Deterioration and Rehabilitation of Berth Faces in Tidal Zones at the Port of Saint John

by Paul Gilbride, Dudley R. Morgan, and Theodore W. Bremner

Editor's Comments: *This paper was selected, by the editor, for reader interest as a "Shotcrete Classic." It is a shortened version of a paper first published in the CANMET/ACI International Conference on Concrete in Marine Environment in St. Andrews-by-the Sea, New Brunswick, Canada, in 1988. Brief reference is also made to a subsequent paper on the 10-year "Performance of Shotcrete Repairs to Berth Faces at the Port of Saint John" by the same authors published in the CANMET/ACI Odd Gjørv Symposium, held at the same venue in 1996.*

The Port of Saint John is situated at the mouth of the Saint John River on the northeast coast of the Bay of Fundy and is one of the major cargo ports on Canada's east coast. Figure 1 gives a general aerial view of the Port of Saint John. A large percentage of the port's berths are at wharves of concrete construction dating back to the 1920s and 1930s. Due to the prohibitive cost of replacing these older wharves, it was decided to upgrade a number of them that showed signs of berth deterioration from the years of exposure to this harsh environment.

Marine structures in Saint John Harbour are subjected to the world's highest tidal range and to one of the highest number of freezing and thawing cycles per year for a marine environment. Combined with this, the concrete is at a high degree of saturation due to a location famed for rain, fog, windblown salt spray, and a generally high ambient relative humidity. To make matters worse, much of the aggregate used has since been found to be susceptible to alkali-reactivity attack. In view of the severe conditions involved, it is surprising that these early structures have lasted as long as they have and that they can still be upgraded to serve a modern function.

Figure 1: Aerial view of Port of Saint John.

Deterioration Patterns in Berth Faces

The first form of deterioration evident in the berth faces is freezing and thawing damage suffered by the concrete, particularly in a zone about 2 to 3 m in height occurring around midtide. This type of deterioration is well illustrated in Fig. 2. The overall height of the wharf face at low water is approximately 10 m and the tidal range is about 8.5 m.

The zone that suffers the most damage is around the midtide, which is exposed to repeated cycles of wetting and drying and freezing and thawing in a saturated condition. It is estimated that concrete in this zone is subjected to 200 to 300 freezing and thawing cycles per year.

The second problem involves the presence of alkali reactivity in the concrete. These aggregates react with the alkalis released by the hydrating portland cement, causing expansion, cracking, and deterioration of the concrete. The concrete suffers further deterioration due to the leaching of cement passed from cracks caused by expansion. This type of deterioration is prevalent both within and above the tidal range. It acts concomitantly with freezing and thawing attacks to accelerate deterioration of the wharf faces.

In addition to the observed problems of alkali-aggregate reactivity, deterioration attributed to chemical interaction between the concrete and seawater has been observed in the outer 25 mm of the concrete wharf faces. This outer 25 mm layer of concrete has been removed in the wharf restoration process.

Selection of Repair Method

A review was carried out of possible improvements that could be made to the current methods of repair and also of what alternatives were available. In reviewing the shotcreting process, it was learned that in recent years, there has been rapid development in the technology. Through the use of air-entraining and chemical admixtures, steel fiber, and condensed silica fume, shotcrete of higher quality was being produced. More and more of this was being done using the wet-mix shotcrete process as opposed to the dry-mix system. Many of these advances in shotcrete technology have originated in the Scandinavian countries, particularly Norway where shotcreting is done to stabilize rock excavations and in tunneling for hydropower, highway, and railroad construction.[1] Some innovative developments have, however, also taken place in Western Canada.[2]

Besides reviewing the state of the art in shotcreting, the more conventional method of casting a new face behind reusable steel forms was examined. In looking at wet-mix shotcreting versus forming, it was estimated that costs for berth facing repair for either method would be quite similar at approximately $120 to $130 per m^2 or approximately 2% of the replacement cost of a typical $10 million wharf. It was decided to use the wet-mix shotcrete process for the following reasons:

- More versatile; that is, it's not tied to a certain form size and therefore is usable throughout the Port for concrete repair;
- More mobile; this is, less time is required to clear a work area along a berth face to allow for docking of ships;
- Better suited to a small crew; that is, it does not involve such things as use of cranes and handling of forms;
- Relatively low cost to set up; and
- With recent developments in shotcrete technology and an effective quality-control program, it was felt a high-quality repair material could be produced.

Selection of Shotcrete Type

In selecting the shotcrete type to be used on this project, a number of important performance requirements were identified:

- The shotcrete should be capable of being applied in an intertidal zone, where it would be subjected to strong tidal currents soon after application, without becoming washed out or dislodged;
- The shotcrete should be capable of application in layers of up to 120 mm thick in a single pass on a vertical face, without sagging or sloughing;
- The use of shotcrete accelerators in the structural shotcrete face was viewed as undesirable because of the well-known propensity of accelerators to compromise long-term shotcrete quality;
- The selected shotcrete system should be durable to freezing and thawing;
- The selected shotcrete materials should be resistant to alkali-aggregate reaction degradation; and
- The selected reinforcing system should have a good potential for long-term resistance to corrosion-induced deterioration.

