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Deicer Salt Scaling Resistance of Dry- and Wet-Process Shotcrete

by Denis Beaupré, Caroline Talbot, Martin Gendreau, Michel Pigeon, and Dudley R. Morgan

ASTM C 672 deicer salt scaling tests were carried out on both dry- and wet-mix shotcretes. Twenty-five dry-mix shotcretes and eleven wet-mix shotcretes were used to fabricate different test panels. The mix variables included cement type (Types 10 and 30), silica fume, latex (dry-mix process only), polypropylene and steel fibers, set-accelerating and air-entraining admixtures. All test panels were wet-cured for 7 days except two additional panels, one of which was not cured and the other of which was cured with a curing compound. Water containing 2.5 or 3 percent NaCl solutions was used for the scaling tests. The scaling residues were collected and weighed to evaluate deterioration. The mass of scaling residues was found to vary between 0. l and 24.0 kg/m^2*. These tests indicate that the scaling resistance of both dry- and wet-mix shotcrete improves with an increase in the air content, and that the use of silica fume generally reduces the mass of scaling residues. These tests also indicate that the use of a set-accelerating admixture can significantly reduce the scaling resistance of shotcrete. The use of Type 30 cement and of an air-entraining admixture was found to markedly improve the scaling resistance of dry-mix shotcretes.*

Keywords: absorption; air entrainment; compression tests; curing; **deicers**; **dry process**; freeze-thaw durability; **scaling**; **shotcrete**; **wet process**.

Deterioration from deicer salt scaling observed on concrete structures is often mainly superficial, so repairs are predominantly made with thin layers of concrete. Pneumatic techniques for application of mortar or concrete (wet- or dry-mix shotcrete processes) can frequently be the best methods for this repair, as, in most cases, they both reduce operating costs and eliminate the inconveniences of traditional methods. The use of shotcrete in this type of repair has been limited in Quebec, but is used in Western Canada and the United States.

There are two ways to apply shotcrete: dry- and wet-mix processes. For dry-mix shotcrete, all the constituent ingredients, except water and liquid admixtures, are mixed together. A small amount of water is often added to the mix, prior to discharge into the shotcrete gun, to moisten it, thus reducing dust during application. After water is added, the dry-mix is conveyed with air pressure through hoses until it reaches the nozzle, where the remainder of the liquid component is added. The quantity of liquid incorporated at this point is controlled by the nozzleman, who continually adjusts the flow to maintain good cohesion, so that the mix will bond to the surface being repaired. Since the in-place water-cement ratio depends almost exclusively on the nozzleman, his experience greatly influences the properties of the final product.

In wet-mix shotcrete, the constituent ingredients are mixed together, including water and admixtures. In general, mixing is accomplished using traditional methods. The shotcrete is pumped to the nozzle, where air pressure is added to pneumatically project the shotcrete onto the receiving surface. Since the shotcrete is premixed, the nozzelman's experience is not as critical as in dry-mix shotcrete, as he has no influence on the water addition to the mix.

Both processes have their advantages and disadvantages. The choice of which system to use is a project-specific decision. In Quebec, the dry process is most often used. This article presents the results of a series of tests on the durability (in particular, deicer salt scaling resistance) of mixes applied by both processes. Very few test results on this subject have been published up to now.

RESEARCH SIGNIFICANCE

Deterioration caused by scaling of concrete surfaces is one of the most important causes of damage to concrete infrastructures in North America, and hence an understanding of the factors influencing the durability of shotcrete used for repair of such structures is important.

REVIEW OF LITERATURE ON RESISTANCE OF SHOTCRETE TO FREEZING AND THAWING

Many authors have concluded that the presence of entrained air and use of a low water-cement ratio are two essential conditions for resistance of shotcrete to rapid freeze-thaw cycles.[1-5] Both Scanlon[3] and Reading[4] mention that

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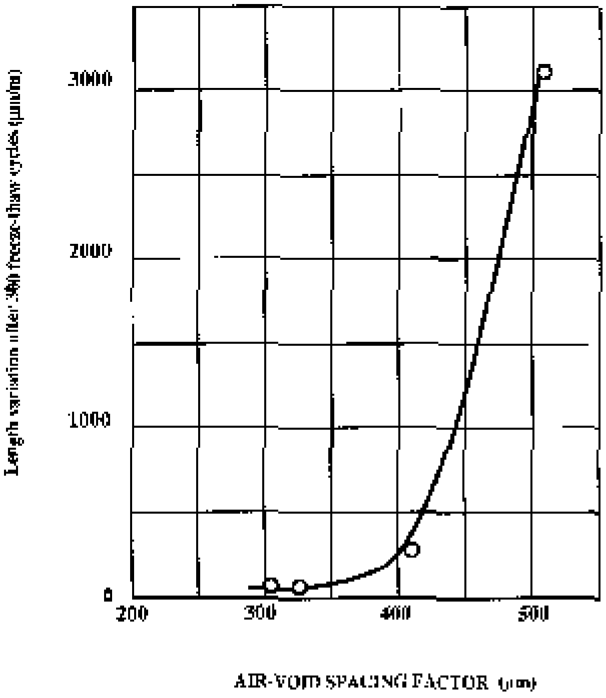


Fig. 1—Length variation after 300 freeze-thaw cycles as function of air-void spacing factor (wet-mix, w/c *= 0.45) (after Gendreau[8])*

high compressive strength (and hence a low water-cement ratio) and a low air-void spacing factor increase the resistance of shotcrete to freeze-thaw cycles (ASTM C 666). Reading found that, contrary to general opinion (no time for the admixture to react), the use of an air-entraining admixture could improve the durability of dry-mix shotcrete. Data by Schrader and Kaden[6] indicate that the durability of shotcrete depends on the presence of entrained air and adequacy of curing, as is the case for conventional concrete. Morgan[5,7] generally found the same results.

It has been shown[8] that the critical spacing factor concept, described by Pigeon[9] for ordinary concrete, also applies to wet-mix shotcrete. Fig. 1 shows that the critical value of the air-void spacing factor for wet-mix shotcrete with a water-cement ratio of 0.45 is about 400 μm, which is nearly the same value found for concrete placed by traditional methods.

The resistance to freeze-thaw cycles of dry-mix shotcrete seems to also depend on the same factors, but no major study has been performed to precisely determine the critical air-void spacing factor. Recent unpublished research suggests that, because of the high turbulence at the nozzle and high level of fine particles found in the dry-mix process, an efficient network of air voids might be created, therefore maintaining the system below the critical spacing factor. The addition of an air-entraining admixture can only reduce the spacing factor or create micro-air voids that will help in severe conditions, such as deicer salt scaling.

Besides qualitative results obtained by Vézina[10] on two samples of wet-mix shotcrete, there are no quantitative results for the scaling resistance of shotcrete reported in the literature. This study was undertaken to fill this void.

STUDY SCHEDULE

This 2-year study included three series of tests. Series A tests concerned mixtures evaluated in the first year. Series B tests were conducted in the second year. Series C tests consisted of testing shotcrete applied at a construction site in Montreal. The composition of all mixes applied during the 2 years are shown in Tables 1 and 2, for dry-mix and wet-mix shotcretes, respectively.

