

Freeze-Thaw Durability of Shotcrete

by Dudley R. (Rusty) Morgan

This 14-year-old "Shotcrete Classic" was selected for reader interest. While the findings and recommendations of this study still apply today, it should be noted that the practice of adding air-entraining admixtures to dry-mix shotcrete had not yet been developed at the time this article was written. In severe freeze-thaw and deicing salt exposure environments, designers, suppliers, and users are encouraged to add either dry-powdered air-entraining admixtures to preblended dry-bagged shotcretes, or liquid air-entraining admixtures to the mix-water added at the nozzle, to enhance shotcrete durability. The article by Daniel Vezina on "Development of Durable Dry-Mix Shotcrete in Quebec" published in ASA's Shotcrete, V. 3, No. 2, Spring 2001, pp. 18-20, gives good guidance in this regard.

Reviews the results of numerous laboratory investigations of the durability of both dry and wet mix shotcretes, looks at the main causes of shotcrete failures and makes recommendations for the production of freeze-thaw durable shotcrete. Based on the response to an ACI Committee 506, Shotcrete Durability Subcommittee Survey.

Shotcrete has been used in construction in North America for almost 80 years. Initially all shotcrete was applied by the dry mix shotcrete process, where the majority of the mix water is added at or near the nozzle just before the shotcrete is pneumatically consolidated by impact on the receiving surface.

In recent years, the advent of improved pumping equipment and shotcrete materials technology (such as the use of superplasticizers and silica fume) has resulted in increased use of wet mix shotcrete. In the wet mix shotcrete process all the materials, including mix water, are premixed, as if for conventional concrete. The shotcrete is pumped down a hose with high pressure air being added at or near the nozzle to convey and consolidate the shotcrete by impact on the receiving surface.

Shotcrete has often been used in new construction or repair of damaged or deteriorated structures in applications such as:

- construction of canals, dikes, creek stabilization and protection of bridge abutments.
- construction of swimming pools, reservoirs, ornamental rockscapes

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and watercourses in theme parks, zoos, aquariums, golf courses and other structures exposed to water.

- rock slope stabilization and soil nailing.
- tunnel lining and support of underground openings such as shafts, adits, drifts and chambers in mining applications.
- rehabilitation of deteriorated marine structures such as berth faces, piles, jetties, sea walls, light stations and caissons.
- rehabilitation of deteriorated locks, drydocks, and dams.
- repair of deteriorated bridges and highway structures.

In many of the above applications, particularly in the northern United States and Canada, the shotcrete is subjected to frequent cycles of freezing and thawing, often in a saturated condition and sometimes in the presence of marine salts or deicing salts.

For example, the exposure environment in the intertidal zones of marine structures on the Atlantic coast of the northern U.S. and maritime provinces of Canada represents some of the most aggressive freeze-thaw conditions to which concrete or shotcrete structures are subjected. Similarly, shotcrete in the locks and dikes on the river systems and lakes of the northern U.S. and Canada is often subjected to many cycles of freezing and thawing in a saturated condition.

ACI Shotcrete Committee Survey

In 1985, ACI Committee 506, Shotcrete, convened a subcommittee to investigate shotcrete durability, with a particular emphasis on the freeze-

thaw durability of shotcrete. Letters were sent to a wide range of owners, designers, specifiers, contractors and users of shotcrete structures soliciting:

- case history data on the performance of aged shotcrete structures, particularly those subjected to aggressive exposure conditions.
- results of laboratory evaluations of the freeze-thaw durability of wet and dry mix shotcretes.

Organizations that responded with case history and/or laboratory test records included the U.S. Army Corps of Engineers, North Pacific Division and Waterways Experiment Station; Construction Technology Laboratories, Skokie, Illinois; British Columbia Hydro and Power Authority; Port of Saint John, New Brunswick; and a number of private consultants, contractors and owners in the U.S. and Canada.

From a review of the case history data provided, it is apparent that the majority of applied shotcrete has served its intended function well. There are, however, examples of less than adequate performance in aggressive freeze-thaw exposure conditions. This is true of both the performance of shotcrete in the field and the results of tests conducted in the laboratory.

It is recognized that accelerated freeze-thaw durability testing in the laboratory does not necessarily accurately represent the real exposure environment in the field. The best means of assessing shotcrete durability probably is to conduct detailed investigation of aged shotcrete structures in the field in various exposure environments.

