Durability of Dry-Mix Shotcrete

by G.W. Seegebrecht, A. Litvin, and S.H. Gebler

Please see editorial comment at end of article.

Dry-mix shotcrete specimens sawed from field-shot panels were tested for freeze-thaw durability, resistance to chloride-ion penetration, compressive strength, characteristics of their air-void systems, and absorption. Results showed that characteristics of the air-void systems, relatively high compressive strength, and low permeability resulted in freeze-thaw resistance in a fresh water environment comparable to that of properly air-entrained concrete. However, for salt water exposure in a freeze-thaw environment, dry-mix shotcrete made with portland cement may require treatment with sealers or coatings, or greater cover of shotcrete may be necessary to protect embedded steel reinforcement.

Freeze-thaw durability of dry-mix shotcrete has been a subject of much controversy in recent years. Even among engineers knowledgeable in shotcrete construction, judgment of durability varies. Litvin and Shideler[1] reported excellent durability, except for specimens indicative of poor gunning practice, which visually exhibited layering or sand lenses.

Reading[2] reported on a user survey and on a number of laboratory and field studies. While the results varied, durability generally was considered good. Some instances of poor durability were explained by poor control or application techniques, or by poor bond to substrate. Some failures were not satisfactorily explained.

Some engineers contend, based on the supposition that air cannot be entrained in dry-mix shotcrete, that dry-mix shotcrete is not durable. Others[1] have made linear traverse measurements and found air voids similar in size and spacing to those in air-entrained concrete. Some investigators believe that this type of air-void system together with low water-cement ratio, high strength, and low permeability of high quality dry-mix shotcrete account for good durability.

To develop additional data on durability of dry-mix shotcrete, the Portland Cement Association sponsored the laboratory investigation reported here.

Objective and scope

The purpose of the study was to evaluate the durability of dry-mix shotcrete. Shotcrete test panels were obtained from three contractors (A, B, and C) known for quality workmanship. Specimens were sawn from two of the panels (Contractors A and B) to test freeze-thaw durability in fresh and salt water, parameters of the air-void system, chloride-ion permeability, compressive strength, specific gravity, absorption, and volume of permeable voids.

The third panel was fabricated by Contractor C and tested as part of an earlier program. Specimens sawn from the third panel were tested two years prior to testing specimens from the other two panels. Specimens from the third panel were tested for freeze-thaw durability in fresh water, parameters of the air-void system, and compressive strength.

Findings

Based on laboratory tests conducted in this investigation, the following findings are presented.

1. Freeze-thaw durability after 300 cycles in fresh water was comparable to that of high quality, air-entrained concrete.

In salt water tests, length change and relative dynamic moduli of elasticity were satisfactory. However, specimen weight loss was relatively high and indicates potential for problems in actual field use. Thus, for salt water exposure in a freeze-thaw environment dry-mix shotcrete made with portland cement may require treatment with sealers or coatings, or additional cover of shotcrete may be necessary to protect embedded steel reinforcement.

2. Air-void systems were variable in the shotcrete panels studied. Two panels were found to possess air-void distributions similar to those of properly air-entrained concretes while the other did not. Total volume of air in the shotcrete panels was lower than that for properly air-entrained concrete.

3. Chloride-ion permeability, when tested according to 90-day chloride ponding tests, indicated permeability of the shotcrete was very low. Chloride-ion content was determined from powder samples obtained by drilling to a depth of between 1 to 1½ in. (25 to 38 mm) below the specimen surface.

4. The 28-day compressive strength of cubes from all panels tested ranged from 7340 to 11,400 psi (50.6 to 78.6 MPa).

5. The mean specific gravity, absorption, and volume of permeable void space of specimens from the

Keywords: absorption; air entrainment; chlorides; compressive strength; **durability**; freeze-thaw durability; permeability; **shotcrete.**

Table 1 — Results of freeze and thawing tests after 300 cycles*

Panel	Expansion, percent	Weight change, percent†	Relative dynamic modulus of elasticity, percent
Fresh water testing			
A	0.010	−3.7	104.4
B	0.003	−0.8	100.7
C	‡	+0.8	100.0
Salt water testing			
Panel	**Expansion, percent**	**Weight change, percent†**	**Relative dynamic modulus of elasticity, percent**
A	0.020	−27.6	114.1
B	‡	−8.8	97.0

*Test conducted in accordance with ASTM C 666-84, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." Data shown represent the mean for six specimens tested.
†"+" denotes weight gain; "−" denotes weight loss.
‡Gage pins loosened during testing.