A range of different tests [including deicer salt scaling (ASTM C 672) and measurement of the characteristics of the air-void system (ASTM C 457)] were conducted on samples of each mix. Detailed results of these tests are available in a document submitted to the Department of Transportation of Quebec.[11]

MIX DESCRIPTION

A code with letters and numbers was used to identify all mixes. Each code begins with two letters: the first indicates the series (A, B, C), i.e., a first-year, second-year, or field mix, respectively. The second letter indicates the shotcrete process used: D for dry-mix shotcrete and W for wet-mix shotcrete. This is followed by a number indicating the type of cement: 1 for Type 10, 3 for Type 30, or "sfc" for silica fume cement. The type of cement (1 or 3) may be followed by S or S5, meaning that a part of the cement has been replaced by a certain percentage of silica fume by mass of cement. S represents a value of 10 percent silica fume, and S5 represents a 5 percent silica fume mixture. The letters "acc" indicate the use of a set-accelerating admixture added as a powder during the projection and "latex" indicates the use of latex during shotcrete application. An "A" may be followed by 20, 30, or 40, meaning that an air-entraining admixture was used at a concentration of 20, 30, or 40 ml per liter of water. Finally, a code ending with "pf" or "sf" indicates the use of polypropylene or steel fibers, respectively. The letters "a," "b," "c," or "d" are used to distinguish, within a group of concretes of the same general composition, different

Table 1—Dry-mix shotcrete proportions by mass (as-batched)

Mix	Binder, percent	Silica fume, percent binder	Sand, percent	Aggregates, percent	Description
AD1	24.8		55.0	20.2	Cement type 10 (1)
AD3	25.0		55.0	20.0	Cement type 30 (3)
AD1acc	21.5		58.6	19.9	Type 10, set-accelerating = 2.2 percent of binder (acc)
AD1latex	24.8		55.0	20.2	Type 10 solid latex = 12 percent of binder (latex)
AD1-pf	24.3		54.7	21.0	Type 10, polypropylene fibers = 1 kg/m^3 (pf)
AD1S5	25.1	5.0	57.1	17.8	Type 10, 5 percent silica fume (S5)
AD1S	24.3	10.0	54.6	21.1	Type 10, 10 percent silica fume (S)
BD1	27.5		47.5	24.9	Type 10
BD1A20	27.5		47.6	24.9	Type 10, AEA = 20 ml/l water (A20)
BD1A40	27.5		47.6	24.9	Type 10, AEA = 40 ml/l (A40)
BD1S	27.5	9.7	51.4	21.1	Type 10, silica fume
BD1SA30	27.5	9.7	51.4	21.1	Type 10, silica fume, AEA = 30 ml/l (A30)
BD1-sf	25.2		48.0	26.8	Type 10, steel fibers = 48 kg/m^3 (sf)
BD1A30-sf	25.2		48.0	26.8	Type 10, steel fibers = 48 kg/m^3 AEA 30 ml/l
BD1S-sf	28.5	9.5	46.0	25.5	Type 10, silica fume, steel fibers = 48 kg/m^3
BD1SA40-sf	28.5	9.5	46.0	25.5	Type 10, silica, steel fibers = 48 kg/m^3 AEA = 40 ml/l
BD3	25.6		49.7	24.7	Type 30
BD3A30	25.6		49.7	24.7	Type 30, AEA = 30 ml/l
BD3S	31.0	9.5	44.0	25.0	Type 30, silica fume
BD3SA30	31.0	9.5	44.0	25.0	Type 30, silica fume, AEA = 30 ml/l
BD1 latex	27.5		47.6	24.9	Type 10, solid latex = 12 percent of binder
BD3S latex	31.0	9.5	44.0	25.0	Type 30, silica fume, solid latex = 12 percent of binder
CDsfc	26.3	8.0	73.7	0.0	Silica fume cement
CD3	21.5		68.0	10.5	Type 30
CD3A30	21.5		68.0	10.5	Type 30, AEA = 30 ml/l

Table 2—Wet-mix shotcrete proportions by mass

Mix	Cement,[*] kg/m^3	Silica fume, kg/m^3	Water, kg/m^3	Sand, kg/m^3	Coarse aggregate, kg/m^3	W.R.A.,[‡] ml/kg	A.E.A.,[§] ml/kg	Description
AW1a@[†]	429	0	171	1188	445	2.7	0.93	
AW1b@	438	0	181	1153	463	2.7	0.46	
AW1c@	431	0	162	1144	469	3.2	0	
AW1d@	435	0	162	1153	445	0.0	0	
AW1-pf	429	0	157	4466	449	2.7	0.58	Polypropylene fibers = 1.8 kg
AW1S5@	411	22	158	1153	503	2.4	0.46	5 percent silica fume
AW1S@	388	43	163	1153	454	2.5	0.58	10 percent silica fume
BW1	430	0	200	1122	472	1.4	0.35	
BW1S	387	45	195	1105	435	0.4	0.35	10 percent silica fume
BW1-sf	428	0	199	1109	426	1.4	0.35	Steel fibers = 30 kg/m^3
BW1S-sf	385	45	194	1128	436	0.0	0.35	10 percent silica fume, steel fibers

[*] Cement Type 10.
[†] @ = Liquid set-accelerating admixture used.
[‡] W.R.A. = Water-reducing admixture.
[§] A.E.A = Air-entraining admixture.

quantities of entrained air measured in the fresh concrete. The sign "@" is used for a liquid set-accelerating admixture. A legend to these codes may be found in Fig. 2.

MATERIALS

The composition and properties of the cements and silica fume used are summarized in Table 3. The coarse aggregate used in the dry-mix shotcretes was a 10-mm nominal-size crushed hard dolomite, and that for the wet-mix shotcrete was a 10-mm nominal-size crushed granitic gneiss.

SERIES A TESTS

The dry-mix shotcrete process was used in seven mixes (Table 1). A ratio of sand:cement:aggregate of about 2:1:1

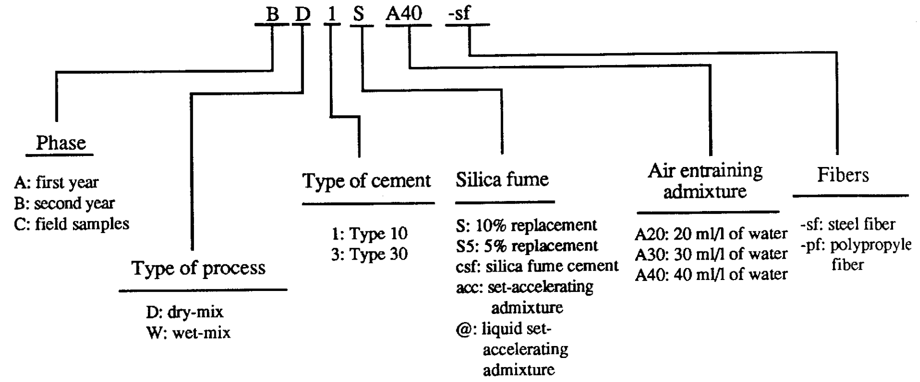


Fig. 2—Identification code

Table 3—Properties of cements

	Type I (wet-mix), percent	Type I (dry-mix), percent	Type III (dry-mix), percent		Silica fume, percent	
			Series A	Series B	Series A	Series B
SiO_2	21.0	20.5	20.3	21.36	91.8	95.2
$Al2O_3$	4.2	4.5	4.7	4.63	0.2	0.02
$Fe2O_3$	3.1	2.9	2.2	1.92	0.4	0.94
CaO	62.2	62.3	62.2	62.42	4.1	0.17
MgO	2.2	2.1	2.5	3.13	0.5	0.23
SO_3	3.3	3.0	4.3	3.77	0.1	0.19
Na_2O(eq.)	0.84	0.82	0.71	0.82	0.0	0.14
Fineness, m^2/kg	363	356	549	465	N/A	N/A

Table 4—Tests on fresh shotcrete, dry-mix

Mix series	Mix designation*	Water-binder ratio	Air content, percent
AD	AD1	0.43	—
	AD3	0.43	—
	AD1S5	0.47	—
	AD1S	0.49	—
BD	BD1A40	—	9.5
	BD1S	—	3.0
	BD1SA30	—	6.0
	BD1-sf	—	3.0
	BD1S-sf	—	2.5
	BD1SA40-sf	—	11.0
	BD3	—	3.2
	BD3A30	—	4.2
	BD3S	—	3.8
	BD3SA30	—	5.4
	BD1 latex	—	5.5
	BD3S latex	—	5.0
CD	CD3	—	3.4
	CD3A30	—	5.5

* For Mixes BD1, BD1A20, and BD1A30-sf, air content missing due to field problems.

Table 5—Tests on fresh shotcrete, wet-mix

Mix designation	Air content, percent		Slump, mm	
	Before shooting	After shooting	Before shooting	After shooting
AW1a@*	8.8	4.4	95	50
AW1b@	7.0	4.1	70	40
AW1c@	4.4	3.3	120	40
AW1d@	4.3	3.2	30	35
AW1-pf	6.2	4.2	50	25
AW1S5@	6.8	4.0	30	25
AW1S@	7.4	4.3	30	20
BW1	9.0	—	130	—
BW1S	9.5	—	80	—
BW1-sf	11.5	—	210	—
BW1S-sf	8.5	—	55	—

* @ = Liquid set-accelerating admixture used.

for all mixes was used. The effect of five variables in this series was studied: type of cement (Type 10, an ordinary cement, and Type 30, one with a high early strength); silica fume in different percentages (0, 5, and 10 percent by mass of cement substitution); incorporation of polypropylene fibers (1.8 kg/m^3); use of a powdered set-accelerating admixture (2.2 percent of cement weight); and, finally, addition of latex to the mix. All mixes were dry-mixed and bagged in a factory (AD in Table 1).