Shotcrete Classics

Table 1 — Shotcrete properties - Series I

Mix no.	28-Day compressive strength		Absorption (percent)	Freeze-thaw tests to ASTM C666 - Procedure A*			
	psi	MPa		Expansion (percent)	Change in mass (percent)	Percent of original <i>E</i>	cycles at failure
WS-1	4,230	29.2	6.7	0.045	- 3.8	91	NF
WS-2	3,140	21.7	7.1	0.116	- 2.1	66	200
WS-3	3,440	23.7	6.8	0.208	- 0.2	38	25
WS-4	3,780	26.1	8.3	0.270	-13.4	20	75
WS-5	5,310	36.6	7.5	0.032	- 6.8	82	150
WC-6	9,400	64.8	7.0	0.079	- 0.8	88	NF
WC-7	10,460	72.1	7.4	0.120	+ 0.6	56	50
WC-8	7,440	51.3	8.1	0.171	+ 0.3	45	100
WC-9	9,330	64.3	6.4	0.177	+ 0.3	51	75
DS-10	12,050	83.1	7.0	0.020	+ 0.6	101	NF
DS-11	10,130	69.9	7.0	0.070	- 0.9	102	NF
DS-12	10,340	71.3	6.6	0.022	+ 0.3	107	NF
DS-13	8,710	60.0	—	0.120	- 3.2	79	150
DC-14	9,480	65.4	7.3	0.157	+ 0.5	49	75
DC-15	6,080	41.9	7.8	0.079	- 5.6	78	150
DC-16	9,120	62.9	7.5	0.033	- 2.3	108	NF
DC-17	9,290	64.1	11.6	0.028	- 0.4	106	NF

*Method modified: specimens fog cured 14 days, air dried for 14 days and water soaked for 3 days prior to testing.

*NF indicates no failure after 300 freeze/thaw cycles.

While a number of case history statements on the performance of shotcrete in the field were submitted in response to the ACI Committee 506 Shotcrete Durability Subcommittee inquiry, most of the information submitted was limited to visual assessment of the performance of the various structures. Cores were extracted from only a few of the structures and additional physical test data reported. The test data, where available, has been included in this report.

Because of the limited mix proportion and physical test performance data available concerning aged field structures, this report concentrates on the results of laboratory investigations into the freeze-thaw durability of shotcrete. A separate report that deals with the performance of aged shotcrete structures in the field is planned for future publication.

This article reviews the results of laboratory investigations of the freeze-thaw durability of shotcretes and provides a synthesis report that attempts to:

- define those aspects of shotcrete that lead to less than adequate performance in freeze-thaw exposure environments.
- make recommendations for procedures for shotcrete mixture pro-

portioning and application, which will lead to the construction of freeze-thaw durable shotcrete structures.

Study by A. Litvin and J.J. Shideler

Perhaps the most systematic laboratory study of the durability of both wet and dry mix shotcretes is the work that was carried out by A. Litvin and J.J. Shideler at the Portland Cement Association in 1966.¹ In this study, the physical properties of 16 different wet mix shotcretes and 22 different dry mix shotcretes were evaluated.

Two series of tests were conducted. In the Series I tests, shotcrete contractors were asked to shoot material typical of their normal practice and supply the pertinent mix data. The cement content of the in-place shotcrete ranged from 370 to 494 kg/m³ (623 to 832 lb/yd³) for the wet mix shotcretes and from 463 to 810 kg/m³ (780 to 1,364 lb/yd³) for the dry mix shotcretes. The water/cement ratio of both the dry and wet mix shotcretes was in the range of 0.20 to 0.38, with the exception of wet mix shotcretes containing asbestos fines, where it was in the range of 0.50 to 0.75. Clearly the incorporation of 2 percent by mass of cement of asbes-

tos fines had a major influence on water demand.

In the Series II tests, all the mixes were shot in the Portland Cement Association laboratory. The in-place shotcrete cement contents in this study ranged from 391 to 833 kg/m³ (659 to 1,404 lb/yd³). The as-batched proportions of cement to aggregate for this range of mixes was 1:6 to 1:3, respectively. Water-cement ratios ranged from 0.22 to 0.44, with the exception of a single mix containing asbestos fines, which had a water-cement ratio of 0.55.

Specimens cut or cored from test panels were evaluated for compressive strength, flexural strength, modulus of elasticity, dry unit weight, and absorption. All shotcretes also were assessed for freeze-thaw durability, using ASTM C666, Procedure A (modified). The modification to the standard test procedure was in the curing regime. The specimens were fog cured for 14 days, followed by air drying at 20 C (73 F) and 50 percent R.H. for 14 days, and soaking in water at 20 C (73 F) for three days prior to being subjected to freeze-thaw cycling.

Compressive strength at 28 days and absorption data is given in Table 1 for the Series I tests, together with the freeze-thaw test data. Freeze-thaw testing included measurement of expansion, change in mass, and dynamic modulus of elasticity (*E*) of shotcrete prisms. Also noted was the number of freeze-thaw cycles at failure.