Having reviewed all these considerations, it was decided that the requirements of the project could best be met through the use of air-entrained wet-mixture, steel fiber-reinforced silica fume shotcrete.

Repair Procedures

The wharf face is prepared for shotcreting by removal of the existing deteriorated concrete face to a depth of 100 to 150 mm. It has been found that generally at this depth, sound concrete is encountered. The chipping is done using chipping hammers in the 14 to 18 kg size range. The work is done from a mobile hanging staging as well as from a floating barge alongside the berth face.

Upon completion of the chipping, an anchorage system is installed using 20 mm Grade 60 threadbar grouted into drilled 50 mm-diameter holes. The holes are drilled on a 15-degree incline from the horizontal to allow installation of a 1.12 m-long anchor with a 100 mm projection. The grout is a one part sand to one part Type 10 portland cement mixture. After the anchors are installed, a grid of 15 mm rebar is run horizontally and vertically between anchors. The bars are positioned on the anchors to allow for 50 mm of cover on the outer bar. During the shotcreting operation, a 100 x 100 x 9 mm steel plate is fitted on each anchor and secured with a 15 mm-deep hexagonal nut. Anchors are spaced in a grid to allow for a design loading of 78 kN in tension. This would be sufficient to hold the new facing in the event it completely debonded from the existing concrete surface and was subject to full hydrostatic pressure. Anchors are randomly tested in tension up to approximately the yield strength of 115 kN of the bar. A general view of a typical anchor layout is shown in Fig. 3 and 4. Details of the anchor system are given in Fig. 5.

Materials and Mixing Procedures

The mixture proportions for the shotcrete are given in Table 1. The following is a discussion of the materials used.

Silica Fume

In silica fume concrete and shotcrete systems, the calcium hydroxide produced by the hydrating portland cement is largely consumed in the ensuing pozzolanic

Figure 2: Deterioration in intertidal zone of berth face.

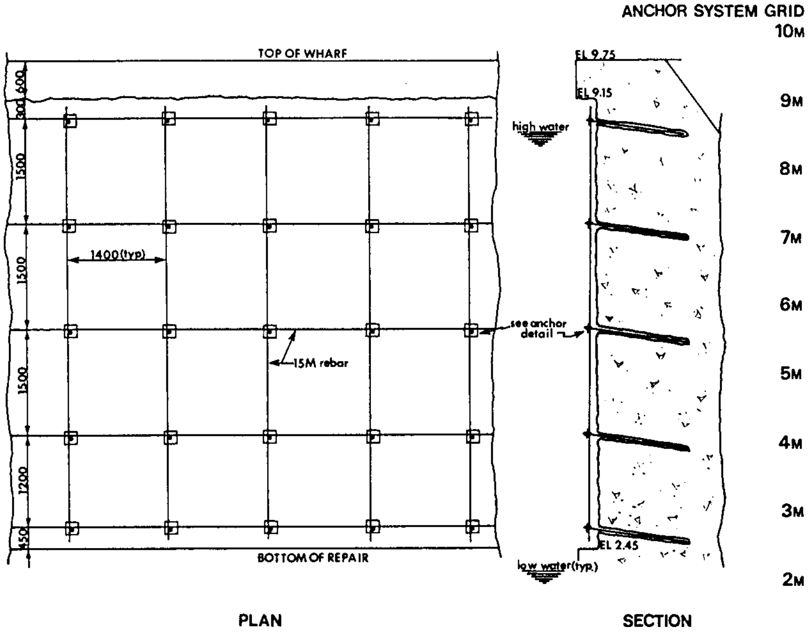


Figure 3: General view of anchor layout used in berth face repair.

Figure 4: Prepared berth face, with anchor system installed, ready for shotcreting.

reactions. This results in a product with a very low permeability and absorption and enhances resistance to deterioration in aggressive environments. Silica fume concretes and shotcretes have also been found to have very low permeability to chloride ion intrusion and enhanced resistance to alkali-aggregate attack.[3,4]

The incorporation of silica fume in shotcrete imparts a number of benefits to the plastic shotcrete. These include:

- Improved adhesion and cohesion and ability to build up greater thickness of shotcrete in a single pass, without having to resort to the use of accelerators;
- Improved resistance to washout when freshly applied shotcrete is subjected to running water or the influences of tidal cycling; and
- Improved economy through reduced rebound and increased rates of productivity.