The wet process was used in seven other mixes (Table 2). Four of these mixes had the same composition except for the quantity of entrained air. Besides entrained air, the use of silica fume substituted in quantities of 0, 5, and 10 percent by mass of cement, addition of polypropylene fibers (1.8 kg/m^3), and use of a liquid set-accelerating admixture was studied. These mixes are identified as AW in Table 2.

SERIES B TESTS

The choice of mixes was influenced by the results of Series A tests, with the recommendations of representatives of the central laboratory of the Department of Transportation of Quebec taken into account. Nineteen mixtures were projected. Fifteen were applied by the dry-mix shotcrete process, since this technique is most often used by the Department of Transportation to repair structures in Quebec. A particular example is the repair recently conducted on the 8-km long Metropolitan Boulevard elevated freeway structure in Montreal.

For dry-mix shotcrete (BD in Table 1), we wanted to know if the use of a high level of air-entraining admixture would be efficient in producing a good network of air voids to improve scaling resistance. Type of cement, use of 10 percent of silica fume by mass of cement, and addition of steel fibers or latex were also studied.

For the last four mixes, wet-mix shotcrete was used (BW in Table 2). The use of 10 percent of silica fume by mass of cement and addition of steel fibers (30 kg/m^3) was also studied.

Table 6—Tests on hardened concrete, dry-mix

Mix	ASTM C 39, compressive strength, MPa	ASTM C 457			ASTM C 642		ASTM C 672	
		Air content, percent	Specific surface, 1/mm	Spacing factor, µm	Absorption after immersion, percent	Permeable voids, percent	Visual rating	Scaling residues, kg/m^2
AD1	43.7	3.6	21.8	341	7.7	16.7	5	13.9
AD3	58.7	5.5	19.9	303	6.9	14.4	4	7.6
AD1 acc	21.6	8.2	20.1	256	9.9	20.7	5	22.6
AD1 latex	40.9	13.4	40.0	60	5.7	14.5	2.5	1.8
AD1-pf	45.5	3.5	21.5	354	8.3	17.6	5	16.7
AD1S5	49.4	4.7	21.2	316	8.5	17.6	4	3.8
AD1S	59.4	4.5	19.3	361	7.5	15.7	3	4.2
BD1	—	6.3	11.0	505	7.3	16.6	4	3.4
BD1A20	—	5.4	18.0	322	7.6	17.6	2	1.1
BD1A40	31.3	7.4	23.7	206	7.8	18.0	5	8.3
BD1S	—	3.5	23.5	302	7.2	17.1	3	3.4
BD1SA30	31.9	5.9	16.8	361	5.3	16.7	3	3.1
BD1-sf	—	6.1	11.5	502	7.6	17.6	5	4.0
BD1A30-sf	38.7	7.2	16.4	291	7.9	19.7	4	3.0
BD1S-sf	—	5.4	14.2	412	6.1	14.8	5	4.0
BD1SA40-sf	51.5	4.9	24.5	270	7.1	19.2	3	2.5
BD3	—	3.9	18.6	377	6.5	15.0	2	1.4
BD3A30	53.9	4.6	20.6	310	6.7	15.3	1	0.4
BD3S	—	5.2	17.4	355	5.4	12.9	3	2.4
BDSA30	45	6.5	18.8	292	6.3	14.5	3	1.4
BD1 latex	—	4.8	19.9	296	4.7	17.4	3	1.9
BD3S latex	61.6	7.0	19.3	284	2.9	7.7	3	1.0
CDsfc	52.0	3.0	11.8	560	5.7	13.8	3	3.6
CD3	45.2	5.5	13.7	409	6.2	14.3	2.5	4.1
CD3A30	43.5	7.1	18.7	271	6.7	15.4	0	0.1

Table 7—Tests on hardened shotcrete, wet-mix

Mix	ASTM C 39, compressive strength, MPa	ASTM C 457			ASTM C 642		ASTM C 672	
		Air content, percent	Specific surface, 1/mm	Spacing factor, µm	Apsorption after immersion, percent	Permeable voids, percent	Visual rating	Scaling residues, kg/m^2
AW1a@[*]	29.7	4.9	18.6	306	7.3	15.7	4	2.4
AW1b@	32.5	4.6	18.1	322	7.5	16.1	5	8.6
AW1c@	33.6	5.8	12.6	412	7.9	17.3	5	8.5
AW1d@	32.4	4.0	12.2	501	8.4	18.9	5	14.0
AW1-pf	47.4	5.1	15.6	312	6.9	15.0	3	1.8
AW1S5@	38.4	5.2	17.3	323	7.1	16.2	4	3.4
AW1S5@-M[†]	—	5.2	17.3	323	—	—	3	2.2
AW1S5@-sm[‡]	26.4	5.2	17.3	323	8.4	18.4	4	3.4
AW1S@	45.2	5.6	21.6	248	6.0	12.9	3.5	4.2
BW1	32.3	3.7	16.7	387	8.0	17.9	5	24.0
BW1S	36.4	3.5	15.8	417	7.4	16.7	4	4.7
BW1-sf	31.1	2.5	15.5	481	7.6	17.8	5	9.4
BW1S-sf	41.9	4.6	19.5	304	8.1	17.0	2	0.8

[*] @ = Liquid set-accelerating admixture used.

[†] Curing compound.

[‡] Without curing.

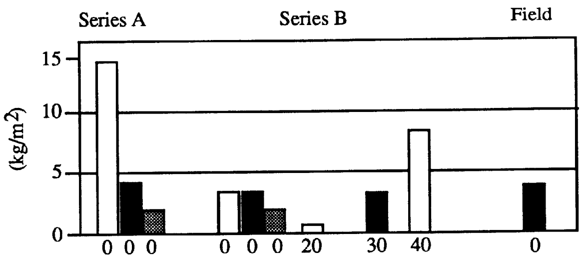
SERIES C TESTS

The shotcrete evaluated in this part of the study came from two construction projects in Montreal, where repairs were carried out for the Department of Transportation of Quebec (the first in 1989 and the second in 1990). The mix from the first site, CDsfc in Table 1, contained 2.8 parts of sand for 1 part of cement by mass, with 7 to 8 percent of silica fume by mass of cement.

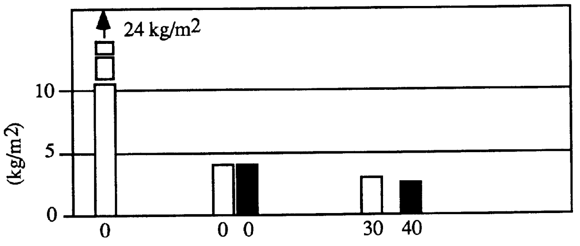
In the second field study, a shotcrete with mass proportions of 21.5 percent of Type 30 cement, 68 percent sand, and 10.5 percent aggregate (10 mm) was used. The shotcrete without the addition of air-entraining admixture is identified as CD3, and the mix with 30 ml/l of air-entraining admixture is CD3A30 in Table 1.

APPLICATION AND CURING

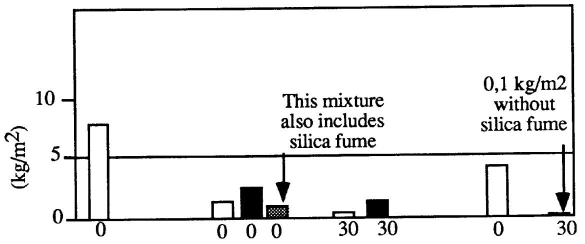
All the mixes were tested. Descriptions of each test conducted may be found in the next section. When the dry-mix shotcretes of the first series (AD) were applied, in some cases the quantity of water added in the premoisturizer and at the nozzle was measured and used to estimate the water-binder ratio of the in-place shotcrete. These ratios are pre-



a) Cement type 10 without fibers



b) Cement type 10 with fibers



c) Cement type 30 without fibers

LEGEND

☐ Without silica fume ■ With silica fume

▨ With latex 30 air entraining admixture (ml/l water)

Fig. 3—Scaling residues after 50 cycles (dry-mix)

sented in Table 4. Note that this is only an estimation of the water-binder ratios, because not all the water added reaches the applied surface. However, variations in the water-binder ratio from one mix to another can be observed.