In this study five of the eight dry mix shotcretes tested displayed excellent freeze-thaw durability, as indicated by *E* values in excess of 100 percent of the original *E* value. The

Table 2 — Shotcrete properties - Series II

Mix no.	28-day compressive strength		Absorption (percent)	Freeze-thaw tests to ASTM C666 - Procedure A*			
	psi	MPa		Expansion (percent)	Change in mass (percent)	Percent of original <i>E</i>	cycles to failure
2DS-1	10,510	72.5	6.7	0.025	+0.5	103	NF*
2DS-1A	10,470	72.2	7.1	0.025	+0.2	101	NF
2DS-2	10,540	72.7	6.8	0.025	+0.4	105	NF
2DS-2A	7,210	49.7	8.3	0.038	-1.7	99	NF
2DS-2AE	7,770	53.6	7.5	0.022	0.0	106	NF
2DS-3	10,130	69.9	7.3	0.029	+0.1	103	NF
2DS-3A	6,610	45.6	7.4	0.073	-3.2	88	NF
2DS-4	8,550	59.0	7.0	0.034	+0.4	103	NF
2DS-4A	9,950	68.6	7.4	0.036	-2.8	101	NF
2DS-4B	8,280	57.1	8.1	0.047	-2.2	100	NF
2DS-5	12,930	89.2	6.4	0.034	+0.4	103	NF
2DS-6	10,730	74.0	6.9	0.056	-0.5	77	200
2DS-7	8,920	61.5	6.9	0.055	-1.3	102	NF
2DS-8	9,250	67.8	7.0	0.057	-4.7	96	NF
2WC-4	9,070	62.6	7.0	0.033	-0.4	95	NF
2WC-5	8,860	61.1	6.6	0.052	+0.1	91	NF
2WC-6	8,600	59.3	6.4	0.052	+0.3	93	NF
2WS-2	7,870	54.3	7.3	0.017	+0.2	104	NF
2WS-3	4,600	31.7	7.8	0.019	-0.4	99	NF
2WS-4	5,140	35.4	7.5	0.029	-0.4	100	NF
2WS-4A	3,070	21.2	11.6	0.013	-6.1	99	100

*Method modified: specimens fog cured 14 days, air dried for 14 days and water soaked for 3 days prior to testing.

*NF indicates no failure after 300 freeze/thaw cycles.

as-batched and in-place cement contents and compressive strengths tended to be lower in the three mixes that displayed less than adequate freeze-thaw durability (*E* values at 150 cycles or less of less than 80 percent of the original *E* value).

In the wet mix shotcretes evaluated in the Series I tests, only two of the nine mixes tested displayed *E* values of greater than 80 percent of original *E* after 300 freeze-thaw cycles (Table 2). It should, however, be noted that most of the mixes that displayed less than adequate freeze-thaw durability were either not adequately air entrained or had high water-cement ratios because of the incorporation of asbestos fines. The two mixes that performed well (WS-1 and WC-6), had high plastic air contents (10.3 and 7.5 percent, respectively).

In the Series II tests, 13 of the 14 dry mix shotcretes tested displayed excellent freeze-thaw durability. Similarly six of the seven wet mix shotcretes tested displayed excellent freeze-thaw durability. All of the wet mix shotcretes were air entrained (plastic air contents being in the range of 4.3 to 12.5 percent). The only wet mix shotcrete that performed poorly was the mix containing asbestos fines, which had a high water-cement ratio of 0.55 and a low compressive strength of only 21.2 MPa (3,070 psi).

Studies Reported by T.J. Reading

In 1981, Reading² published a comprehensive report reviewing the freeze-thaw durability of shotcrete. He presented the results of systematic studies by the Corps of Engineers, Missouri River Division, on six different shotcrete mixtures

from four different projects. Five of the shotcretes were applied by the dry mix process and one by the wet mix process. The hardened shotcrete properties are summarized in Table 3.

Using the Corps of Engineers freeze-thaw durability rating factors, one of the dry mix shotcretes had an excellent rating, one a fair rating and four had a poor rating.

At the Corps of Engineers exposure plot at Treat Island in Maine, specimens are placed on racks in the intertidal range where they are typically exposed to about 250 cycles of freezing and thawing every two years. For structures designed for a 100-year life, at least a 10-year specimen life at Treat Island is usually desired, although as little as seven years has been accepted where better materials are not available.²

When evaluated against these criteria, all of the shotcrete from the tests reported by Reading performed considerably better at Treat Island than in the laboratory tests to ASTM C666, Procedure A. Only Panel C had a specimen life of less than seven years at Treat Island. Panels A-1 and A-2 had specimen lives in excess of 10 years.

This proves that it is possible to produce both dry and wet mix shotcrete that will survive the highly aggressive natural freezing and thawing conditions that prevail at Treat Island. The ASTM C666 Procedure A, rapid freezing and thawing to 300 cycles test, appears to be even more severe than some of the harshest freezing and thawing conditions existing in nature. Hence the results of this laboratory test should be interpreted with caution.

Studies Reported by E. Schrader and R. Kaden

This report on the durability of shotcrete was published by ACI in 1987.³ The authors brought together the results of shotcrete durability studies from some 13 different U.S. Army Corps of Engineers' projects. The studies included tests on both dry and wet mix shotcretes. The results of these studies are summarized in Table 4 for dry mix shotcrete, and Table 5 for wet mix shotcrete. These test results present a more pessimistic scenario regarding the potential freeze-thaw durability of shotcrete than the information presented in the Litvin and Shideler study.¹

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Table 3 — Studies reported by T.J. Reading, 1981.

