^3$ |
|---|---|---|---|---|
| Control | 1 | 635 | 0.40 | 1,497 |
| Control | 2 | 705 | .40 | 1,366 |
| Control | 3 | 752 | .40 | 1,278 |
| SF1 | 4 | 635(5) | .40 | 1,508 |
| SF1 | 5 | 705(5) | .40 | 1,377 |
| SF1 | 6 | 752(5) | .40 | 1,290 |
| SF1 | 7 | 635(10) | .40 | 1,497 |
| SF1 | 8 | 705(10) | .40 | 1,369 |
| SF1 | 9 | 752(10) | .40 | 1,275 |
| Control | 10 | 635 | .45 | 1,414 |
| SF1 | 11 | 635(5) | .45 | 1,403 |
| SF1 | 12 | 635(10) | 0.45 | 1,392 |

Notes:
1,505 lb/yd$^3$ of coarse aggregate used in all mixtures. Numbers in parentheses indicate percentages of silica fume by weight.

TABLE 2

Mixtures for Main Testing Program

| Mixture | w/c | SF, % | w/c | FA,lb/yd$^3$ |
|---|---|---|---|---|
| Control | 0.40 | --- | 0.40 | 1,497 |
| SF1 | .40 | 5 | .40 | 1,485 |
| SF2 | .40 | 5 | .40 | 1,485 |
| Control | .35 | --- | .35 | 1,579 |
| SF1 | .35 | 5 | .35 | 1,568 |
| Base Concrete | 0.45 | --- | 0.45 | 1,104 |

Notes:
Type II Portland cement + SF = 635 lb/yd$^3$

Coarse aggregate = 1,505 lb/yd$^3$, except 1,819 lb/yd$^3$ in base concrete.

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## INITIAL PHASE TESTING AND RESULTS

The freshly mixed concretes from 1-$ft^3$ batches were tested for air content following ASTM C 231, slump by ASTM C 143, and unit weight by ASTM C 138. A total of 12 batches of concrete were prepared. The results given in Table A-3 show that workable concretes were obtained in all the mixtures by the addition of the HRWR. Slumps ranged from 3.1 to 8.2 in, and the air contents from 4.8% to 7.9%.

Cylinders measuring 4 x 8 in were prepared for compressive strength and rapid permeability tests. A total of 144 cylinders were tested for compressive strength at 1, 3, 7, and 28 days. The cylinders for strength tests were moist cured until tested. The number of specimens prepared and the tests conducted are given in Table 3, along with other tests discussed below. The results on compressive strength summarized in Table A-4 indicate that satisfactory strengths were achieved in all the mixtures, and that those with a low w/c gave higher strengths as expected. The variation in cement content did not have much effect on strength, but high amounts of cement could be needed in achieving workable concretes at a low dosage of HRWR.

The permeability of the concrete to intrusion of chloride ions was determined by measuring the electrical charge in coulombs passing through the concrete.(6) It is strongly influenced by the curing and age of the specimens. For this study, the specimens were moist cured for 2 weeks, air dried for 6 weeks, and then tested.

Latex modified concrete (LMC), which is used quite extensively for deck overlays in Virginia, exhibits low permeability values. In a Council report LMC tested at 3 weeks was noted to have exhibited an average value of 1,462 coulombs.(7) In a limited laboratory investigation by the present author, tests at 8 weeks on LMC that had higher air than desired at 8% resulted in an average value of 1,248 coulombs for 2 cylinders. Similar tests on samples taken from a LMC placed as an overlay gave an average value of 2,162 coulombs for 2 cylinders.

Based on the foregoing, the design of the silica fume mixtures attempted to produce concrete with coulomb values below 2,000 and preferably around 1,000. The mixture data were shown in Table 1. Twenty-four rapid permeability tests were made on the 8-week-old specimens. The results shown in Table A-4 indicate that the permeability was considerably lower in the experimental mixtures with SF than in the control concrete. The control specimens had values exceeding 3,130 coulombs. At the low w/c of 0.40, the experimental mixtures with SF at 5% replacement exhibited values ranging from 880 to 1,530 coulombs, and those at 10% replacement gave values from 450 to 1,220 coulombs. These values are considered to be indicative of low permeability and are comparable to values expected for overlays made with LMC. However, at the w/c of 0.45, the mixtures with SF at 5% had an average value of 2,410, which is higher than that expected for low permeability concretes.