For Series B and C dry-mix shotcretes, the air-entraining admixture was first added to the water before pneumatic application. Table 4 gives the air content in the shotcrete when directly shot into an air meter base. A mobile unit truck was used for batching shotcrete for Series C shotcretes. When no air-entraining admixture was added, an air content of about 3 percent was obtained; an air content of about 5 percent was achieved with 30 ml of air-entraining admixture per liter of water, and about 10 percent air content with 40 ml of air-entraining admixture per litre of water.

For wet-mix shotcrete, both air content and slump were measured. Table 5 gives all results for the shotcrete before and after its application. All panels, except two from Mix AD 1S5, were cured with water, using burlap kept moist for 7 days. One of the two AD 1S5 panels was cured with a curing compound, and the other was not cured. The noncured shotcrete cracked after only a few hours in the sun.

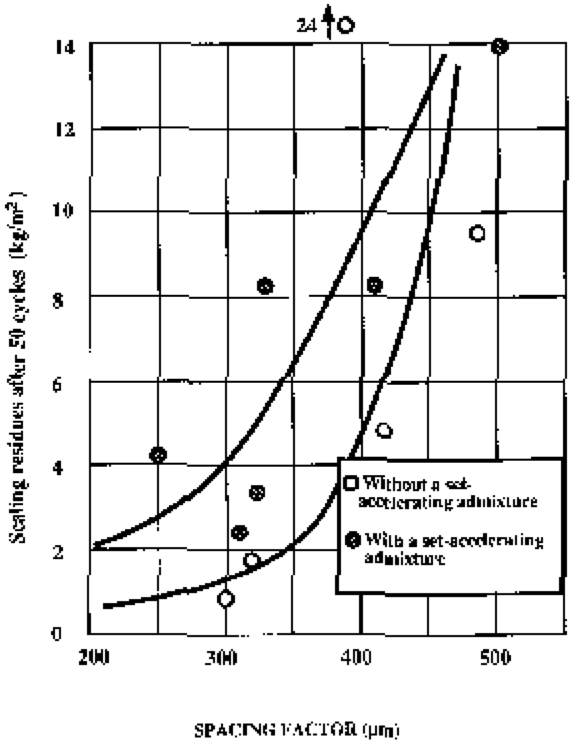


Fig. 4—Scaling residues after 50 cycles as function of spacing factor (wet-mix)

TEST RESULTS

Compression tests

Core samples 75 mm in diameter and 150 mm long (or 100 by 200 mm) were tested in compression according to ASTM C 39. All samples were cured for 7 days, then dried for a minimum of 28 days before being tested, except Series CDs-fc samples, which were cured for 28 days before testing. Tables 6 and 7 show results for the dry- and wet-mix shotcretes, respectively.

Compressive strengths obtained with conventional dry-mix shotcretes are usually superior to those obtained with wet-mix shotcretes. As for ordinary concretes, addition of silica fume or use of a Type 30 cement increases compressive strength. On the other hand, the addition of air-entraining or set-accelerating admixtures reduces compressive strength.

Determination of air-void characteristics

Air-void characteristics for all mixes were measured on two polished samples 100 by 100 mm, according to ASTM C 457. Tables 6 and 7 summarize results for dry- and wet-mix shotcrete processes. Air content, specific surface, and spacing factor of air voids $(\bar{L})$ can be found in these tables. Note that an acceptable spacing factor for certain mixtures (BD1A40 with 206 µm) was obtained with the addition of a high quantity of air-entraining admixture (40 ml/l of water) in the dry-mix shotcrete process. The addition of latex seems to insure a good spacing factor as well, with a value of 300 µm recorded.

Absorption tests

These tests were carried out according to ASTM C 642. Tables 6 and 7 give results after immersion and volume of permeable voids for each mix. Values for absorption and permeable voids are, in general, inferior for the mix with latex or Type 30 cement, as well as mixes with silica fume, though to a lesser degree. Comparing the same mix with and without entrained air, it can be seen that, generally, increases in air content increase the measured absorption and volume of permeable voids.

Scaling tests with deicing salts

These tests conformed to ASTM C 672, except that a 2.5 percent NaCl solution was used in the first year and a 3 percent solution in the second year instead of a solution of 4 percent $CaCl_2$, since the Department of Transportation in Quebec uses NaCl as a deicer. The concentration of 2.5 or 3.0 percent was chosen because, according to Verbeck and Klieger,[12] it is approximately the most damaging.

Every five cycles, surfaces were rated and all the residues that fell from the surfaces were collected. The visual rating and mass of scaling residues (in kg/m^2) after 50 freeze-thaw cycles are shown in Table 6 (dry-mix) and in Table 7 (wet-mix). A concrete is considered durable if the total mass of scaling residues is below 1 kg/m^2 after 50 freeze-thaw cycles (Reference 9 and Swedish standard).

For all mixes, the mass of residues vary between 0. 1 and 24 kg/m^2. Even if there is a broad range (not uncommon with this test), these results show that scaling resistance is greatly influenced by the mix composition, particularly by the binder type and air-void spacing factor. The two best mixes, BD3A30 and CD3A30, were both dry-mix shotcretes made with Type 30 cement and an air-entraining admixture. Fig. 3 shows that use of a Type 30 cement and air-entraining admixture is very useful with dry-mix shotcrete. Despite the variability in results, it is clear that use of a Type 30 cement and air-entraining admixture can efficiently improve scaling resistance.

Use of set-accelerating admixtures is not uncommon in shotcrete. The mix made with a shotcrete accelerator displayed the worst performance in the scaling test and also had the lowest compressive strength. The strength-reducing influence of the accelerator is consistent with data reported in the literature.[13]

Use of a set-accelerating admixture for wet-mix shotcrete again had a negative effect. Fig. 4 shows scaling residues as a function of the air-void spacing factor for all mixes made both with and without a set-accelerating admixture. This figure shows the importance of the spacing factor and negative effect of the admixture. Results shown in Fig. 4 indicate clearly that scaling residues diminish with a reduction in the spacing factor, and, as with ordinary concrete, a spacing factor of about 200 to 250 μm yields good resistance to scaling (residues < 1 kg/m^2). Incorporation of silica fume in dry-mix shotcrete had little effect on the results, at least for mixes of Series B. Silica fume seems to improve a concrete of marginal quality but has almost no effect on a good concrete.

CONCLUSIONS

As can be seen from this study, it is possible to obtain good resistance to deicer salt scaling with dry-mix shotcrete when an air-entraining admixture is added to the mix water injected at the nozzle. The spacing factor obtained without an air-entraining admixture, although adequate for resistance to freezing and thawing, does not insure resistance to deicer salt scaling. In the ASTM C 672 test, shotcrete was not found to perform very differently from ordinary concrete. Shotcrete does, however, differ from ordinary concrete in one way (which for the moment cannot be explained); when a Type 30 cement, which is finer and reacts more rapidly, is used in dry-mix shotcrete, a better resistance to scaling is obtained. Also, even with a good spacing factor, good performance in the scaling test is not always found. As observed in the case of BD1A40, with a spacing factor of 206 μm, 8.3 kg/m^2 of residues were collected in the scaling test.

For wet-mix shotcrete, the spacing factor is very important in obtaining good resistance to scaling, even with a normal cement (Type 10).

Use of a set-accelerating admixture in both wet-and dry-mix shotcrete processes increased scaling residues. The effect of silica fume is not as well established. In tests from the first year, addition of silica fume seemed to improve scaling resistance of the mixes, but in tests from the second year, no significant improvement was found, at least for dry-mix mixes. For some of the second year dry-mix mixes, in fact, scaling residues increased with silica fume addition. Some improvements were found for the wet-mix mixes of the second year. In general, however, silica fume seems to improve a shotcrete of marginal quality but appears to have little effect on a good-quality shotcrete. Further studies on silica fume and effects of different cement types, admixtures, and set-accelerating admixtures are recommended to better understand the influences of such variables on shotcrete durability.

