Silica Fume in Shotcrete

by John Wolsiefer, Sr., and Dudley R. Morgan

Silica fume is a highly pozzolanic mineral admixture that has been used mainly to improve concrete durability and strength and as a portland cement replacement. Silica fume has been used primarily in the United States, Canada, and the Scandinavian countries, but is now finding increasing use elsewhere in the world. Significant improvements in both dry-mix and wet-mix shotcretes have been achieved through the use of silica fume resulting in superior performance for applications such as rock stabilization, tunnel linings, and infrastructure rehabilitation.

Silica fume was first used in shotcrete in the 1970s in Norway where the country's rocky terrain promoted the development of shotcrete tunnel lining. In the early 1980s, the use of silica fume in shotcrete developed in the western hemisphere, first in Western Canada and then in the United States.[1] Silica fume shotcrete has been used in a variety of projects: rock slope stabilization; highway and rail tunnel linings; rehabilitation of beams, columns, and abutments on highway substructures; rehabilitation of marine structures, such as piles, sea walls, and dock supports; rehabilitation of chemical plant structures; and the creation of artificial rock scapes for zoos and marine aquariums.

Improvements in shotcrete performance and production techniques achieved through the use of silica fume include:

- Reduction of rebound in dry-mix shotcrete, thus improving material cost effectiveness.
- Increased one-pass vertical and overhead application thicknesses without accelerators, thus improving productivity.
- Improved cohesion to resist washout in repair of piles and seawalls in intertidal zones.
- Increased freeze-thaw durability produced by lower permeability. (Note that wet-mix shotcrete must be properly air entrained.)
- Increased compressive and flexural strengths at both early and later ages.
- Enhanced resistance to chemical attack from chlorides, nitrates, sulphates, acids, and alkali-aggregate reactions.
- High electrical resistivity and low permeability mitigating corrosion of rebar and steel mesh in concrete rehabilitation applications in chloride environments.

Shotcrete processes

Shotcrete is a cement/aggregate mortar or concrete mix that is shot at high velocity onto a surface by compressed air. There are two basic processes for shotcreting: wet-mix and dry-mix.[2] Silica fume admixtures can be introduced quite easily in either process. In the dry-mix process, it can be introduced as:

- a premix in super sacks (typically 1 Mg) with cement, aggregates, silica fume, and fibers, if required
- dry-mix transit mix with cement and aggregate batched at the plant and the silica fume and fibers batched into the transit mixer on the job site
- weight-calibrated volumetric batching on site, with silica fume added in bags or as a preblended portland-silica fume cement
- silica fume slurry addition at the nozzle (a recent innovation in Europe)

In the wet-mix process, the silica fume can be introduced as:

- transit mix, just like ready mix concrete, with the silica fume bulk batched at the plant (either central mix or dry batch plant) along with the cement, admixtures, and aggregates
- transit mix concrete from a ready mix plant with the silica fume batched in bags at the job site
- slurry addition at the batch plant

Dry-mix shotcrete tends to be preferred in such applications as:

- sites that are remote or difficult to access, where providing wet-mix shotcrete would be difficult, e.g., certain mining applications and repair of offshore structures
- where small volumes of intermittent shotcrete supply are required, e.g., tunnel repair in active road or rail tunnels or small-volume remedial projects

In recent years, the wet-mix process has been gaining in usage. Its advantages over dry-mix include:

- better control over water-cement ratio through in-plant batching (in the dry-mix process, the nozzleman controls the water content)
- less rebound, greater rates of placement and productivity and, hence, lower cost
- less dust and more homogeneity in mixing*

Table 1 — Wet-mix shotcrete mix designs, kg/m³

Mix	A	B	C	D
Mix type	PC	USF	CLDSF	CHDSF
Portland cement, Type I	401	350	353	359
Silica fume	—	47	48	46
Coarse aggregate, 10 mm, SSD	462	485	475	467
Concrete sand, SSD	1258	1213	1239	1263
Water	171	177	177	176
Water-reducing admixture, ml	887	1952	1952	1922
Superplasticizer, ml	—	1597	1597	1360
Air-entraining admixture, ml	118	296	296	296
Total	2294	2297	2296	2314