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Values for concrete with 10% SF were at a low level indicating acceptable permeability. It was desired to use as low an amount of SF as possible because of economy.

From the above it was concluded that concretes having a w/c of 0.40 and 5% SF replacement of the normal cement factor of 635 $lb/yd^3$ would provide the strength and permeability desired in thin overlays. It was also decided that mixtures with a lower w/c of 0.35 would be tried to determine its effects on the permeability of the concretes.

## MAIN TESTING PROGRAM

In the main testing program, 2 $ft^3$ of mixtures were prepared using the material combinations shown in Table 2. The fresh concretes were tested for air content following ASTM C 231, slump by ASTM C 143, and unit weight by ASTM C 138, and the results are summarized in Table A-5. The results indicate that workable concretes were obtained, with the slumps ranging from 3.7 to 7.0 in and air contents from 5.3% to 6.9%.

Three cylinders were prepared from the base concrete mixture for compressive strength tests at 28 days, and 2 cylinders for permeability tests at 8 weeks. The values were 5,020 $lbf/in^2$ for strength and 9,568 coulombs for permeability. This latter value is very high and indicates high permeability. Cylinders 4 in high and 4 in in diameter were prepared from the base concrete for shear and permeability tests. Samples for the control and experimental mixtures were prepared for the tests shown in Table 3, and the results are discussed under the subsequent headings.

### Compressive Strength

The compressive strengths were determined in accordance with AASHTO T23 using 4 x 8 in cylinders, except that neoprene pads in steel end caps were used for capping. The results of tests at 1, 7, 14, and 28 days are summarized in Table 4. These indicate that all the mixtures had high strengths, and that the concretes with SF had values at 1 day comparable to those of the control concretes and higher values at later ages. The mixtures with SF2 exhibited higher strengths than those with SF1, which was expected because SF2 had a higher silica content. Also as expected, concretes with the lower w/c gave higher strengths.

### Flexural Strength

The flexural strengths were determined at 28 days in accordance with ASTM C 78 using simple beams measuring 3 x 3 x 11 1/4 in. The test results, given in Table 5, indicate that satisfactory values were obtained. The experimental mixtures had equal or higher strengths than the controls.

TABLE 3

Number of Specimens and Tests from Each Batch

| Tests | No. of Specimens | Age at Test, Days |
|---|---|---|
| Compressive strength | 8 | 1, 7, 14, 28 |
| Flexural strength | 2 | 28 |
| Bond strength[a] | 2 | 28 |
| Elastic modulus | 1 | 28 |
| Permeability | 2 | 56 (AASHTO T277)[b] |
| Freeze-thaw | 2 | 21 |
| Drying shrinkage | 2 | 32 weeks (ASTM C 157) |
| Thermal expansion[c] | 2 | (CRD-C 39-81) |
| Petrographic examination | 1 | 28 |

[a] The bond strength between the experimental overlay and the base concrete was determined by applying a shear force acting through the interface.

[b] 90-day ponding tests (AASHTO T259) were conducted on some specimens.

[c] To investigate the thermal compatibility between the overlay and the base concrete, the coefficient of thermal expansion for each material was determined following the designated Army Corps of Engineers procedure.

TABLE 4

Compressive Strength Data, lbf/in$^2$

| Mixture | w/c | Compressive Strength[a] | | | |
|---|---|---|---|---|---|
| | | 1 Day | 7 Day | 14 Day | 28 Day |
| Control | 0.40 | 3,380 | 5,710 | 6,440 | 7,190 |
| SF1 | 0.40 | 3,330 | 5,760 | 6,920 | 7,470 |
| SF2 | 0.40 | 3,620 | 6,260 | 7,390 | 8,580 |
| Control | 0.35 | 3,940 | 6,440 | 7,080 | 7,780 |
| SF1 | 0.35 | 4,040 | 6,780 | 7,930 | 8,760 |

[a] Average of 4 cylinders, 2 from each duplicate batch.

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## Bond Strength

The bond strength of mixtures bonded to base concretes was determined using samples prepared by placing 2 in thick overlays with and without SF over the cylinders made of base concrete. The samples were subjected to shear at the interface at 28-day moist curing of the overlays. The base concretes had already been kept at least 3 months in the moist room when the overlays were placed. About an hour before the overlays were applied, the base concrete cylinders were taken out of the moist room to assure that the top surfaces would dry. The results, shown in Table 5, indicate that satisfactory bond strengths were obtained for all the mixtures, with the lowest value being 740 $lbf/in^2$.