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CONVERSION FACTORS

1 MPa = 145 psi
1 mm = 0.0394 in.
1 m = 3.2808 ft
1 mm^{-1} = 25.4 $in.^{-1}$
1 kg = 2.204 lb
1 kg/m^2 = 0.2048 lb/ft^2
1 kg/m^3 = 1.6856 lb/yd^3
1 m^2/kg = 4.8828 ft^2/lb

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ACI MATERIALS JOURNAL TECHNICAL PAPER

Title no. 91-M49

Deicer Salt Scaling Resistance of Dry- and Wet-Process Shotcrete

by Denis Beaupré, Caroline Talbot, Martin Gendreau, Michel Pigeon, and Dudley R. Morgan

ASTM C 672 deicer salt scaling tests were carried out on both dry- and wet-mix shotcretes. Twenty-five dry-mix shotcretes and eleven wet-mix shotcretes were used to fabricate different test panels. The mix variables included cement type (Types 10 and 30), silica fume, latex (dry-mix process only), polypropylene and steel fibers, set-accelerating and air-entraining admixtures. All test panels were wet-cured for 7 days except two additional panels, one of which was not cured and the other of which was cured with a curing compound. Water containing 2.5 or 3 percent NaCl solutions was used for the scaling tests. The scaling residues were collected and weighed to evaluate deterioration. The mass of scaling residues was found to vary between 0. l and 24.0 kg/m^2. These tests indicate that the scaling resistance of both dry- and wet-mix shotcrete improves with an increase in the air content, and that the use of silica fume generally reduces the mass of scaling residues. These tests also indicate that the use of a set-accelerating admixture can significantly reduce the scaling resistance of shotcrete. The use of Type 30 cement and of an air-entraining admixture was found to markedly improve the scaling resistance of dry-mix shotcretes.

Keywords: absorption; air entrainment; compression tests; curing; **deicers**; **dry process**; freeze-thaw durability; **scaling**; **shotcrete**; **wet process**.

Deterioration from deicer salt scaling observed on concrete structures is often mainly superficial, so repairs are predominantly made with thin layers of concrete. Pneumatic techniques for application of mortar or concrete (wet- or dry-mix shotcrete processes) can frequently be the best methods for this repair, as, in most cases, they both reduce operating costs and eliminate the inconveniences of traditional methods. The use of shotcrete in this type of repair has been limited in Quebec, but is used in Western Canada and the United States.

There are two ways to apply shotcrete: dry- and wet-mix processes. For dry-mix shotcrete, all the constituent ingredients, except water and liquid admixtures, are mixed together. A small amount of water is often added to the mix, prior to discharge into the shotcrete gun, to moisten it, thus reducing dust during application. After water is added, the dry-mix is conveyed with air pressure through hoses until it reaches the nozzle, where the remainder of the liquid component is added. The quantity of liquid incorporated at this point is controlled by the nozzleman, who continually adjusts the flow to maintain good cohesion, so that the mix will bond to the surface being repaired. Since the in-place water-cement ratio depends almost exclusively on the nozzleman, his experience greatly influences the properties of the final product.

In wet-mix shotcrete, the constituent ingredients are mixed together, including water and admixtures. In general, mixing is accomplished using traditional methods. The shotcrete is pumped to the nozzle, where air pressure is added to pneumatically project the shotcrete onto the receiving surface. Since the shotcrete is premixed, the nozzelman's experience is not as critical as in dry-mix shotcrete, as he has no influence on the water addition to the mix.

Both processes have their advantages and disadvantages. The choice of which system to use is a project-specific decision. In Quebec, the dry process is most often used. This article presents the results of a series of tests on the durability (in particular, deicer salt scaling resistance) of mixes applied by both processes. Very few test results on this subject have been published up to now.

RESEARCH SIGNIFICANCE

Deterioration caused by scaling of concrete surfaces is one of the most important causes of damage to concrete infrastructures in North America, and hence an understanding of the factors influencing the durability of shotcrete used for repair of such structures is important.

REVIEW OF LITERATURE ON RESISTANCE OF SHOTCRETE TO FREEZING AND THAWING

Many authors have concluded that the presence of entrained air and use of a low water-cement ratio are two essential conditions for resistance of shotcrete to rapid freeze-thaw cycles.[1-5] Both Scanlon[3] and Reading[4] mention that

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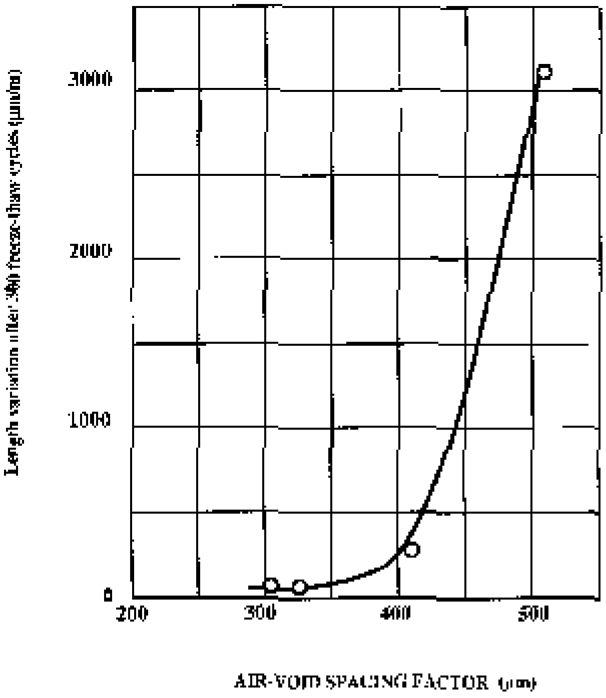


Fig. 1—Length variation after 300 freeze-thaw cycles as function of air-void spacing factor (wet-mix, w/c *= 0.45) (after Gendreau[8])*

high compressive strength (and hence a low water-cement ratio) and a low air-void spacing factor increase the resistance of shotcrete to freeze-thaw cycles (ASTM C 666). Reading found that, contrary to general opinion (no time for the admixture to react), the use of an air-entraining admixture could improve the durability of dry-mix shotcrete. Data by Schrader and Kaden[6] indicate that the durability of shotcrete depends on the presence of entrained air and adequacy of curing, as is the case for conventional concrete. Morgan[5,7] generally found the same results.

It has been shown[8] that the critical spacing factor concept, described by Pigeon[9] for ordinary concrete, also applies to wet-mix shotcrete. Fig. 1 shows that the critical value of the air-void spacing factor for wet-mix shotcrete with a water-cement ratio of 0.45 is about 400 µm, which is nearly the same value found for concrete placed by traditional methods.

The resistance to freeze-thaw cycles of dry-mix shotcrete seems to also depend on the same factors, but no major study has been performed to precisely determine the critical air-void spacing factor. Recent unpublished research suggests that, because of the high turbulence at the nozzle and high level of fine particles found in the dry-mix process, an efficient network of air voids might be created, therefore maintaining the system below the critical spacing factor. The addition of an air-entraining admixture can only reduce the spacing factor or create micro-air voids that will help in severe conditions, such as deicer salt scaling.

Besides qualitative results obtained by Vézina[10] on two samples of wet-mix shotcrete, there are no quantitative results for the scaling resistance of shotcrete reported in the literature. This study was undertaken to fill this void.

STUDY SCHEDULE

This 2-year study included three series of tests. Series A tests concerned mixtures evaluated in the first year. Series B tests were conducted in the second year. Series C tests consisted of testing shotcrete applied at a construction site in Montreal. The composition of all mixes applied during the 2 years are shown in Tables 1 and 2, for dry-mix and wet-mix shotcretes, respectively.