Table 2 — Air-void characteristics of hardened dry-mix shotcrete*

Panel	Air content, percent	Spacing factor, in. (mm)	Specific surface, in.^{2}/in.^{3}, (mm^2/mm^3)	Voids per linear in. (mm)
A	3.6	0.011 (0.28)	482 (19)	4.4 (0.17)
B	3.0	0.008 (0.20)	687 (27)	5.1 (0.20)
C	3.8	0.008 (0.20)	683 (27)	6.6 (0.26)

Generally accepted criteria for properly air-entrained concrete†

1. Spacing factor less than 0.008 in. (0.20 mm).
2. Specific surface greater than 600 in.^{2}/in.^{3} (23.6 mm^2/mm^3).
3. Recommended number of voids per linear inch, 1½ to 2 times greater than the numerical value of the air content when using the English system of units.
4. An air content ranging from 4½ to 7½ percent for severe exposure.

*Test conducted in accordance with ASTM C 457-82, "Standard Practice to Microscopical Determination of Air-Void and the Parameters of the Air-Void System in Hardened Content."

two panels tested were 2.49, 5.5 percent, and 12.0 percent, respectively.

Fabrication and curing of test panels

Materials used by the three contractors who submitted dry-mix shotcrete test panels followed these guidelines:

Dry-mix shotcrete proportions (by volume) — 1:3.5 Cement:Sand; portland cement — Type I; water — potable; fine aggregate grading — ASTM C 33-85.

Double-chamber gun equipment was used to fabricate all panels, which were shot into vertically positioned 36 x 36 x 3 in. (914 x 914 x 76 mm) plywood forms. All panels were screeded and floated to a flat finish after shotcreting was completed.

Initial curing consisted of covering the panels with wet burlap for 24 hours. Panels were to be covered with polyethylene during shipment to the laboratory; however, panels from Contractor B were received uncovered. General appearance of all panels was very good. Shipping time varied; panels were received at the laboratory from five to 11 days after shotcreting. All participants reported using experienced shotcrete crews to fabricate the test panels.

Laboratory test program

The following tests were conducted to determine properties of the dry-mix shotcrete.

- To determine resistance to freezing and thawing, tests were conducted on 3 x 3 x 11.25 in. (76 x 76 x 286 mm) sawn prisms obtained from panels. The test procedure conducted was in accordance with ASTM C 666-84, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" Procedure A.

Prior to testing, prisms were stored in laboratory air at 73 ± 3 F (23 ± 1.7 C) and 50 ± 5 percent relative humidity for 14 days. Specimens from all panels were tested in fresh water. In addition, specimens from two of the panels were tested in a 4 percent NaCl (sodium chloride) solution.

- To determine the air-void parameters, tests were conducted on sawn slabs in accordance with ASTM C 457-82a, "Standard Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete."
- To determine resistance to chloride-ion penetration, testing was performed on specimens from two of the panels in accordance with AASHTO T 259, "Method of Test for Resistance of Concrete to Chloride Ion Penetration." Curing for this test consisted of 14 days at 100 percent relative humidity and 73 ± 3 F (23 ± 1.7 C), then 28 days of drying at the same temperature and 50 ± 5 percent relative humidity.

The 12 in. (305 mm) square by 3 in. (76 mm) thick specimens were ponded with a 3 percent NaCl solution for 90 days, then air dried for 28 days. Powder samples were obtained from the test slabs by drilling to a depth of between 1 and 1½ in. (25 and 38 mm) below the panel surface. This depth was selected as being representative of the location of embedded reinforcement.

- Compressive strength determinations were made on 3-in. (76-mm) cubes sawed from each of the panels. The cubes were moist cured at 73 ± 3 F (23 ± 1.7 C) and 100 percent relative humidity until they were tested at 7 and 28 days. Specimens from one panel (Contractor C) could not be tested at 7 days due to the shipping time involved.
- Specific gravity, absorption, and permeable pore space (voids) were measured on specimens from two of the panels in accordance with ASTM C 642-82, "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete." The specimens were moist cured at 73 ± 3 F (23 ± 1.7 C) and 100 percent relative humid-

Table 3 — Results of 90-day chloride-ion ponding*

Panel	Percent chloride by weight of sample at a depth of 1 to 1½ in. (25 to 38 mm)		
	Control	After ponding	Difference
A	<0.007	<0.007	0.00
B	<0.007	<0.007	0.00

*Test conducted in accordance with AASHTO T-259-80I, "Method of Test for Resistance of Concrete to Chloride Ion Penetration."

Table 4 — Dry-mix shotcrete cube compressive strength

Panel	Compressive strength, psi (MPa)*	
	7 day	28 day
A	6290 (43.4)	7,340 (50.6)
B	6110 (42.1)	8,590 (59.2)
C	†	11,400 (78.6)

*Mean of three specimens.
†Early-age compressive strength not determined due to late specimen shipment.