TABLE 5

Flexural and Bond Strengths $lbf/in^2$

| Mixture | w/c | Strength[a] Flexural | Bond |
|---|---|---|---|
| Control | 0.40 | 750 | 760 |
| SF1 | 0.40 | 810 | 780 |
| SF2 | 0.40 | 800 | 870 |
| Control | 0.35 | 850 | 865 |
| SF1 | 0.35 | 850 | 740 |

[a] Average of 4 specimens, 2 from each duplicate batch.

## Modulus of Elasticity

The modulus of elasticity, E, of the mixtures was determined following ASTM C 469. From each mixture, one 6 x 12-in cylinder was used, and the results are summarized in Table 6. The stress-strain curves were fairly linear until the specified 40% of the ultimate strength was reached. The E values, results for an average of 2 cylinders, ranged from $4.1 \times 10^6$ $lbf/in^2$ to $4.8 \times 10^6$ $lbf/in^2$, in general, with the cylinders having the higher strengths giving higher values. Also, E was determined using the empirical formula given in the American Concrete Institute building code

$$E = 33\, w^{1.5}\sqrt{f'_c}\,,$$

where w is the unit weight and $f'_c$ the compressive strength of concrete. The results, given in Table 6, show that the measured values were about 8% to 20% lower than the calculated values.

TABLE 6

Modulus of Elasticity x $10^6$ lbf/in²

| Mixture | w/c | Measured E[a] | Calculated E |
|---|---|---|---|
| Control | 0.40 | 4.1 | 4.9 |
| SF1 | 0.40 | 4.2 | 4.9 |
| SF2 | 0.40 | 4.4 | 5.3 |
| Control | 0.35 | 4.8 | 5.2 |
| SF1 | 0.35 | 4.7 | 5.3 |

[a] Average of 2 specimens, 1 from each duplicate batch.

## Permeability

The permeability to chloride ions of all the mixtures was determined using AASHTO T277 and test specimens from the top 2 in of 4 x 8 in cylinders. For the experimental mixtures, additional cylinders were prepared with 1 1/4 in thick overlays containing concrete with SF on top of base concrete. The total thickness of the test specimen was 2 in. The results, given as the total charge passed over a 6-hour period in coulombs, are summarized in Table 7. These indicate that concretes containing 5% SF had considerably lower values than did the controls. The values were lower in concretes with a low w/c, with the difference being larger for the controls than for the experimental mixtures. The highest value for concretes containing SF and a w/c of 0.40 was 1,580 coulombs. At a w/c of 0.35, the highest value decreased to 960. The mixture with SF2 had a lower value than that with SF1 at the same w/c. In samples where the experimental mixtures were only 1 1/4 in deep, the other 3/4 in being the base concrete, the coulomb values were similar but slightly higher than those for the samples with 2-in layers of the experimental mixtures.

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TABLE 7

Permeability Data

| Mixture | w/c | Depth, in | Coulombs[a] |
|---|---|---|---|
| Control | 0.40 | 2 | 4,660 |
| SF1 | 0.40 | 2 | 1,580 |
| SF2 | 0.40 | 2 | 1,180 |
| Control | 0.35 | 2 | 3,180 |
| SF1 | 0.35 | 2 | 960 |
| SF1 | 0.40 | 1 1/4[b] | 1,630 |
| SF2 | 0.40 | 1 1/4[b] | 1,240 |
| SF1 | 0.35 | 1 1/4[b] | 1,060 |

[a] Average of 4 specimens, 2 from each duplicate batch.

[b] Specimen depth was 2 in; top 1 1/4 in was the concrete with SF.

The resistance to chloride ion intrusion of some of the mixtures, SF1 and the control at a w/c of 0.40, was also determined following AASHTO T259. Specimens measuring 4 x 8 in were ponded for 90 days with 3% NaCl, and powdered concrete samples were obtained at two depth levels: 1/4 in to 3/4 in and 1 1/2 in to 2 in. The total chloride contents of the samples were determined and the results are given in Table 8. For the 1/4-to-3/4-in depth, the use of SF was found to have lowered the amount of chlorides by a factor of 2, although both the control and experimental mixtures had chloride contents above the threshold level of 1.3 $lb/yd^3$. At the 1 1/2-to-2-in depth both the control and SF mixtures had negligible amounts of chlorides. For overlays that are about 1 1/4 in thick, use of concretes with SF should reduce the amount of chlorides at the level of the reinforcing bars to acceptable values.