A range of different tests [including deicer salt scaling (ASTM C 672) and measurement of the characteristics of the air-void system (ASTM C 457)] were conducted on samples of each mix. Detailed results of these tests are available in a document submitted to the Department of Transportation of Quebec.[11]

MIX DESCRIPTION

A code with letters and numbers was used to identify all mixes. Each code begins with two letters: the first indicates the series (A, B, C), i.e., a first-year, second-year, or field mix, respectively. The second letter indicates the shotcrete process used: D for dry-mix shotcrete and W for wet-mix shotcrete. This is followed by a number indicating the type of cement: 1 for Type 10, 3 for Type 30, or “sfc” for silica fume cement. The type of cement (1 or 3) may be followed by S or S5, meaning that a part of the cement has been replaced by a certain percentage of silica fume by mass of cement. S represents a value of 10 percent silica fume, and S5 represents a 5 percent silica fume mixture. The letters “acc” indicate the use of a set-accelerating admixture added as a powder during the projection and “latex” indicates the use of latex during shotcrete application. An “A” may be followed by 20, 30, or 40, meaning that an air-entraining admixture was used at a concentration of 20, 30, or 40 ml per liter of water. Finally, a code ending with “pf” or “sf” indicates the use of polypropylene or steel fibers, respectively. The letters “a,” “b,” “c,” or “d” are used to distinguish, within a group of concretes of the same general composition, different

Table 1—Dry-mix shotcrete proportions by mass (as-batched)

Mix	Binder, percent	Silica fume, percent binder	Sand, percent	Aggregates, percent	Description
AD1	24.8		55.0	20.2	Cement type 10 (1)
AD3	25.0		55.0	20.0	Cement type 30 (3)
AD1acc	21.5		58.6	19.9	Type 10, set-accelerating = 2.2 percent of binder (acc)
AD1latex	24.8		55.0	20.2	Type 10 solid latex = 12 percent of binder (latex)
AD1-pf	24.3		54.7	21.0	Type 10, polypropylene fibers = 1 kg/m^3 (pf)
AD1S5	25.1	5.0	57.1	17.8	Type 10, 5 percent silica fume (S5)
AD1S	24.3	10.0	54.6	21.1	Type 10, 10 percent silica fume (S)
BD1	27.5		47.5	24.9	Type 10
BD1A20	27.5		47.6	24.9	Type 10, AEA = 20 ml/l water (A20)
BD1A40	27.5		47.6	24.9	Type 10, AEA = 40 ml/l (A40)
BD1S	27.5	9.7	51.4	21.1	Type 10, silica fume
BD1SA30	27.5	9.7	51.4	21.1	Type 10, silica fume, AEA = 30 ml/l (A30)
BD1-sf	25.2		48.0	26.8	Type 10, steel fibers = 48 kg/m^3 (sf)
BD1A30-sf	25.2		48.0	26.8	Type 10, steel fibers = 48 kg/m^3 AEA 30 ml/l
BD1S-sf	28.5	9.5	46.0	25.5	Type 10, silica fume, steel fibers = 48 kg/m^3
BD1SA40-sf	28.5	9.5	46.0	25.5	Type 10, silica, steel fibers = 48 kg/m^3 AEA = 40 ml/l
BD3	25.6		49.7	24.7	Type 30
BD3A30	25.6		49.7	24.7	Type 30, AEA = 30 ml/l
BD3S	31.0	9.5	44.0	25.0	Type 30, silica fume
BD3SA30	31.0	9.5	44.0	25.0	Type 30, silica fume, AEA = 30 ml/l
BD1 latex	27.5		47.6	24.9	Type 10, solid latex = 12 percent of binder
BD3S latex	31.0	9.5	44.0	25.0	Type 30, silica fume, solid latex = 12 percent of binder
CDsfc	26.3	8.0	73.7	0.0	Silica fume cement
CD3	21.5		68.0	10.5	Type 30
CD3A30	21.5		68.0	10.5	Type 30, AEA = 30 ml/l

Table 2—Wet-mix shotcrete proportions by mass

Mix	Cement,* kg/m^3	Silica fume, kg/m^3	Water, kg/m^3	Sand, kg/m^3	Coarse aggregate, kg/m^3	W.R.A.,‡ ml/kg	A.E.A.,§ ml/kg	Description
AW1a@†	429	0	171	1188	445	2.7	0.93	
AW1b@	438	0	181	1153	463	2.7	0.46	
AW1c@	431	0	162	1144	469	3.2	0	
AW1d@	435	0	162	1153	445	0.0	0	
AW1-pf	429	0	157	4466	449	2.7	0.58	Polypropylene fibers = 1.8 kg
AW1S5@	411	22	158	1153	503	2.4	0.46	5 percent silica fume
AW1S@	388	43	163	1153	454	2.5	0.58	10 percent silica fume
BW1	430	0	200	1122	472	1.4	0.35	
BW1S	387	45	195	1105	435	0.4	0.35	10 percent silica fume
BW1-sf	428	0	199	1109	426	1.4	0.35	Steel fibers = 30 kg/m^3
BW1S-sf	385	45	194	1128	436	0.0	0.35	10 percent silica fume, steel fibers

* Cement Type 10.

† @ = Liquid set-accelerating admixture used.

‡ W.R.A. = Water-reducing admixture.

§ A.E.A = Air-entraining admixture.

quantities of entrained air measured in the fresh concrete. The sign “@” is used for a liquid set-accelerating admixture. A legend to these codes may be found in Fig. 2.

MATERIALS

The composition and properties of the cements and silica fume used are summarized in Table 3. The coarse aggregate used in the dry-mix shotcretes was a 10-mm nominal-size crushed hard dolomite, and that for the wet-mix shotcrete was a 10-mm nominal-size crushed granitic gneiss.

SERIES A TESTS

The dry-mix shotcrete process was used in seven mixes (Table 1). A ratio of sand:cement:aggregate of about 2:1:1

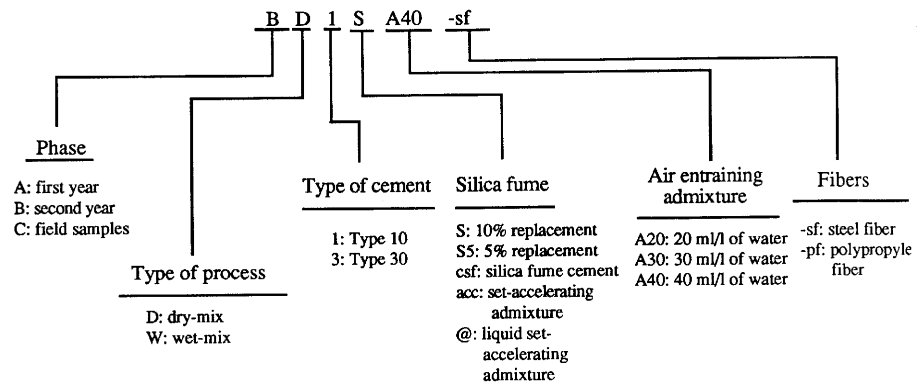


Fig. 2—Identification code

Table 3—Properties of cements

	Type I (wet-mix), percent	Type I (dry-mix), percent	Type III (dry-mix), percent		Silica fume, percent	
			Series A	Series B	Series A	Series B
SiO_2	21.0	20.5	20.3	21.36	91.8	95.2
Al2O$_3$	4.2	4.5	4.7	4.63	0.2	0.02
Fe2O$_3$	3.1	2.9	2.2	1.92	0.4	0.94
CaO	62.2	62.3	62.2	62.42	4.1	0.17
MgO	2.2	2.1	2.5	3.13	0.5	0.23
SO_3	3.3	3.0	4.3	3.77	0.1	0.19
Na_2O(eq.)	0.84	0.82	0.71	0.82	0.0	0.14
Fineness, m^2/kg	363	356	549	465	N/A	N/A

Table 4—Tests on fresh shotcrete, dry-mix

Mix series	Mix designation*	Water-binder ratio	Air content, percent
AD	AD1	0.43	—
	AD3	0.43	—
	AD1S5	0.47	—
	AD1S	0.49	—
BD	BD1A40	—	9.5
	BD1S	—	3.0
	BD1SA30	—	6.0
	BD1-sf	—	3.0
	BD1S-sf	—	2.5
	BD1SA40-sf	—	11.0
	BD3	—	3.2
	BD3A30	—	4.2
	BD3S	—	3.8
	BD3SA30	—	5.4
	BD1 latex	—	5.5
	BD3S latex	—	5.0
CD	CD3	—	3.4
	CD3A30	—	5.5

* For Mixes BD1, BD1A20, and BD1A30-sf, air content missing due to field problems.

for all mixes was used. The effect of five variables in this series was studied: type of cement (Type 10, an ordinary cement, and Type 30, one with a high early strength); silica fume in different percentages (0, 5, and 10 percent by mass of cement substitution); incorporation of polypropylene fibers (1.8 kg/m^3); use of a powdered set-accelerating admixture (2.2 percent of cement weight); and, finally, addition of latex to the mix. All mixes were dry-mixed and bagged in a factory (AD in Table 1).

Table 5—Tests on fresh shotcrete, wet-mix

Mix designation	Air content, percent		Slump, mm	
	Before shooting	After shooting	Before shooting	After shooting
AW1a@*	8.8	4.4	95	50
AW1b@	7.0	4.1	70	40
AW1c@	4.4	3.3	120	40
AW1d@	4.3	3.2	30	35
AW1-pf	6.2	4.2	50	25
AW1S5@	6.8	4.0	30	25
AW1S@	7.4	4.3	30	20
BW1	9.0	—	130	—
BW1S	9.5	—	80	—
BW1-sf	11.5	—	210	—
BW1S-sf	8.5	—	55	—

* @ = Liquid set-accelerating admixture used.