Panel no.	28-Day compressive strength		ASTM C642		Hardened air content (percent)	Air-void spacing factor		Durability factor at 300 cycles	Durability rating	Life at Treat. (yrs.)
	psi	MPa	Boiled absorption (percent)	Permeable voids (percent)		in.	mm			
A-1	7,000	48	5.8	8.9	5.0	0.008	0.20	78	Excellent	14
A-2	6,500	45	6.5	8.8	6.0	—	—	29	Fair	13
B-1	5,300	37	7.0	9.4	4.6	0.020	0.50	14	Poor	8
B-2	5,300	37	7.2	9.5	6.3	0.012	0.30	6	Poor	7
C	5,200	36	—	—	7.0	—	—	8	Poor	5
D	8,100	56	4.2	5.7	6.4	0.009	0.23	36	Fair	9

For example, in the dry mix shotcrete studies summarized in Table 4, only four of the 20 mixes tested were rated by Schrader and Kaden as having excellent freeze-thaw durability. Four of the mixes were rated as fair, and one as poor-fair. Of the mixes rated as excellent, two were latex modified.

The other two mixes (Reading A-1 and Spirit Lake 1) which produced excellent ratings displayed the following beneficial physical properties:

- good air contents in the hardened shotcrete — 5.0 percent for both mixes.
- excellent spacing factor — 0.08 mm (0.003 in.) for Reading A-1.
- high compressive strengths — 48.2 MPa (7,000 psi) at 28 days for Reading A-1 and 86.0 MPa (12,480 psi) at 500 days for Spirit Lake 1.

Six of the dry mix shotcretes that displayed poor freeze-thaw durability had air contents in the range of 3.6 to 9.1 percent. The spacing factors ranged from 0.30 to 0.51 mm (0.012 to 0.020 in.). This lack of a suitable spacing factor in part explains the poor freeze-thaw durability performance.

The other factor believed to be important for dry mix shotcrete is the compressive strength for the six mixes mentioned above. The recorded compressive strengths ranged from 35.9 to 36.6 MPa (5,200 to 5,300 psi). By contrast, the 18 dry mix shotcretes tested by Lit-

vin and Shideler that displayed excellent freeze-thaw durability had compressive strengths in the range of 45.6 to 89.2 MPa (6,610 to 12,930 psi), with most mixes having strengths in excess of 60 MPa (8,700 psi). Thus it appears that strength level plays an important role in the freeze-thaw durability of dry mix shotcretes.

The wet mix shotcrete studies reported by Schrader and Kaden are summarized in Table 5. Freeze-thaw durability performance was generally better than that reported for dry mix shotcretes, with seven of the 19 mixes tested rated as displaying poor performance, six displaying fair-to-good performance, and six showing excellent performance.

Only limited air voids parameters test data was available, but two of the mixes that had poor performance were non air-entrained. The mixes displaying fair-to-good and excellent performances were air entrained, with air contents in the hardened shotcrete being in the range of 3.4 to 8.0 percent and spacing factors in the range of 0.20 to 0.38 mm (0.008 to 0.015 in.). Compressive strengths in these mixes ranged from 31.7 to 55.9 MPa (4,600 to 8,100 psi).

However, high compressive strength alone does not appear to provide a guarantee of adequate freeze-thaw durability in wet mix shotcrete, as several mixes with compressive strengths in the range of 55 to 85 MPa (8,000 to 12,300

psi) performed poorly in freeze-thaw testing, presumably because of inadequate air void parameters.

Study by Morgan et al

In 1987, Morgan et al⁴ published the results of a detailed evaluation of the performance of both wet and dry mix shotcretes, made both with and without additions of steel fiber and silica fume. Steel fiber use has increased in North America since the early 1980s, and silica fume use since the mid 1980s. This study was conducted to evaluate the influence of these additions on a variety of plastic and hardened properties of more recently developed types of shotcrete. The results of the freeze-thaw durability studies were published separately in 1988.⁵

Tests were conducted according to ASTM C666 Procedure A, rapid freezing and thawing in water to 300 cycles. The tests followed the ASTM procedure, except that the dry mix shotcrete was allowed to moist cure for 99 days and the wet mix shotcrete for 56 days before being subjected to freeze-thaw cycling. The shotcrete mix proportions used are summarized in Table 6 and properties of both the plastic and hardened shotcrete are summarized in Table 7. A 10 mm (3/8 in.) maximum size aggregate, conforming to the gradation requirements of ACI 506R-85, Table 2.1 was used.