TABLE 8

Total Chloride Contents, $lb/yd^3$

| Mixture | w/c | Depth: 1/4-3/4 in | Depth: 1 1/2-2 in |
|---|---|---|---|
| Control | 0.40 | 3.4 | 0.1 |
| SF1 | 0.40 | 1.7 | 0.2 |

Note:
Chloride contents are averages of 4 specimens, 2 from each duplicate batch.

## Resistance to Freezing and Thawing

The resistance of concretes to damage from cycles of freezing and thawing was determined using ASTM C666 Procedure A with two modifications: one in the curing of the specimens and the other the addition of 2% NaCl to the test water. In the ASTM test procedure, specimens are moist cured for 2 weeks, unless some other age is specified. The samples in this study were air dried for 1 week in addition to the 2 weeks of moist curing prior to testing. Also, because of a breakdown of the freeze-thaw machine at the beginning of the tests, specimens were stored in a frozen condition for a few months, as is permitted by the standard method.

The acceptance criteria required that for satisfactory performance at 300 cycles the average weight loss be 7% or less, the durability factor, DF, be 60 or more, and the surface rating, SR, be 3% or less. The surface rating was determined by estimating the proportion of the surface having ratings given in ASTM C672. The top surface was rated separately from the molded surfaces. The final rating for each beam was calculated by averaging the weighted ratings computed for the top and molded surfaces separately.

The weight loss, DF, and SR values at 300 cycles are summarized in Table 9. These indicate that all the mixtures, except the control at a w/c of 0.40, met the acceptance criteria when based on averages. However, one of the two experimental mixtures with a w/c of 0.40 for both SF1 and SF2 also exhibited DFs below 60, which indicates failure. When the two batches were averaged, DF values of 69 and 60 were obtained. These values are low compared to those obtained on ordinary bridge deck concretes with entrained air contents of 5% to 8% used in Virginia. For such concretes the DFs are normally above 90 and in most cases are around 100. The lower DF values are attributed to the use of the HRWR, which results in coarse bubbles in concrete, as will be explained further in the section on petrographic examinations.

## Drying Shrinkage

The drying shrinkage was determined following ASTM C 157 and using specimens measuring 3 x 3 x 11 1/4 in with gage studs at both ends. The specimens were moist cured for a month and then kept in the laboratory ambient air. The shrinkage values at 32 weeks are given in Table 10. The results show that the experimental mixtures had similar but lower shrinkage values than the controls.

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## TABLE 9

Freeze-Thaw Data at 300 Cycles

| Mixture | w/c | Batch | Wt.Loss | DF | SR |
|---|---|---|---|---|---|
| Control | 0.40 | 1[a] | 10.7 | 57 | 2.8 |
| | | 2 | 5.8 | 54 | 2.6 |
| Average | | | 8.2 | 56 | 2.7 |
| SF1 | 0.40 | 1 | 1.1 | 46 | 1.0 |
| | | 2 | 1.6 | 92 | 1.2 |
| Average | | | 1.4 | 69 | 1.1 |
| SF2 | 0.40 | 1 | 1.8 | 69 | 1.3 |
| | | 2[b] | --- | 50 | --- |
| Average | | | 1.8 | 60 | 1.3 |
| Control | 0.35 | 1 | 1.0 | 97 | 1.0 |
| | | 2[c] | --- | --- | --- |
| Average | | | 1.0 | 97 | 1.0 |
| SF1 | 0.35 | 1 | 0.4 | 80 | 0.6 |
| | | 2 | 0.6 | 105 | 0.6 |
| Average | | | 0.5 | 92 | 0.6 |

Note:
Values given are averages of 2 beams for each batch.

[a] End of one beam broke off at 215 cycles, yielding a DF of 41. Weight loss and SR were not determined.

[b] One beam was broken in half at 145 cycles; the other broken at one end at 235 cycles. Weight loss and SR were not determined.

[c] Beams misplaced and readings not taken.