Table 5 — Specific gravity, absorption, and voids*

Panel	Apparent specific gravity	Absorption after immersion and boiling, percent	Volume of permeable pore space, percent
A	2.50	6.3	13.6
B	2.48	4.8	10.5

*Tests conducted in accordance with ASTM C 642-82, "Standard Test Method for Specific Gravity, Absorption and Voids in Hardened Concrete." Test results represent mean of two samples.

ity until they were tested at approximately 6 months.

Discussion of test results

Resistance to freezing and thawing

Table 1 presents results of freezing-thawing tests after 300 cycles. Tests conducted in fresh water indicated excellent relative dynamic moduli of elasticity with minimal expansions and relatively low weight losses. Freeze-thaw tests in salt water also indicated excellent relative dynamic moduli of elasticity. However, weight losses were high, ranging from approximately 9 to 28 percent. These results suggest no internal disruption, but exposed surfaces were severely deteriorated.

These results indicate that dry-mix shotcrete exposed to salt water and subjected to freezing and thawing may be susceptible to excessive surface deterioration. Thus, for salt water exposure in freeze-thaw environments, dry-mix shotcrete may require treatment with sealers or coatings, or greater cover of shotcrete (extra thickness) may be necessary to maintain sufficient shotcrete cross section and cover over embedded reinforcement.

Air-void system

Examination of linear traverse results, shown in Table 2, revealed variations in the air-void systems. Two of the shotcrete panels exhibited air-void systems with characteristics similar to those of properly air-entrained concrete, except for total air content values. All dry-mix shotcrete specimens tested had less than 4 percent air content. Panel A, which had a very coarse air-void system, had a slightly higher relative dynamic modulus of elasticity than the other specimens, but a substantially greater weight loss, especially in salt water.

Eliminating slight differences in equipment and materials, it appears reasonable that the major difference in air-void systems is the result of differences in application techniques and moisture contents of the mixes.

Resistance to chloride-ion penetration

Resistance to chloride-ion penetration was determined using the 90-day chloride ponding method. After the ponding period there was no increase in chloride content at a depth between 1 and 1½ in. (25 to 38 mm) below the specimen surface when compared to the unponded control specimen, as shown in Table 3.

Compressive strength development

Mean cube compressive strengths for the three panels are shown in Table 4. All three mixes had relatively high compressive strengths. Shotcretes B and C had the greatest strengths and also had the lowest weight losses in the freeze-thaw tests.

Specific gravity, absorption, and voids

Specific gravity, percent absorption, and volume of permeable pore space data are shown in Table 5. Absorptions ranged from 4.8 to 6.3 percent. Generally, absorptions in the 5 to 6 percent range are considered low. The low absorption values appear to be consistent with the relatively high specific gravities (2.48 to 2.50) and the low chloride penetrations observed in the ponding tests. The volume of permeable pore space ranged from 10.5 to 13.6 percent, which is considered low and is consistent with chloride penetration and absorption values obtained in this study.

Summary

The tests described here indicated that properly placed dry-mix shotcrete possessed high compressive strength and good resistance to freezing and thawing in fresh water. However, freezing and thawing in salt water resulted in high measured weight losses. Ponding tests indicated that dry-mix shotcrete was relatively impermeable to chloride-ion penetration, which indicates the shotcrete can protect reinforcing steel against corrosion.

In summary, dry-mix shotcrete made using sound materials, in the proper proportions, and applied by an experienced shotcrete crew, can provide a high-strength durable shotcrete.

Acknowledgments

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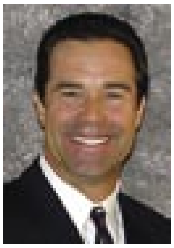

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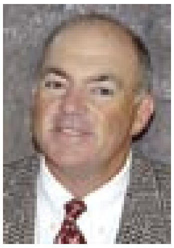

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Editor's Comment

Prior to the early 1990s, many engineers and contractors were of the opinion that it was not possible to entrain air in dry-mix shotcrete. Thus, dry-mix shotcrete exposed to freezing and thawing was typically made without air-entraining admixtures. Since then, however, extensive research at Laval University in Quebec and elsewhere has demonstrated that not only is it possible to entrain air in dry-mix shotcrete using either liquid air-entraining admixtures added to the mix water added at the nozzle, or dry-powdered air-entraining admixtures preblended in with the dry-mix shotcrete materials, but that such air entrainment adds substantially to the freezing-and-thawing durability and deicer salt-scaling resistance of the dry-mix shotcrete. This process has now been successfully used to produce durable shotcrete in Canada and elsewhere in North America for over 10 years and is now referred to in the just published ACI 506R-05, "Guide to Shotcrete." For an excellent overview of this technology (with supporting references), see the paper "Development of Durable Dry-Mix Shotcrete in Quebec" by Daniel Vezina, *Shotcrete*, V. 3, No. 2, Spring 2001, pp. 18-20. You can access it on the American Shotcrete Association website, **www.shotcrete.org**. Click on the Publications page and search the archives using the keyword "Vezina."