In these studies, the compressive strength of the shotcretes was high and the water-cement ratio low. The compressive strength of the dry mix shotcretes varied from 41.9 MPa (6,080 psi) in the accelerated shotcrete mix (9D) to 51.8 MPa (7,510 psi) in the silica fume shotcrete (2D). The compressive strength of the wet mix shotcretes ranged from 55.8 MPa (8,090 psi) for the plain

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Table 4 — Freeze-thaw durability data for dry mix shotcrete

Project	28-Day compressive strength		Hardened air content (percent)	Air-void spacing factor		Freeze thaw cycles	Mass loss (percent)	Durability factor at 300 cycles	Durability rating
	psi	MPa		in.	mm				
Reading B-2	5,300	36.6	6.3	0.012	0.30	300	—	6.0	Poor
Lower Monumental 2	—	—	9.1	—	—	142	40.0	—	Poor
Reading C	5,200	35.9	7.0	—	—	300	—	8.0	Poor
Goose P31-P32*	5,860	40.4	—	—	—	300	—	10.0	Poor
Goose P7 -P17*	4,160	28.7	—	—	—	300	—	10.0	Poor
Goose P1 -P6 *	4,040	27.9	—	—	—	300	—	10.0	Poor
Lower Monumental 1	—	—	4.4	—	—	196	31.0	—	Poor
Bonneville	8,110	55.9	—	—	—	300	42.0	—	Poor
Reading B-1	5,300	36.6	4.6	0.020	0.51	300	—	14.0	Poor
Goose P33-P34	5,860	40.4	—	—	—	300	—	17.0	Poor
Lock and Dam 8	—	—	3.6	0.015	0.38	300	—	24.0	Poor
WES C-74-5	9,160	63.1	—	—	—	300	—	22.0	Poor-Fair
WES C-74-5	5,220	36.0	—	—	—	300	—	26.0	Fair
Reading A-2	6,500	44.8	6.0	—	—	300	—	29.0	Fair
Goose P21-P23*	4,160	28.7	—	—	—	300	—	42.0	Fair
Reading A-1	7,000	48.2	5.0	0.003	0.08	300	—	78.0	Excellent
Bonneville*	5,540	38.2	—	—	—	300	4.0	—	Excellent
Bonneville*	6,870	47.4	—	—	—	300	0	—	Excellent
Spirit Lake - 1	12,480*	86.0	5.0	—	—	300	2.3	93.6	Excellent
Spirit Lake - 2	6,600*	45.5	4.1	—	—	300	20.6	33.6	Fair

*latex modified shotcrete.

*specimens contained fiber reinforcement.

*at age 300 days.

**at age 448 days.

mix (1W) to 65.7 MPa (9,530 psi) for the silica fume mix (2W). All of the shotcretes displayed durability factors at 300 cycles in excess of 95 percent.

No attempt was made to entrain air in the dry mix shotcrete. The wet mix shotcrete, by contrast, was air-entrained. The as-batched wet mix shotcrete was air entrained to 8 ± 1 percent before shooting. Plastic air content was determined by two procedures:

- shotcrete was applied directly into the base of an ASTM C231 air pressure meter.
- shotcrete was applied to a vertical wall, the shotcrete removed by scoop and reconsolidated in an air pressure meter base by rodding.

Both procedures were found to produce very similar values for plastic air content. Examination of the data in Table 7 shows that, for this study, approximately one-half of the as-batched plastic air content was lost in the pumping and shooting process. Measurements indicated that generally less than 1.5 percent of the air content was lost in the actual pumping process; the remainder was lost in the shotcreting process. The air content in the hardened shotcrete was, however, on the average about 1.5 percent higher than that measured in the plastic shotcrete.

Perhaps of more significance than the air content alone, are the other parameters of the air void system, such as the spacing factor and specific surface. The specific surface values, with the exception of Mix 9D, are in the range of 16 to 32 mm^{-1} (400 to 800 in.^{-1}), suggested by Neville⁶ as being indicative of concrete with suitable air entrainment for freeze-thaw durability.

There is remarkable correspondence between the spacing factor in both the wet and dry mix shotcretes. With the exception of the plain wet mix (1W), these vary between 0.28 and 0.31 mm (0.011 and 0.012 in.). These values are in excess of the maximum of 0.20 mm

(0.008 in.) suggested by ACI Committee 201 and CSA/CAN3-A23.1-M77 as being required for freeze-thaw durable concrete. However, if the data is evaluated against the suggestions of Pigeon et al⁷ for a critical spacing factor (\bar{l} crit), for freeze-thaw durable high strength, silica fume concrete, then the shotcretes would be indicated as being durable. This is consistent with the results of the freeze-thaw durability study of ASTM C666 Procedure A to 300 cycles.

The quality of the hardened shotcrete was excellent in all test panels, with no indications of sand lenses, excessive voids, laminations or other defects. On completion of freeze-thaw cycling, test specimens were observed to still be in excellent condition, with no significant scaling or surface deterioration; saw cut edges were still sharp.

It is possible to produce freeze-thaw durable wet and dry process shotcretes, made with and without additions of steel fiber, accelerators and silica fume, provided that:

- the shotcrete is properly proportioned, using freeze-thaw durable aggregates.
- the shotcrete is properly batched, mixed, supplied, and applied (free

of excessive voids, dry patches, sand lenses, laminations, etc.).

- the water-cement ratio is kept sufficiently low (preferably less than 0.40). This in turn should generally result in compressive strengths of 50 MPa (7,250 psi) or better in non-accelerated shotcretes.

- for wet mix shotcretes, adequate air entrainment must be provided; this will generally require as-batched air contents of 8 to 10 percent, or possibly even higher, to produce satisfactory parameters of the air voids system in the hardened wet mix shotcrete.