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TABLE 10

Drying Shrinkage at 32 Weeks

| Mixture | w/c | Shrinkage, in/in $10^{-6}$ |
|---|---|---|
| Control | 0.40 | 573 |
| SF1 | 0.40 | 509 |
| SF2 | 0.40 | 522 |
| Control | 0.35 | 572 |
| SF1 | 0.35 | 450 |

Note:
Values are averages of 4 specimens, 2 from each duplicate batch.

## Coefficient of Thermal Expansion

The coefficient of linear thermal expansion of the mixtures was determined using the test method of the Army Corps of Engineers, CRD-C 39-81. Specimens measuring 3 x 3 x 11 1/4 in were prepared with studs at both ends and cured for 28 days in the moist room. Then, they were placed in water at 40°F and 140°F and their lengths measured at each temperature. Coefficients of linear thermal expansion were calculated from the readings and the differences in temperature between the two length readings. The results, summarized in Table 11, show that comparable values were obtained for concretes with and without SF, even though some variability was indicated. Therefore, the addition of SF had no significant effect on the thermal compatibility of the overlays.

TABLE 11

Coefficient of Thermal Expansion

| Mixture | w/c | Coefficient, $10^{-6}$ |
|---|---|---|
| Control | 0.40 | 6.9 |
| SF1 | 0.40 | 5.5 |
| SF2 | 0.40 | 7.6 |
| Control | 0.35 | 5.8 |
| SF1 | 0.35 | 6.1 |

Note:
Values are average of 4 specimens, 2 from each duplicate batch.

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## Petrographic Examination

A 4 x 8-in cylinder was prepared from each mixture for the determination of the air void system in the hardened concrete using the linear traverse method of ASTM C 457. The specimens were moist cured for at least a month, and then a slab was cut and lapped for the linear traverse analysis. The values for small, large, and total voids, specific surface, and spacing factor are summarized in Table 12. These show that the control and experimental mixtures had air void contents ranging from 4.3% to 7.2%; values, in general, very close to those determined on the freshly mixed concretes. The large voids were in excess of 2%.

TABLE 12

Air Void System of Hardened Concrete

| Mixture | w/c | Batch | Void Content >1mm | Void Content <1mm | Void Content Total | Specific Surface, $in^{-1}$ | Spacing Factor, in |
|---|---|---|---|---|---|---|---|
| Control | 0.40 | 1 | 2.7 | 2.8 | 5.5 | 248 | 0.0184 |
| | | 2 | 2.7 | 2.1 | 4.8 | 267 | 0.0184 |
| SF1 | 0.40 | 1 | 2.6 | 3.8 | 6.4 | 412 | 0.0102 |
| | | 2 | 2.5 | 3.8 | 6.3 | 449 | 0.0096 |
| SF2 | 0.40 | 1 | 2.2 | 4.2 | 6.4 | 345 | 0.0122 |
| | | 2 | 3.6 | 2.9 | 6.5 | 304 | 0.0137 |
| Control | 0.35 | 1 | 2.1 | 2.6 | 4.7 | 288 | 0.0172 |
| | | 2 | 2.3 | 2.0 | 4.3 | 261 | 0.0198 |
| SF1 | 0.35 | 1 | 4.0 | 3.2 | 7.2 | 288 | 0.0129 |
| | | 2 | 2.9 | 4.0 | 6.9 | 405 | 0.0096 |

In regular air entrained concretes without an HRWR, small air voids less than 1 mm in diameter, are considered to result from air entrainment, and those exceeding 1 mm from a lack of consolidation or from extra water in the mixture. In regular concretes most of the entrained air voids are smaller than 100 µm in diameter. The amount of large voids is generally about 2% or less in properly prepared concretes.

The specific surface values ranged from 248 to 449 $in^{-1}$ and the spacing values from 0.0096 to 0.0198 in. The controls exhibited the lowest specific surfaces and the highest spacing factors. The values imply a coarse air void system and are not desirable for resistance to damage from cycles of freezing and thawing. The coarseness of the air void system is attributed to the addition of the HRWR. For adequate protection of critically saturated concrete from extreme exposures, specific surface values of 600 $in^{-1}$ or more and spacing factors of 0.008 in or less have been recommended by Milenz et al.(8) and these values are generally accepted for satisfactory protection. However, Powers has stated that the maximum allowable spacing factor is 0.01 in for frost resistant concretes.(9)

In this study, specimens with a w/c of 0.40 and spacing factors all above the desired value of 0.008 in gave variable results, but on the average the concretes with SF showed satisfactory resistance to cycles of freezing and thawing. The controls, which had the highest spacing factors, had marginally low resistance. The high spacing factors and the variable results were also obtained in an earlier study where HRWRs were used.(10) All the specimens with a w/c of 0.35 and spacing factors as high as 0.0172 in exhibited a satisfactory freeze-thaw performance. The specimens with the highest spacing factor of 0.0198 in have been misplaced and thus not tested.