Table 2 — Dry-mix shotcrete mix designs, kg/m³

Mix	E	F	G	H
Mix type	PC	USF	CLDSF	CHDSF
Portland cement, Type I	425	373	373	373
Silica fume	—	49	49	49
Coarse aggregate, 10 mm, SSD	495	491	491	491
Concrete sand, SSD	1216	1204	1204	1204
Water (estimated)	163	165	165	165
Total	2300	2281	2281	2281

Table 3 — Plastic properties of wet-mix shotcrete

Mix	A	B	C	D
Mix type	PC	USF	CLDSF	CHDSF
Ambient temperature, C	9	10	13	14
Shotcrete temperature, C	14	12	15	13
Slump, mm				
Base shotcrete	40	50	45	100
After SF & superplasticizer	—	50	35	20
Air content, percent				
Base shotcrete	8.5	7.2	8.0	7.4
After SF & superplasticizer	—	6.4	5.8	5.8
As-shot	4.8	3.9	3.2	2.6
Thickness to bond break				
Overhead application, mm	95	130	280	180
Vertical application, mm	305	330	380	405
Overhead rebound, percent	—	12.9	12.3	10.4
Vertical rebound, percent	3.4	2.7	3.7	3.9

Table 4 — Plastic properties of dry-mix shotcrete

Mix	E	F	G	H
Mix type	PC	USF	CLDSF	CHDSF
Ambient temperature, C	6	6	8	7
Shotcrete temperature, C	14	16	14	13
Thickness to bond bread				
Overhead application, mm	65	380	280	230
Vertical application, mm	205	460	560	460
Overhead rebound, percent	42.7	20.4	25.2	18.6
Vertical rebound, percent	45.4	21.1	22.9	24.6

Shotcrete test program

A study was undertaken to evaluate the performance characteristics of three different silica fume product forms in both wet-mix and dry-mix shotcrete:

- as-produced uncompacted silica fume (USF)
- compacted low-density silica fume (CLDSF)
- compacted high-density silica fume (CHDSF)

The performance characteristics evaluated included rebound loss, thickness to bond breaking (sloughing) on overhead and vertical surfaces, compressive strength, flexural strength, drying shrinkage at 50 percent relative humidity, chloride permeability, electrical resistivity, boiled absorption, and volume of permeable voids. These parameters were compared to the performance of a shotcrete control mix prepared with plain portland cement.

*Morgan, D. R., "Recent Developments in Shotcrete Technology," Materials Engineering Perspective presented at the World of Concrete 1988, Las Vegas.

Mix designs and supply

The wet- and dry-mix shotcrete mix designs used are shown in Tables 1 and 2. These mix designs are typical of those used in rock slope stabilization and tunnelling projects in the United States and Canada. The cement was a portland Type I, with aggregates meeting the requirements of the ACI Standard Specification for Materials, Proportioning, and Application of Shotcrete, ACI 506.2, Gradation No. 2. The control mixes are labelled A (Wet) and E (Dry). The silica fume mix designs, prepared with USF, CLDSF, and CHDSF are designated, respectively, B, C, and D for the wet-mix and F, G, and H for the dry-mix shotcretes.

The silica fume dosage averaged 13 percent (by mass of cement) for all silica fume shotcrete mix designs. A naphthalene sulphonate-based superplasticizer was used to control the water-cement ratio in the wet shotcrete mix. Superplasticizer is not required for dry-mix shotcrete, since most of the water in the mix is added at the shotcrete nozzle; contact time for the water reacting with the cement and silica fume is too short for effective water reduction before the mix is actually consolidated in place on the shotcrete surface.

The wet-mix shotcrete was brought to the field test site by transit truck, with the silica fume and superplasticizer added on-site. A shotcrete piston pump was used to apply the wet-mix shotcrete. The dry-mix shotcrete was weight-batched in premixed super sacks with cement, aggregate, and silica fume all premixed. The dry-mix was premoisturized to a moisture content of 3 to 4 percent prior to discharge in a rotating barrel feed shotcrete gun.