The wet process was used in seven other mixes (Table 2). Four of these mixes had the same composition except for the quantity of entrained air. Besides entrained air, the use of silica fume substituted in quantities of 0, 5, and 10 percent by mass of cement, addition of polypropylene fibers (1.8 kg/m^3), and use of a liquid set-accelerating admixture was studied. These mixes are identified as AW in Table 2.

SERIES B TESTS

The choice of mixes was influenced by the results of Series A tests, with the recommendations of representatives of the central laboratory of the Department of Transportation of Quebec taken into account. Nineteen mixtures were projected. Fifteen were applied by the dry-mix shotcrete process, since this technique is most often used by the Department of Transportation to repair structures in Quebec. A particular example is the repair recently conducted on the 8-km long Metropolitan Boulevard elevated freeway structure in Montreal.

For dry-mix shotcrete (BD in Table 1), we wanted to know if the use of a high level of air-entraining admixture would be efficient in producing a good network of air voids to improve scaling resistance. Type of cement, use of 10 percent of silica fume by mass of cement, and addition of steel fibers or latex were also studied.

For the last four mixes, wet-mix shotcrete was used (BW in Table 2). The use of 10 percent of silica fume by mass of cement and addition of steel fibers (30 kg/m^3) was also studied.

Table 6—Tests on hardened concrete, dry-mix

Mix	ASTM C 39, compressive strength, MPa	ASTM C 457			ASTM C 642		ASTM C 672	
		Air content, percent	Specific surface, 1/mm	Spacing factor, µm	Absorption after immersion, percent	Permeable voids, percent	Visual rating	Scaling residues, kg/m^2
AD1	43.7	3.6	21.8	341	7.7	16.7	5	13.9
AD3	58.7	5.5	19.9	303	6.9	14.4	4	7.6
AD1 acc	21.6	8.2	20.1	256	9.9	20.7	5	22.6
AD1 latex	40.9	13.4	40.0	60	5.7	14.5	2.5	1.8
AD1-pf	45.5	3.5	21.5	354	8.3	17.6	5	16.7
AD1S5	49.4	4.7	21.2	316	8.5	17.6	4	3.8
AD1S	59.4	4.5	19.3	361	7.5	15.7	3	4.2
BD1	—	6.3	11.0	505	7.3	16.6	4	3.4
BD1A20	—	5.4	18.0	322	7.6	17.6	2	1.1
BD1A40	31.3	7.4	23.7	206	7.8	18.0	5	8.3
BD1S	—	3.5	23.5	302	7.2	17.1	3	3.4
BD1SA30	31.9	5.9	16.8	361	5.3	16.7	3	3.1
BD1-sf	—	6.1	11.5	502	7.6	17.6	5	4.0
BD1A30-sf	38.7	7.2	16.4	291	7.9	19.7	4	3.0
BD1S-sf	—	5.4	14.2	412	6.1	14.8	5	4.0
BD1SA40-sf	51.5	4.9	24.5	270	7.1	19.2	3	2.5
BD3	—	3.9	18.6	377	6.5	15.0	2	1.4
BD3A30	53.9	4.6	20.6	310	6.7	15.3	1	0.4
BD3S	—	5.2	17.4	355	5.4	12.9	3	2.4
BDSA30	45	6.5	18.8	292	6.3	14.5	3	1.4
BD1 latex	—	4.8	19.9	296	4.7	17.4	3	1.9
BD3S latex	61.6	7.0	19.3	284	2.9	7.7	3	1.0
CDsfc	52.0	3.0	11.8	560	5.7	13.8	3	3.6
CD3	45.2	5.5	13.7	409	6.2	14.3	2.5	4.1
CD3A30	43.5	7.1	18.7	271	6.7	15.4	0	0.1

Table 7—Tests on hardened shotcrete, wet-mix

Mix	ASTM C 39, compressive strength, MPa	ASTM C 457			ASTM C 642		ASTM C 672	
		Air content, percent	Specific surface, 1/mm	Spacing factor, µm	Apsorption after immersion, percent	Permeable voids, percent	Visual rating	Scaling residues, kg/m^2
AW1a@*	29.7	4.9	18.6	306	7.3	15.7	4	2.4
AW1b@	32.5	4.6	18.1	322	7.5	16.1	5	8.6
AW1c@	33.6	5.8	12.6	412	7.9	17.3	5	8.5
AW1d@	32.4	4.0	12.2	501	8.4	18.9	5	14.0
AW1-pf	47.4	5.1	15.6	312	6.9	15.0	3	1.8
AW1S5@	38.4	5.2	17.3	323	7.1	16.2	4	3.4
AW1S5@-M†	—	5.2	17.3	323	—	—	3	2.2
AW1S5@-sm‡	26.4	5.2	17.3	323	8.4	18.4	4	3.4
AW1S@	45.2	5.6	21.6	248	6.0	12.9	3.5	4.2
BW1	32.3	3.7	16.7	387	8.0	17.9	5	24.0
BW1S	36.4	3.5	15.8	417	7.4	16.7	4	4.7
BW1-sf	31.1	2.5	15.5	481	7.6	17.8	5	9.4
BW1S-sf	41.9	4.6	19.5	304	8.1	17.0	2	0.8

* @ = Liquid set-accelerating admixture used.

† Curing compound.

‡ Without curing.

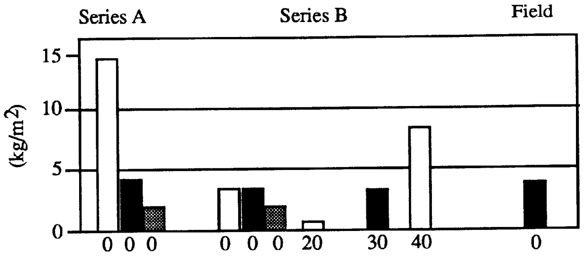
SERIES C TESTS

The shotcrete evaluated in this part of the study came from two construction projects in Montreal, where repairs were carried out for the Department of Transportation of Quebec (the first in 1989 and the second in 1990). The mix from the first site, CDsfc in Table 1, contained 2.8 parts of sand for 1 part of cement by mass, with 7 to 8 percent of silica fume by mass of cement.

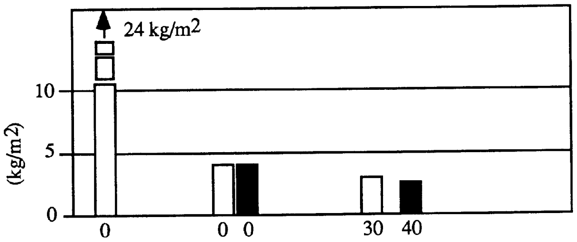
In the second field study, a shotcrete with mass proportions of 21.5 percent of Type 30 cement, 68 percent sand, and 10.5 percent aggregate (10 mm) was used. The shotcrete without the addition of air-entraining admixture is identified as CD3, and the mix with 30 ml/l of air-entraining admixture is CD3A30 in Table 1.

APPLICATION AND CURING

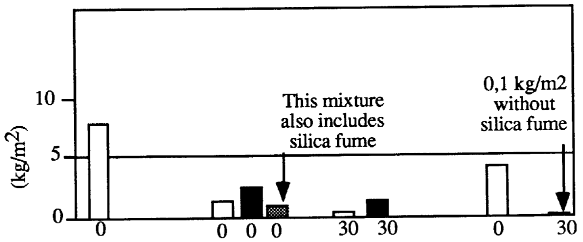
All the mixes were tested. Descriptions of each test conducted may be found in the next section. When the dry-mix shotcretes of the first series (AD) were applied, in some cases the quantity of water added in the premoisturizer and at the nozzle was measured and used to estimate the water-binder ratio of the in-place shotcrete. These ratios are pre-



a) Cement type 10 without fibers



b) Cement type 10 with fibers



c) Cement type 30 without fibers

LEGEND

☐ Without silica fume ■ With silica fume

▨ With latex 30 air entraining admixture (ml/l water)

Fig. 3—Scaling residues after 50 cycles (dry-mix)

sented in Table 4. Note that this is only an estimation of the water-binder ratios, because not all the water added reaches the applied surface. However, variations in the water-binder ratio from one mix to another can be observed.