It should be recognized that the mixtures in this study had a low w/c and low permeability that would make it difficult to get them critically saturated on bridge decks where normally they would not be continuously exposed to water. Similarly, LMC overlays have been found to exhibit even coarser air void systems with higher spacing factors, but their field performance has been satisfactory.(7)

## COMPARISONS OF SF CONCRETE WITH LMC

In this study, concretes containing SF were evaluated for use in overlays with a minimum thickness of 1 1/4 in.

At present, LMC costs at least an additional \$100/$yd^3$, and for mixing requires special mobile mixers that are more expensive than the ready-mix trucks. In addition, mobile mixers are not as readily available in all the concrete producing plants as are the ready-mix trucks. Contractors usually own or contract for mobile mixers.

Two difficulties with SF are its cost in Virginia and its handling characteristics. It is sold in dry form as well as in a slurry. Its use in slurry form is recommended because of convenience. In this study, dry SF was mixed with some of the mixing water to form the slurry.

Concretes containing SF can be mixed in a mobile mixer or a ready-mix truck, and the use of an HRWR is recommended. The use of SF and an HRWR separately or in a proprietary slurry including an HRWR and a low 5% SF rate is not expected to add more than \$20/$yd^3$ to the cost of concrete.

1954

## SUMMARY OF RESULTS AND CONCLUSIONS

Based on the test results from this study, the following conclusions are drawn.

1. Concrete containing SF at a low replacement rate of 5% and at a w/c of 0.40 or less can provide satisfactory strength and a low permeability for bridge deck overlays with a minimum thickness of 1 1/4 in.

2. The compressive strengths of all the mixtures were satisfactory, and the strengths of the mixtures with SF were comparable to those of the controls at 1 day and higher at later ages.

3. The flexural strengths of all the mixtures were satisfactory, and the experimental mixtures with SF yielded equal or better results compared to the controls.

4. The bond strengths of all the mixtures bonded to base concrete were satisfactory.

5. The measured modulus of elasticity values were found to be somewhat lower than the ones determined using the empirical formula.

6. The permeability, measured in coulombs, of concretes containing SF was lower than that of the controls. At the lower w/c, lower coulomb values were obtained. In the 90-day ponding test, the amounts of chlorides found at the 1/4-to-3/4-in depth of the test cylinders were above the threshold level for the initiation of corrosion in both the control concrete and the concrete containing SF, but the values for the concretes containing SF were one-half of those for the controls.

   For overlays with a minimum thickness of 1 1/4 in, the use of concrete with 5% SF should reduce the amount of chlorides at the level of the reinforcing bars to acceptable values.

7. The average freeze-thaw performance of concretes with SF was satisfactory, even though they had coarse air void systems that result in spacing factors exceeding the generally accepted value of 0.008 in. The coarse air void system is attributed to the use of an HRWR in the mixtures.

-1955

8. The drying shrinkage of the experimental mixtures were similar in magnitude but lower than those for the controls.

9. The coefficient of linear thermal expansion values were comparable in all the mixtures.

## RECOMMENDATIONS

The installation of full-scale experimental overlays using silica fume as a replacement for 5% of the cement in hydraulic cement concrete is recommended. The silica fume should have a minimum silica content of 85% and meet the other requirements for this class of pozzolan that are under consideration for inclusion in ASTM C 618. Compliance with these requirements will result in concrete of satisfactory strength and low permeability. Concretes of this type should be tried in overlays with a minimum thickness of 1¼ in as a protective system for bridge decks.