Thickness to bond break and rebound loss

Silica fume addition to shotcrete increases adhesion to the bonding surface and cohesion within the shotcrete; consequently, the thickness of shotcrete build-up attainable on overhead and vertical surfaces is substantially improved. There is no standard ASTM or ACI test to measure attainable

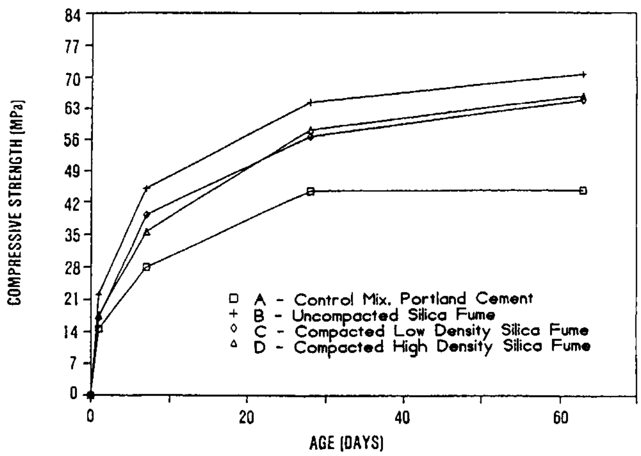

Fig. 1 — Compressive strength of wet-mix shotcrete.

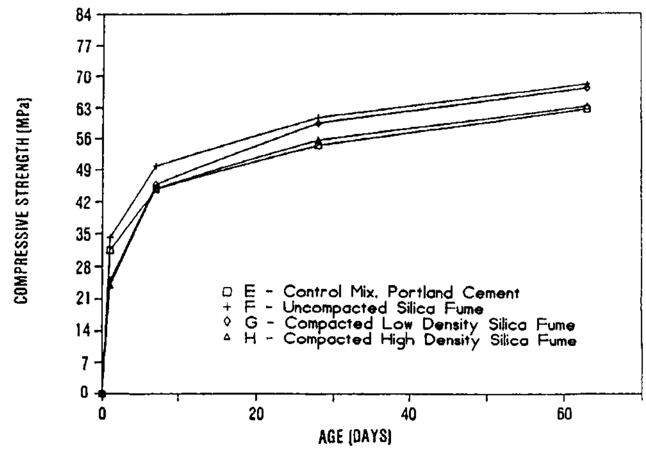

Fig. 2 — Compressive strength of dry-mix shotcrete.

Table 5 — Hardened properties of wet-mix shotcrete

Mix	ASTM	A	B	C	D
Mix type	test procedure	PC	USF	CLDSF	CHDSF
Compressive strength, MPa	C 39				
24 hours		14.5	21.7	16.8	17.3
7 days		—	44.4	38.6	35.1
28 days		43.8	63.5	55.9	57.4
63 days		44.0	69.7	64.0	64.9
Flexural strength, MPa	C 78				
7 days		—	4.9	3.8	4.1
28 days		5.3	6.7	6.0	6.5
Boiled absorption, percent, 28 days	C 642	5.9	6.6	6.9	6.3
Volume of permeable voids, percent, 28 days		12.9	14.3	14.9	13.9
Bulk specific gravity after immersion and boiling		2.296	2.304	2.307	2.341

Table 6 — Hardened properties of dry-mix shotcrete

Mix	ASTM	A	B	C	D
Mix type	test procedure	PC	USF	CLDSF	CHDSF
Compressive strength, MPa	C 39				
24 hours		—	—	24.7	23.7
29 hours		31.1	33.8	—	—
7 days		44.2	49.2	45.2	44.4
28 days		53.8	59.9	58.7	54.9
63 days		61.8	67.2	66.3	62.4
Flexural strength, MPa	C 78				
28 days		7.4	8.4	6.6	7.5
Boiled absorption, percent, 28 days	C 642	4.9	2.7	3.6	4.0
Volume of permeable voids, percent, 28 days		11.2	6.3	8.3	9.2
Bulk specific gravity after immersion and boiling		2.380	2.398	2.371	2.370

thickness build-up, so thickness to bond break (sloughing) and rebound loss were measured in a specially constructed rebound chamber. These parameters are shown in Tables 3 and 4.