Study by Gilbride et al

Marine structures in the Saint John Harbour, New Brunswick, Canada are exposed to some of the world's highest tidal ranges and temperatures, which in the winter can drop to -30 C (-13 F). The tidal range varies up to 8.5 m (28 ft.) and between 200 and 300 freeze-thaw cycles can be experienced by concrete in the intertidal zone in a single year. This is an even more aggressive freeze-thaw environment than that experienced at Treat Island in Maine, and has resulted in pronounced deterioration of the concrete berth faces.

Shotcrete Classics

Table 5 — Freeze-thaw durability data for wet mix shotcrete

Project	28-Day compressive strength		Hardened air content (percent)	Air-void spacing factor		Freeze thaw cycles	Mass loss (percent)	Durability factor at 300 cycles	Durability rating
	psi	MPa		in.	mm				
WES C-74-5	8,370	57.7	—	—	—	300	—	14.0	Poor
Mill Creek FP80*	5,790	39.9	—	—	—	100	42.0	—	Poor
Mill Creek DP80*	6,680	46.1	—	—	—	100	57.0	—	Poor
WES C-74-5	8,440	58.2	—	—	—	300	—	21.0	Poor
Lower Monumental 3	—	—	1.8	—	—	276	37.0	—	Poor
Lower Monumental 4	—	—	2.2	—	—	276	26.0	—	Poor
Reading - D	8,100	55.9	6.4	—	—	300	—	36.0	Fair
Mill Creek FP120*	5,640	39.1	—	0.009	0.23	100	10.0	—	Fair
Mill Creek FP80*	6,360	43.9	—	—	—	100	15.0	—	Fair
Oklahoma - 4*	—	—	6.8	0.015	0.38	300	4.0	1.0	Fair-Good
Oklahoma - 6	—	—	8.0	0.013	0.33	300	4.0	1.0	Fair-Good
Mill Creek - CP	6,730	46.4	—	—	—	100	2.0	—	Good
Willow Creek	4,600	31.7	4.5	0.008	0.20	100	1.0	—	Excellent
Mill Creek - CP*	6,790	46.8	—	—	—	100	1.0	—	Excellent
Emsworth 7 & 8	—	—	3.4	0.012	0.30	300	—	80.0	Excellent
Lower Monumental 5*	—	—	2.5	—	—	345	0	—	Excellent
Lower Monumental 6*	—	—	3.0	—	—	345	1.0	—	Excellent
Mill Creek	12,280*	84.7	4.1	—	—	300	4.6	4.2	Poor
Mill Creek	9,010*	62.1	6.8	—	—	300	8.7	89.3	Excellent

*latex modified shotcrete
 *specimens contained fibre reinforcement
 *at age 741 days
 *at age 789 days.

The Port of Saint John was faced with rehabilitation of these deteriorated, 60-year old concrete berth faces in the intertidal zone in this extremely aggressive freeze-thaw environment. After studying various remedial alternatives, the Port of Saint John Authority elected to carry out the works with its own forces, using ready-mix supplied, wet mix, steel fiber reinforced, air entrained, silica fume shotcrete.

Extensive preconstruction testing was conducted to assess the ability of local ready mix concrete suppliers to provide a suitable freeze-thaw durable shotcrete. Details of the study are given in the paper by Gilbride et al.⁸ Preconstruction freeze-thaw durability tests on these shotcretes produced durability factors which ranged from 95 percent to in excess of 100 percent after 300 cycles of freezing and thawing when tested to ASTM C666 Procedure A.

During construction, routine quality control tests were conducted to assess:

- air content of the shotcrete at the point of discharge from the ready mix concrete truck.
- air content as shot into an air pressure meter base.

- parameters of the air voids system in cores extracted from the in-place shotcrete (measurements included air content, specific surface and spacing factor).

Results from routine quality control tests conducted on shotcrete that was applied in 1986 and 1987 are summarized in Table 8. Results of compressive strength tests conducted on cylinders made from shotcrete sampled at the point of discharge from the transit mixer, and on cores extracted from test panels are also given in Table 8. Compressive strength at 28 days of the as-batched shotcrete varied between 41.0 to 52.3 MPa (5,950 to 7,580 psi).

By contrast the strength of cores from in-place shotcrete at 28 days varied from 52.9 to 66.2 MPa (7,670 to 9,600 psi). The higher in-place strengths are attributed primarily to the lower air content of the in-place shotcrete compared to the as-batched shotcrete. Shotcrete was delivered at air contents in the range of about 9 to 11 percent, to produce in-place air contents of about 5 to 7 percent.

Air contents in cores extracted from the hardened in-place shotcrete varied from 3.7 to 8.3 per-

cent. Of more significance with respect to the freeze-thaw durability of the shotcrete was the observation that the spacing factors were generally quite low, being in the range of 0.16 to 0.26 mm (0.006 to 0.010 in.). Specific surface values, with one exception, were in the range of 22.3 to 34.2 mm⁻¹ (570 to 870 in.⁻¹), well within the range of 16 to 32 mm⁻¹ (400 to 800 in.⁻¹), as suggested by Neville⁶ as being required for durable concrete.