1956

1957

# METRIC CONVERSION SHEET

## SI CONVERSION FACTORS

| To Convert From | To | Multiply By |
|---|---|---|
| **Length:** | | |
| in | cm | 2.54 |
| in | m | 0.025 4 |
| ft | m | 0.304 8 |
| yd | m | 0.914 4 |
| mi | km | 1 . 609 344 |
| **Area:** | | |
| $in^2$ | $cm^2$ | 6.451 600 E+00 |
| $ft^2$ | $m^2$ | 9.290 304 E-02 |
| $yd^2$ | $m^2$ | 8.361 274 E-01 |
| $mi^2$ | Hectares | 2.589 988 E+02 |
| acre (s) | Hectares | 4.046 856 E-01 |
| **Volume:** | | |
| oz | $m^3$ | 2.957 353 E-05 |
| pt | $m^3$ | 4.731 765 E-04 |
| qt | $m^3$ | 9.463 529 E-04 |
| gal | $m^3$ | 3.785 412 E-03 |
| $in^3$ | $m^3$ | 1.638 706 E-05 |
| $ft^3$ | $m^3$ | 2.831 685 E-02 |
| $yd^3$ | $m^3$ | 7.645 549 E-01 |

NOTE: $1m^3$ = 1,000 L

| To Convert From | To | Multiply By |
|---|---|---|
| **Volume per Unit Time:** | | |
| $ft^3$/min | $m^3$/sec | 4.719 474 E-04 |
| $ft^3$/s | $m^3$/sec | 2.831 685 E-02 |
| $in^3$/min | $m^3$/sec | 2.731 177 E-07 |
| $yd^3$/min | $m^3$/sec | 1.274 258 E-02 |
| gal/min | $m^3$/sec | 6.309 020 E-05 |
| **Mass:** | | |
| oz | kg | 2.834 952 E-02 |
| dwt | kg | 1.555 174 E-03 |
| lb | kg | 4.535 924 E-01 |
| ton (2000 lb) | kg | 9.071 847 E+02 |
| **Mass per Unit Volume:** | | |
| lb/$yd^2$ | kg/$m^2$ | 4.394 185 E+01 |
| lb/$in^3$ | kg/$m^3$ | 2.767 990 E+04 |
| lb/$ft^3$ | kg/$m^3$ | 1.601 846 E+01 |
| lb/$yd^3$ | kg/$m^3$ | 5.932 764 E-01 |
| **Velocity: (Includes Speed)** | | |
| ft/s | m/s | 3.048 000 E-01 |
| mi/h | m/s | 4.470 400 E-01 |
| knot | m/s | 5.144 444 E-01 |
| mi/h | km/h | 1.609 344 E+00 |
| **Force Per Unit Area:** | | |
| lbf/$in^2$ or psi | Pa | 6.894 757 E+03 |
| lbf/$ft^2$ | Pa | 4.788 026 E+01 |
| **Viscosity:** | | |
| $cS_t$ | $m^2$/s | 1.000 000 E-06 |
| P | Pa·s | 1.000 000 E-01 |

**Temperature:** °F-32)5/9 = °C

1958

1959

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1960

-1961

# APPENDIX

## ANALYSES OF CEMENTS AND SILICA FUMES AND PROPERTIES OF FRESH AND HARDENED CONCRETES

-1962

1963

TABLE A-1

Chemical and Physical Analyses of Cements

| Chemical, % | Cement for Initial Stage Tests | Cement for Main Testing Program |
|---|---|---|
| $S_iO_2$ | 21.3 | 21.0 |
| $Al_2O_3$ | 4.8 | 4.8 |
| $Fe_2O_3$ | 4.0 | 4.1 |
| CaO | 62.7 | 63.3 |
| MgO | 2.7 | 2.4 |
| $SO_3$ | 2.7 | 2.5 |
| Total alkalies | 0.73 | 0.79 |
| $C_3S$ | 47.9 | 53.0 |
| $C_3A$ | 6.0 | 6.0 |
| Physical | | |
| Fineness (Blaine) | 3558 | 3556 |

-1964

TABLE A-2

Chemical Compositions of Silica Fumes

| | SF1 | SF2 |
|---|---|---|
| $S_iO_2$ | 87.2 | 93.20 |
| $Al_2O_3$ | 0.26 | 0.07 |
| $Fe_2O_3$ | 2.26 | 0.27 |
| CaO | 1.24 | 0.96 |
| MgO | 0.79 | 0.21 |
| $SO_3$ | 0.26 | 0.01 |
| Loss on Ignition | 3.80 | 1.80 |
| Total alkalies | 0.56 | 0.18 |