In the wet-mix shotcrete study, the overhead thickness at bond-break was 3.5 in. (90 mm) for the plain portland cement Mix A, and reached a maximum of 11 in. (280 mm) in Mix C (CLDSF). The overhead thickness at bond break was typically greater for the dry-mix shotcrete, reaching a maximum of 15 in. (380 mm) in Mix F (USF), compared to 2.5 in. (65 mm) for the plain Mix E. The dry-mix shotcrete overhead rebound was decreased from 42.7 perclent for the plain control to an average of 21.4 percent for the three silica fume product forms. The vertical rebound was reduced from 45.5 percent in the plain control mix to 22.8 percent, on average, for the three silica fume product forms. The wet-mix shotcrete rebound percentages were low in all mixtures.

In summary, the wet-mix data variance for the three silica fume product forms shows no significant difference in rebound loss, but some differences in thickness to bond break. For the dry-mix shotcrete, there is a greater thickness of 15 in. (380 mm) for USF compared to 11 and 9 in. (280 and 230 mm) for the CLDSF and CHDSF mixes, respectively. However, note that these thicknesses were attained in a controlled test environment, and may not be achievable in field applications.

Compressive and flexural strength

Compressive strength was measured at 24 hours, and 7, 28, and 63 days by testing cores extracted from shotcrete test panels. The panels were cured in the field for the first 24 hours, then transferred (in the wooden forms) to a laboratory, where the shotcrete was moist-cured. The strength data shown in Table 5 and Fig. 1 show that using silica fume generated significant increases in the wet-mix shotcrete compressive strength. The control mix compressive strength was 6390 psi (44 MPa) at 63 days compared to an average of 9590 psi (66.1 MPa) for the silica fume shotcretes, about a 50 percent increase.

The dry-mix silica fume shotcrete compressive strengths also were

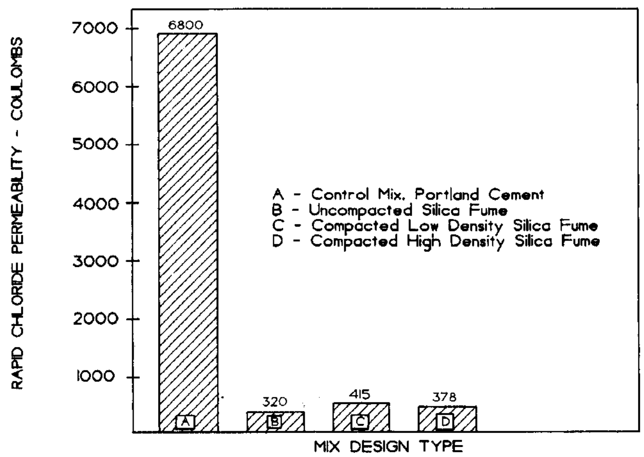

Fig. 3 — Rapid chloride permeability of wet-mix shotcrete.

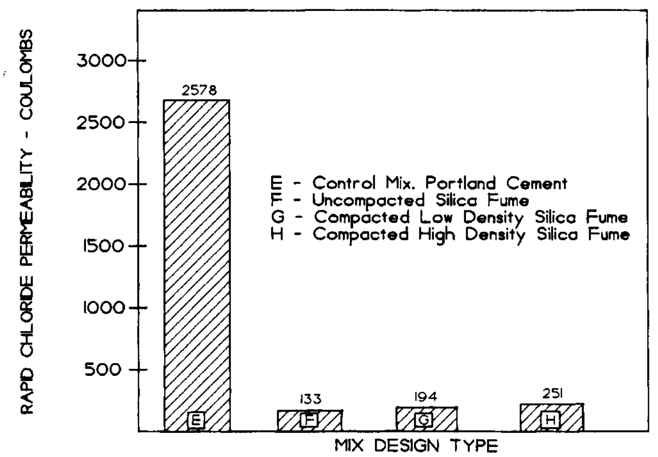

Fig. 4 — Rapid chloride permeability of dry-mix shotcrete.

higher than that of the control mix, though not as pronounced as in the wet-mix shotcretes (Table 6 and Fig. 2).

The flexural strength specimens were cut from the shotcreted panels for 28-day testing. The silica fume wet-mix shotcretes were also tested at 7 days. The flexural strength data is shown in Tables 5 and 6 for the wet-mix and dry-mix shotcretes, respectively. The greatest strength improvement is again in the wet-mix silica fume shotcretes.

In summary, with respect to compressive and flexural strength of the hardened shotcretes, there generally are only small differences in performance between shotcretes made with the three different silica fume product forms.