For Series B and C dry-mix shotcretes, the air-entraining admixture was first added to the water before pneumatic application. Table 4 gives the air content in the shotcrete when directly shot into an air meter base. A mobile unit truck was used for batching shotcrete for Series C shotcretes. When no air-entraining admixture was added, an air content of about 3 percent was obtained; an air content of about 5 percent was achieved with 30 ml of air-entraining admixture per liter of water, and about 10 percent air content with 40 ml of air-entraining admixture per litre of water.

For wet-mix shotcrete, both air content and slump were measured. Table 5 gives all results for the shotcrete before and after its application. All panels, except two from Mix AD 1S5, were cured with water, using burlap kept moist for 7 days. One of the two AD 1S5 panels was cured with a curing compound, and the other was not cured. The noncured shotcrete cracked after only a few hours in the sun.

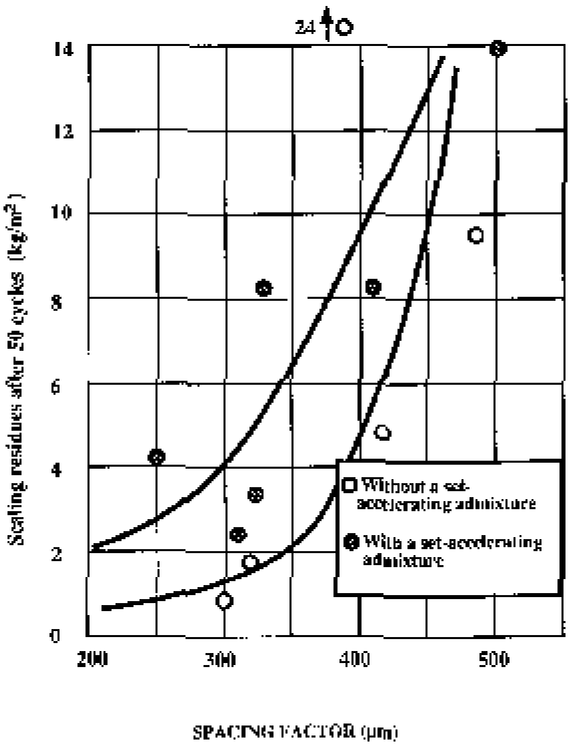


Fig. 4—Scaling residues after 50 cycles as function of spacing factor (wet-mix)

TEST RESULTS

Compression tests

Core samples 75 mm in diameter and 150 mm long (or 100 by 200 mm) were tested in compression according to ASTM C 39. All samples were cured for 7 days, then dried for a minimum of 28 days before being tested, except Series CDs-fc samples, which were cured for 28 days before testing. Tables 6 and 7 show results for the dry- and wet-mix shotcretes, respectively.

Compressive strengths obtained with conventional dry-mix shotcretes are usually superior to those obtained with wet-mix shotcretes. As for ordinary concretes, addition of silica fume or use of a Type 30 cement increases compressive strength. On the other hand, the addition of air-entraining or set-accelerating admixtures reduces compressive strength.

Determination of air-void characteristics

Air-void characteristics for all mixes were measured on two polished samples 100 by 100 mm, according to ASTM C 457. Tables 6 and 7 summarize results for dry- and wet-mix shotcrete processes. Air content, specific surface, and spacing factor of air voids $(\bar{L})$ can be found in these tables. Note that an acceptable spacing factor for certain mixtures (BD1A40 with 206 µm) was obtained with the addition of a high quantity of air-entraining admixture (40 ml/l of water) in the dry-mix shotcrete process. The addition of latex seems to insure a good spacing factor as well, with a value of 300 µm recorded.

Absorption tests

These tests were carried out according to ASTM C 642. Tables 6 and 7 give results after immersion and volume of permeable voids for each mix. Values for absorption and permeable voids are, in general, inferior for the mix with latex or Type 30 cement, as well as mixes with silica fume, though to a lesser degree. Comparing the same mix with and without entrained air, it can be seen that, generally, increases in air content increase the measured absorption and volume of permeable voids.

Scaling tests with deicing salts

These tests conformed to ASTM C 672, except that a 2.5 percent NaCl solution was used in the first year and a 3 percent solution in the second year instead of a solution of 4 percent $CaCl_2$, since the Department of Transportation in Quebec uses NaCl as a deicer. The concentration of 2.5 or 3.0 percent was chosen because, according to Verbeck and Klieger,[12] it is approximately the most damaging.

Every five cycles, surfaces were rated and all the residues that fell from the surfaces were collected. The visual rating and mass of scaling residues (in kg/m^2) after 50 freeze-thaw cycles are shown in Table 6 (dry-mix) and in Table 7 (wet-mix). A concrete is considered durable if the total mass of scaling residues is below 1 kg/m^2 after 50 freeze-thaw cycles (Reference 9 and Swedish standard).

For all mixes, the mass of residues vary between 0. 1 and 24 kg/m^2. Even if there is a broad range (not uncommon with this test), these results show that scaling resistance is greatly influenced by the mix composition, particularly by the binder type and air-void spacing factor. The two best mixes, BD3A30 and CD3A30, were both dry-mix shotcretes made with Type 30 cement and an air-entraining admixture. Fig. 3 shows that use of a Type 30 cement and air-entraining admixture is very useful with dry-mix shotcrete. Despite the variability in results, it is clear that use of a Type 30 cement and air-entraining admixture can efficiently improve scaling resistance.

Use of set-accelerating admixtures is not uncommon in shotcrete. The mix made with a shotcrete accelerator displayed the worst performance in the scaling test and also had the lowest compressive strength. The strength-reducing influence of the accelerator is consistent with data reported in the literature.[13]

Use of a set-accelerating admixture for wet-mix shotcrete again had a negative effect. Fig. 4 shows scaling residues as a function of the air-void spacing factor for all mixes made both with and without a set-accelerating admixture. This figure shows the importance of the spacing factor and negative effect of the admixture. Results shown in Fig. 4 indicate clearly that scaling residues diminish with a reduction in the spacing factor, and, as with ordinary concrete, a spacing factor of about 200 to 250 μm yields good resistance to scaling (residues < 1 kg/m^2). Incorporation of silica fume in dry-mix shotcrete had little effect on the results, at least for mixes of Series B. Silica fume seems to improve a concrete of marginal quality but has almost no effect on a good concrete.

CONCLUSIONS

As can be seen from this study, it is possible to obtain good resistance to deicer salt scaling with dry-mix shotcrete when an air-entraining admixture is added to the mix water injected at the nozzle. The spacing factor obtained without an air-entraining admixture, although adequate for resistance to freezing and thawing, does not insure resistance to deicer salt scaling. In the ASTM C 672 test, shotcrete was not found to perform very differently from ordinary concrete. Shotcrete does, however, differ from ordinary concrete in one way (which for the moment cannot be explained); when a Type 30 cement, which is finer and reacts more rapidly, is used in dry-mix shotcrete, a better resistance to scaling is obtained. Also, even with a good spacing factor, good performance in the scaling test is not always found. As observed in the case of BD1A40, with a spacing factor of 206 μm, 8.3 kg/m^2 of residues were collected in the scaling test.

For wet-mix shotcrete, the spacing factor is very important in obtaining good resistance to scaling, even with a normal cement (Type 10).

Use of a set-accelerating admixture in both wet-and dry-mix shotcrete processes increased scaling residues. The effect of silica fume is not as well established. In tests from the first year, addition of silica fume seemed to improve scaling resistance of the mixes, but in tests from the second year, no significant improvement was found, at least for dry-mix mixes. For some of the second year dry-mix mixes, in fact, scaling residues increased with silica fume addition. Some improvements were found for the wet-mix mixes of the second year. In general, however, silica fume seems to improve a shotcrete of marginal quality but appears to have little effect on a good-quality shotcrete. Further studies on silica fume and effects of different cement types, admixtures, and set-accelerating admixtures are recommended to better understand the influences of such variables on shotcrete durability.

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CONVERSION FACTORS

1 MPa = 145 psi
1 mm = 0.0394 in.
1 m = 3.2808 ft
1 mm^{-1} = 25.4 in.$^{-1}$
1 kg = 2.204 lb
1 kg/m^2 = 0.2048 lb/ft^2
1 kg/m^3 = 1.6856 lb/yd^3
1 m^2/kg = 4.8828 ft^2/lb

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