1965

TABLE A-3

Characteristics of Freshly Mixed Concrete for the Initial Test Program

| Mixture | Batch[a] | w/c | Slump, in | Air, % | Unit Wt., lb/ft$^3$ |
|---|---|---|---|---|---|
| C (635,0)[b] | 1 | 0.40 | 3.5 | 5.5 | 146.4 |
| C (705,0) | 2 | .40 | 8.2 | 5.3 | 145.2 |
| C (752,0) | 3 | .40 | 5.4 | 4.8 | 145.2 |
| SF (635,5) | 4 | .40 | 3.1 | 5.5 | 147.0 |
| SF (705,5) | 5 | .40 | 4.2 | 6.5 | 143.4 |
| SF (752,5) | 6 | .40 | 3.9 | 5.5 | 146.7 |
| SF (635,10) | 7 | .40 | 3.2 | 6.8 | 143.0 |
| SF (705,10) | 8 | .40 | 3.3 | 7.0 | 142.6 |
| SF (752,10) | 9 | .40 | 7.9 | 7.9 | 139.8 |
| C (635,0) | 10 | .45 | 3.8 | 6.0 | 144.4 |
| SF (635,5) | 11 | .45 | 4.2 | 6.8 | 142.8 |
| SF (635,10) | 12 | 0.45 | 3.3 | 5.8 | 143.6 |

[a] Information on ingredients for batches is given in Table 1.

[b] First number in parentheses is cement content, including silica fume; second is the percentage weight of cement replaced by silica fume.

-1966

TABLE A-4

Compressive Strength and Permeability Data for the Initial Test Program

| Mixture | Batch | w/c | Compressive Strength, lbf/in² 1 day | 3 days | 7 days | 28 days | Permeability |
|---|---|---|---|---|---|---|---|
| C | 1 | 0.40 | 3,230[a] | 4.280 | 5,770 | 6,910 | 3,130[b] |
| C | 2 | .40 | 3,310 | 4,360 | 5,800 | 7,110 | 4,500 |
| C | 3 | .40 | 2,900 | 3,870 | 5,180 | 6,470 | 5,180 |
| SF1 | 4 | .40 | 2,950 | 4,320 | 5,400 | 7,660 | 1,250 |
| SF1 | 5 | .40 | 2,940 | 4,080 | 5,460 | 7,350 | 1,530 |
| SF1 | 6 | .40 | 3,690 | 5,060 | 6,650 | 8,490 | 880 |
| SF1 | 7 | .40 | 2,400 | 3,850 | 5,340 | 7,260 | 450 |
| SF1 | 8 | .40 | 2,610 | 3,840 | 5,280 | 7,530 | 730 |
| SF1 | 9 | .40 | 1,990 | 3,330 | 4,730 | 6,150 | 1,220 |
| C | 10 | .45 | 2,300 | 3,960[c] | 4,450 | 6,290 | 4,850 |
| SF1 | 11 | .45 | 2,410 | 3,950[c] | 4,770 | 6,620 | 2,410 |
| SF1 | 12 | 0.45 | 2,240 | 3,820[c] | 4,800 | 6,640 | 1,210 |

Note:
Information on ingredients and the characteristis of freshly mixed concrete are given in Tables 1 and A-3.

[a] All strength values the average of 3 specimens.

[b] All values the average of 2 specimens.

[c] At 4 days.

1967

TABLE A-5

Characteristics of Freshly Mixed Concrete for the Main Testing Program

| Mixture | Batch | w/c | Slump, in | Air, % | Unit Weight, lb/ft$^3$ |
|---|---|---|---|---|---|
| C | 1 | 0.40 | 6.1 | 5.8 | 146.0 |
| | 2 | .40 | 7.0 | 6.0 | 145.2 |
| SF1 | 1 | .40 | 5.7 | 6.5 | 144.4 |
| | 2 | .40 | 4.5 | 6.1 | 144.0 |
| SF2 | 1 | .40 | 4.5 | 5.4 | 145.6 |
| | 2 | .40 | 3.7 | 6.2 | 144.0 |
| C | 1 | .35 | 6.9 | 6.5 | 144.8 |
| | 2 | .35 | 5.2 | 5.3 | 148.0 |
| SF1 | 1 | .35 | 6.7 | 6.7 | 143.6 |
| | 2 | .35 | 6.9 | 6.9 | 144.8 |
| Base Concrete | 1 | 0.45 | 4.3 | 6.6 | 143.2 |

-1968