Boiled absorption and permeable voids

The boiled absorption, volume of permeable voids, and bulk specific gravity were measured after immersion and boiling according to ASTM C 642 test procedures. The data are presented in Tables 5 and 6 for wet- and dry-mix shotcretes, respectively.

In this test, silica fume addition resulted in significant reductions in boiled absorption and permeable voids in dry-mix shotcrete, but not in wet-mix shotcrete. All the wet-mix shotcretes have absorption and permeable voids test results that can be rated as being between "good" and "excellent," with all the dry-mix shotcrete data extremely low, being in the "excellent" category.*

Table 7 — Chloride permeability based on charge passed

Charge passed, coulombs	Chloride permeability	Typical of
Greater than 4000	High	High water-cement ratio (0.6) conventional PCC*
2000 to 4000	Moderate	Moderate water-cement ratio (0.4 to 0.5) conventional PCC*
1000 to 2000	Low	Low water-cement ratio (0.4) conventional PCC*
100 to 1000	Very low	Latex-modified concrete, silica fume concrete (5 to 15 percent)
Less than 100	Negligible	Polymer-impregnated concrete, polymer concrete, and high silica fume content concrete (15 to 20 percent)

*Portland cement concrete.

Rapid chloride permeability and electrical resistivity

Chloride permeability and electrical resistivity data were generated from cores cut from the shotcrete panels. Tests were conducted to the requirements of the "Standard Method of Test for Rapid Determination of Chloride Permeability of Concrete," AASHTO Designation T277-83. Chloride permeability and electrical resistivity are very important characteristics in evaluating the ability of shotcrete in a rehabilitation application to slow down or prevent corrosion of steel reinforcement.

The rapid chloride permeability data are shown in Fig. 3 for wet-mix shotcrete and in Fig. 4 for dry-mix shotcrete. In spite of the fairly good strength, absorption, and permeable void data for the plain portland cement shotcrete control, the rapid chloride permeability was 6800 coulombs for the wet-mix shotcrete and 2573 coulombs for the dry-mix shotcrete. The values are in the "high" and "moderate" classification, respectively, for concrete,[3] as shown in Table 7. Based on historical data, concrete of this quality would have inferior durability performance in an aggressive chloride environment. In contrast to this data, the silica fume shotcrete reduced the chloride permeability to an average of 371 coulombs for the wet-mix shotcrete and 192 coulombs for the dry-mix shotcrete.

The electrical resistivity measurements (Fig. 5 and 6) show correspondingly large improvements over the control shotcrete. The dry-mix silica fume shotcrete shows an average electrical resistivity of 55,290 ohms-cm, compared to the control mix value of 5490 ohms-cm.

All three forms of silica fume in both wet and dry-mix shotcrete result in chloride permeability reduction 10 to 20 times greater than that of the control portland cement shotcrete (Fig. 3 and 4). This observation, together with the electrical resistivity data, is a very significant indication of the benefits of using silica fume in shotcrete for rehabilitation of reinforced concrete structures containing deteriorated

*Morgan, D. R., "Recent Developments in Shotcrete Technology," Materials Engineering Perspective presented at the World of Concrete 1988, Las Vegas.

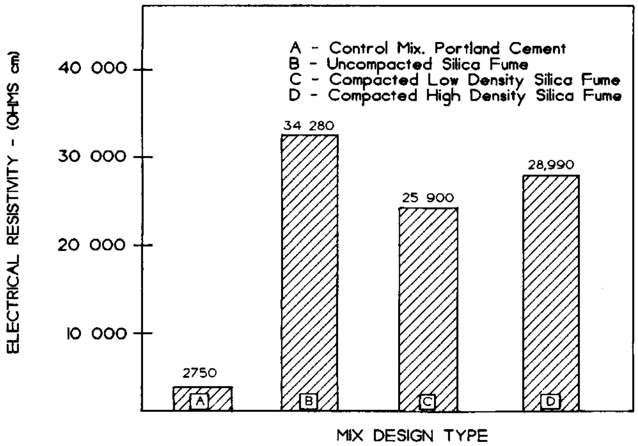

Fig. 5 —Electrical resistivity of wet-mix shotcrete.