The shotcrete placed in 1986 has now been exposed to about 700 cycles of freezing and thawing, and field observations appear to support the results of the laboratory freeze-thaw durability studies. When examined in July 1988, there were no indications of distress from freeze-thaw cycling in any of the shotcrete applied to the berth faces in the Port of Saint John in 1986 or 1987. The performance of this shotcrete will continue to be monitored with time as this same system is planned for continuing use in rehabilitation of the berth faces for many years.

Mechanisms of Shotcrete Failures

A review of case history data submitted in response to the ACI Committee 506 Shotcrete Durability Subcommittee inquiry indicates that most so-called shotcrete failures in external exposure environments do not involve failure of the material itself, but are most often associated with peeling off of sound shotcrete from the substrate to which it was applied. The causes of such failures are many and varied, but include factors such as:

- inadequate preparation of the substrate surface such as dust and microfractured aggregates on chipped concrete surfaces, and clay and dirt on rock surfaces.
- application of a relatively thin layer of shotcrete to non-durable base concrete. The concrete continues to deteriorate behind the shot-

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crete layer from causes such as freeze-thaw cycling or alkali aggregate reactivity, and the shotcrete simply peels off, unless adequately reinforced and anchored with deep anchors.

- failure to provide adequate drainage and pressure relief in applications where substantial water pressures can build up behind the shotcrete lining.
- failure to adequately prepare the face of the existing shotcrete layer by removal of accumulated overspray and/or rebound prior to application of the next layer. This requirement is particularly important for latex modified shotcrete. Water penetrating such a bond plane can severely degrade the bond strength of latex modified shotcrete. In addition, in freezing conditions, ice formation can jack the shotcrete off the substrate.

Schrader and Kaden,³ and McDonald⁹ have all cautioned against the application of relatively impermeable shotcrete to structures where the coating can cause a build-up of either vapor or water pressure in the base concrete. Under such circumstances, the shotcrete coating can enhance saturation of the base concrete. If the shotcrete thickness is insufficient to prevent frost penetration to the base concrete, then resurfacing with shotcrete can actually accelerate deterioration of the structure. In such failures the shotcrete is usually well bonded to the base concrete. The failure actually occurs in behind the bond plane in the base concrete.

Table 6 — Wet and dry mix shotcrete proportions

Mix no.	Shotcrete process	Cement content before gunning		Silica fume content		Water/cement ratio	Steel fiber content	
		lb/yd ³	kg/m ³	lb/yd ³	kg/m ³		lb/yd ³	kg/m ³
1D	Dry	696	413	—	—	0.29	—	—
2D	Dry	608	361	88	52	0.29	—	—
9D*	Dry	608	361	88	52	0.29	101	60
1W	Wet	784	465	—	—	0.35	—	—
2W	Wet	681	404	103	61	0.35	—	—
3W	Wet	681	404	103	61	0.35	101	60

*contained 3 percent by mass of cement shotcrete accelerator.

Recommendations

The recommendations that follow are based on a review of the shotcrete mix proportioning and laboratory physical performance test data presented in this report. It is possible to produce freeze-thaw durable wet and dry process shotcretes in the field, provided the following guidelines are adhered to:

1. The use of aggregates that are susceptible to frost attack should be avoided. If marginal aggregates have to be used in any given application, then the use of smaller Maximum Size Aggregates (MSA) is advisable. For example 20 mm (¾ in.) MSA shotcrete with marginal aggregate is more susceptible to freeze-thaw induced deterioration than 10 or 5 mm (⅜ in. or No. 4) MSA shotcrete.

2. The quality of shotcrete workmanship is crucial, particularly for the dry mix shotcrete process. The in-place shotcrete must be free of excessive voids of incomplete consolidation, laminations, sand lenses, dry spots, entrapped overspray and rebound, subsidence or sloughing tears, or any other defects that lead to excess capillary porosity. Only experienced nozzle men should be

used, who display the ability to consistently produce homogeneous, well-consolidated shotcrete of correct consistency.

3. In proportioning shotcrete mixtures for use in applications where the shotcrete will be subjected to critical saturation at the time of freezing and thawing (such as in locks, dry docks, marine structures, and some dams, canals and dikes in the northern U.S. and Canada) the following general guidelines prevail:

- the shotcrete should have an adequate cement content; lean shotcrete mixtures are often not durable. Minimum cement content in the as-batched shotcrete should be at least 350 kg/m³ (590 lbs./yd³), and preferably exceed 400 kg/m³ (675 lbs/yd³).
- the shotcrete should have a sufficiently low water-cement ratio; at least below 0.45 and preferably below 0.40. In wet mix shotcretes, this may require the use of water-reducing and/or high range water reducing admixtures if excessive total cement contents are to be avoided.