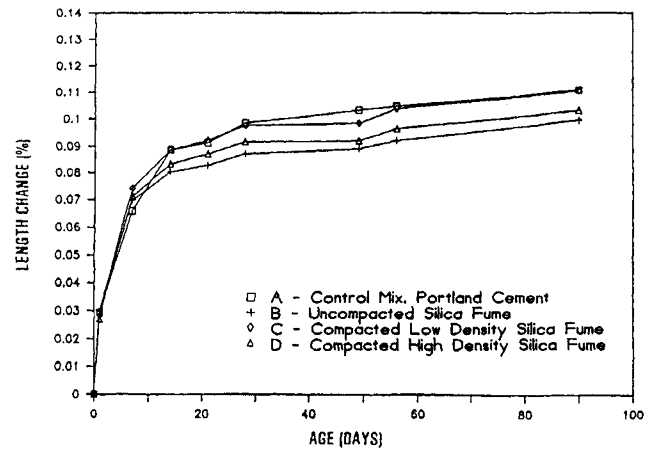

Fig. 7 — Drying shrinkage of wet-mix shotcrete.

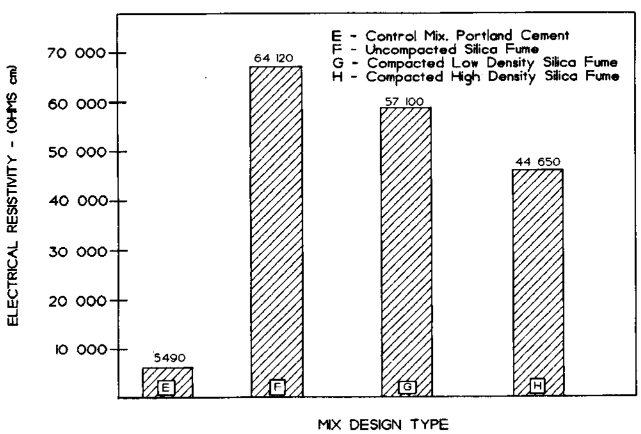

Fig. 6 — Electrical resistivity of dry-mix shotcrete.

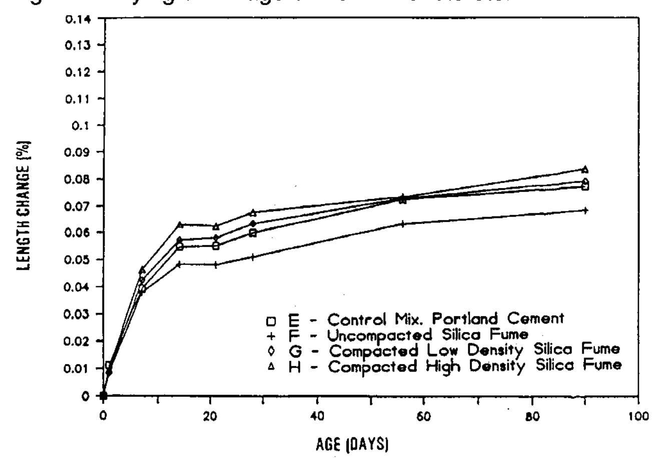

Fig. 8 — Drying shrinkage of dry-mix shotcrete.

steel in environments with chloride exposure.

Drying shrinkage

Drying shrinkage tests were conducted in accordance with ASTM C 341 test procedures using specimens cut from the shotcreted panels. At 56 days, the data show that the uncompacted silica fume shotcrete Mixes B and F had the lowest values of drying shrinkage (Fig. 7 and 8). The dry-mix shotcrete shrinkage was lower than for the wet-mix shotcrete, and can be best explained by the dry-mix shotcrete's lower water demand.

Summary and conclusions

1. This study has demonstrated that all three forms of silica fume studied (uncompacted, compacted low density, compacted high density) can be readily batched, mixed, and applied in both the dry- and wet-mix shotcrete processes.

2. With respect to the wet-mix shotcrete process, incorporating silica fume in the mix resulted in significant increases in achievable thickness of build-up compared to plain portland cement shotcrete. The greatest thickness of build-up on overhead surfaces was achieved with the compacted low density silica fume mixture (CLDSF). Rebound was low in all the wet-mix shotcretes studied, with little difference in rebound between the various mixtures evaluated.