• in wet mix shotcretes, proper air entrainment is considered essential; as much as one-half of the as-batched plastic air content can be lost in the shotcrete application process. Thus it will often be necessary to batch wet mix shotcrete at air contents in the range of 8 to 12 percent (depending on maximum aggregate size) if the in-place shotcrete is to have adequate parameters of the air-void system.

4. If the above shotcrete proportioning and application guidelines are followed, then the in-place shotcrete for use in aggressive

Table 7 — Wet and dry mix shotcrete properties

Mix no.	28-day compressive strength		Plastic air content (percent)	Hardened air content (percent)	Air-void spacing factor		Specific surface		Durability factor at 300 cycles	Durability rating
	psi	MPa			in.	mm	in. ⁻¹	mm ⁻¹		
1D	7,190	49.6	—	5.39	0.011	0.27	467	18.4	97.3	Excellent
2D	7,510	51.8	—	6.00	0.011	0.29	422	16.6	99.2	Excellent
9D	6,080	41.9	—	6.51	0.012	0.31	376	14.8	97.4	Excellent
1W	8,090	55.8	3.8	5.57	0.007	0.17	693	27.3	101.6	Excellent
2W	9,530	65.7	3.7	4.54	0.011	0.28	452	17.8	99.1	Excellent
3W	9,430	65.0	3.8	5.15	0.011	0.27	470	18.5	96.9	Excellent

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Table 8 — Properties of steel fiber reinforced wet mix silica fume shotcrete

Date shot	28-Day compressive strength				Plastic* air content (percent)	Hardened air content (percent)	Specific surface		Spacing factor	
	Cylinder*		Core**				in. ⁻¹	mm ⁻¹	in.	mm
	psi	MPa	psi	MPa						
87-08-24	7,110	49.0	9,090	62.7	10.0	6.8	566	22.3	0.008	0.21
87-06-20	6,100	42.1	8,000	55.2	5.2	—	—	—	—	—
87-06-22	6,760	46.6	8,380	57.8	4.5	3.7	998	39.3	0.006	0.16
86-11-07	6,790	46.8	7,670	52.9	6.6	7.6	627	24.7	0.008	0.20
86-11-07	7,380	50.9	7,740	53.4	5.4	8.3	577	22.7	0.008	0.20
86-10-29	7,580	52.3	9,600	66.2	6.0	5.0	693	27.3	0.008	0.21
86-10-29	7,050	48.6	8,340	57.5	6.5	5.2	869	34.2	0.007	0.17
86-09-10	6,240	43.0	—	—	6.8	4.8	594	23.4	0.010	0.26
86-09-03	5,950	41.0	—	—	7.1	6.3	655	25.8	0.008	0.20

*made from shotcrete discharged from transit mixer, before shooting
 **measured on 100 mm diameter cores extracted from in situ shotcrete
 †measured as shot into air pressure meter base.

freeze-thaw exposure conditions will generally display compressive strengths in excess of 50 MPa (7,250 psi) at 28 days on cores extracted from the in-place shotcrete. However, high compressive strength does not in itself guarantee adequate freeze-thaw durability. While high compressive strength (and low water-cement ratio) help, parameters of the air voids system must be adequate.

5. Solid evidence indicates that a spacing factor \bar{l} greater than the maximum limit of 0.20 mm (0.008 in.) recommended by ACI Committee 201 and the CSA Committee A23.1 for freeze-thaw durable concrete, can be permitted for high quality dry and wet mix shotcretes. At water-cement ratios of 0.40 or less, a spacing factor \bar{l} of as much as 0.30 mm (0.012 in.) can provide adequate freeze-thaw durability. If the water-cement ratio is in the range of 0.40 to 0.50, then \bar{l} should be a maximum of about 0.25 mm (0.010 in.). For water-cement ratios greater than 0.50, the generally recommended maximum limit for \bar{l} of 0.20 mm (0.008 in.) should prevail.

6. It is often difficult to obtain spacing factors as low as 0.20 mm (0.008 in.) in wet mix shotcrete and even more difficult in dry mix shotcrete. By corollary it is difficult to ensure that shotcrete will be freeze-thaw durable in aggressive exposure environments if specifications permit the supply of only 25 or 30 MPa (3,600 or 4,350 psi) shotcrete.

7. Preconstruction testing should be conducted on any project where

the shotcrete is to be subjected to cycles of freezing and thawing in a saturated condition. Such testing should be conducted with the actual materials, equipment and crew proposed for use on the project. The preconstruction testing should aim to prove to the satisfaction of the owner or his representative that:

- the shotcrete materials, equipment and crew are capable of producing sound shotcrete free of excessive defects.
- the water-cement ratio and compressive strength are adequate.
- the air-void content and parameters of the air-void system are adequate.

8. If there is any doubt as to the adequacy of the quality of the in-place shotcrete, then freeze-thaw durability testing to either ASTM C671 or ASTM C666 Procedure A, should be conducted. If the ASTM C666 Procedure A is used, then the severity of the test should be recognized in interpreting the test results. To this end, the Corps of Engineers suggested rating system may be appropriate, rather than a more stringent acceptance criterion.

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Selected for reader interest by the editors.

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