3. With respect to the dry-mix shotcrete process, incorporating silica fume in the mix resulted in substantial increases in achievable thickness of build-up compared to the plain portland cement shotcrete. The greatest thickness of build-up on overhead surfaces was achieved with the uncompacted silica fume (USF).

4. Approximately 50 percent reduction in rebound in dry-mix shotcretes applied to vertical and overhead surfaces was achieved by incorporating silica fume in the mixture; all three forms of silica fume evaluated were effective in reducing rebound. This has significant cost implications for the shotcrete process as significant savings can be achieved by reducing materials costs and enhancing productivity.

5. Substituting silica fume for portland cement resulted in modest increases in compressive and flexural strength in dry-mix shotcrete and substantial increases in compressive and flexural strength in wet-mix shotcrete. Differences in strength attributable to the various forms of silica fume studied generally were small.

6. Significant reductions in the values of boiled absorption and volume of permeable voids were evident in the silica fume mixes compared to plain portland cement for the dry-mix shotcretes, but not for the wet-mix shotcretes. However, the measurement data for these parameters would place all shotcrete in a "good" to "excellent" category.

7. Incorporating silica fume in both dry- and wet-mix shotcretes resulted in order-of-magnitude, or greater, reductions in the coulomb value in the rapid chloride permeability test. The chloride permeability of the wet- and dry-mix portland cement shotcretes was rated as "high" and "moderate," respectively. By contrast, all the silica fume shotcretes were rated as having "very low" chloride permeability. Chloride permeability was lowest in the dry-mix shotcretes; the effect of silica fume form generally was small.

8. Drying shrinkage typically was greater in the wet-mix shotcretes compared to the dry-mix shotcretes; this is not unexpected, given the higher water demand of the wet-mix shotcretes. Water demand of the wet-mix silica fume shotcretes was controlled by the addition of superplasticizer. As a result, all the silica fume shotcretes had similar or slightly lower drying shrinkage compared to the control shotcrete. In general, there was little difference in water demand and, hence, in drying shrinkage between all the dry-mix shotcretes evaluated.

In summary, this study has demonstrated that all three forms of silica fume studied (uncompacted, compacted low density and compacted high density) can be used beneficially in both dry- and wet-mix shotcretes. However, the performance data given is specific to the particular combinations of materials used in the study. Project-specific tests should be conducted for any use of silica fume in shotcrete to assess the performance characteristics of the particular proposed materials and application procedures.

Acknowledgments

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John Wolsiefer, Sr., is President of Norchem Concrete Products, a silica fume manufacturer. He has 23 years' experience, including past CEO positions in consulting, ready mix and concrete construction. He has a BS in applied physics and an MS in management engineering. He is a member of ACI and serves on ACI Committees 234, Silica Fume in Concrete; and 363, High Strength Concrete; and is the Chair of the ASTM Silica Fume Specification Committee. He has given numerous presentations, authored papers on silica fume, and received the Asbjorn Markstad Award for significant contributions to the development of silica fume concrete technology. In 1975, as technical consultant to the Norwegian Cement Industry, Wolsiefer initiated the first United States evaluation program to determine the positive properties of silica fume concrete and the appropriate market applications. In 1976, he conducted the first commercial placements of silica fume concrete for bulk chemical storage warehouses in the United States and Canada. In 1978, he developed silica fume concrete mixes for field placements of up to 18,000 psi concrete. By 1981, high strength and decreased permeability were becoming familiar to knowledgeable researchers, but the first silica fume concrete studies to prevent rebar corrosion were initiated and developed by him and corrosion specialist Kenneth C. Clear. From this work, the evolution of silica fume to enhance concrete durability through the use of high-performance concrete has become the largest single material application.

Dudley R. (Rusty) Morgan is Chief Materials Engineer with AMEC Earth & Environmental Ltd. He is a civil engineer with over 35 years' experience in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. Morgan is a Fellow of the Canadian Academy of Engineering and the American Concrete Institute (ACI), and he is Secretary of ACI Committee 506, Shotcreting. He is a member of several ACI, ASTM, and Canadian Standards Association (CSA) technical committees, and he is a founding member of the American Shotcrete Association. Morgan has provided consulting services on concrete and shotcrete projects throughout North America and around the world.