Chemical Admixtures

Silica fume, having such a high specific surface, has an inherently high water demand when used in concrete and wet-mix shotcrete. This increases the water-cementitious ratio of the mixture quite substantially and is counterproductive in terms of improving properties of the hardened shotcrete such as: volume stability, increased strength, reduced permeability, and increased resistance to chemical attack. To keep the water demand of the mixture under control, it is essential to use appropriate dosages of water-reducing and superplasticizing admixtures.

In this project, a polymer-based water reducer was added at a dosage of 500 ml/100 kg cement. A modified naphthalene sulphonate superplasticizer was added at a dosage of 1750 ml/100 kg cement at the plant, with additional superplasticizer being added at the site as required to maintain the correct workability during the period of shotcrete discharge.

A neutralized vinsol resin air-entraining admixture was added at dosages varying between 130 and 200 ml/100 kg cement. These are higher dosage levels than normally used in conventional air-entrained concretes, but they were found necessary to achieve the required air content in the final in-place fresh shotcrete; that is, with air contents at the plant (after silica fume addition) of about 9 to 11%, actual in-place air contents of 4.5 to 7% were achieved after shooting.

Steel Fiber

Steel fiber is added to shotcrete to improve the ductility, energy absorption (toughness), and impact-resistance characteristics of the shotcrete. Plain shotcrete is vulnerable to thermal and drying shrinkage cracking when applied to existing rock or concrete substrates. Steel fiber helps reduce the amount of cracking and provides residual load-carrying capacity after cracking has occurred.[2]

Two different types of steel fibers have been used on this project: 38 mm-long corrugated steel fibers with an aspect ratio of 42 at dosage levels varying between 60 and 65 kg/m^3 and 30 mm-long hooked-end fibers with an aspect ratio of 60 at a dosage of 60 kg/m^3.

Shotcrete Supply

The wet-mix, silica fume shotcrete was weight batched and mixed in a central mixing plant prior to discharge into a transit mixer. The shotcrete was delivered to the site in 3.5 m^3 loads. At the site, steel fiber was added to the transit mixer together with a superplasticizer and an air-entraining agent. The chemical admixtures were added in sufficient amounts to produce a slump of 75 to 100 mm and air content of 9 to 11% in the mixture prior to shotcreting.

Some entrained air was lost during pumping and shotcreting operations. Similarly, some slump loss was experienced during the period of discharge of the 3.5 m^3 loads. Shotcrete could be applied at slumps as low as 50 mm, with the particular small line pump used. If the slump dropped below this value, then more superplasticizer was added to the shotcrete in the transit mixer.

Shotcrete Application

The shotcrete is applied by a crew of four supervised by a technician. Three of these (nozzleman,

nozzleman's helper, third man) are located on the floating barge while the pump operator and technician are located on the wharf deck. The shotcrete is consolidated by the impact of the high-velocity jet impinging on the wharf face. The other fitting connects to the hose from the accelerator tank and allows addition of accelerator to the mixture when required. The use of the accelerator was minimal and was restricted to isolated areas on the berth face where water was seeping through the concrete. For optimum bond of the shotcrete to the wharf face, the concrete surface should be saturated surface dry at the time of shotcrete application. To make the shotcrete adhere in areas where water was seeping, an accelerator was added at a sufficient dosage to cause almost a flash set in the shotcrete. Such areas received approximately a 50 mm coating of accelerated shotcrete. The location was noted for subsequent drilling of drain holes and then given a finish coat of structural shotcrete without accelerator.

Shotcreting is usually scheduled for the dropping tide to avoid damage by the barge of the freshly placed shotcrete. The outline of the area covered by a load of shotcrete is basically dictated by the tide level and the life of the load of shotcrete. Normally, one load of shotcrete covers a height of about 1.2 m over a length of 27 m. The shotcrete is applied to this area in two lifts over approximately a barge length 9 m at a time. The first lift of 50 mm generally encapsulates the rebar and facilitates setting of the anchor plate in the fresh shotcrete. The second lift of 50 mm covers the steel with approximately an additional 25 mm applied at the anchors to ensure adequate cover on the steel. Figure 6 shows application of the second lift of shotcrete to the berth face.

Localized areas of deterioration resulting in voids of 150 mm or greater are generally filled in stages over successive days. It is the job of the third man on the barge to set the anchor plates, check the depth of the shotcrete, and clean up overspray and rebound that collects on reinforcing steel and adjacent wall surfaces and ledges. Fresh overspray can be incorporated in the work, but if it has started to harden it should not be incorporated into the shotcrete. Rebound—the fraction that contains a high percentage of coarse material—and little fines must always be removed as the shotcrete progresses. It is estimated that approximately 5% material loss is occurring due to rebound.

Upon completion of a section of shotcreting, the face is kept wet for at least three days by means of water-soaker hoses strung along the work. This prevents the shotcrete from drying out between cycles of tidal wetting.

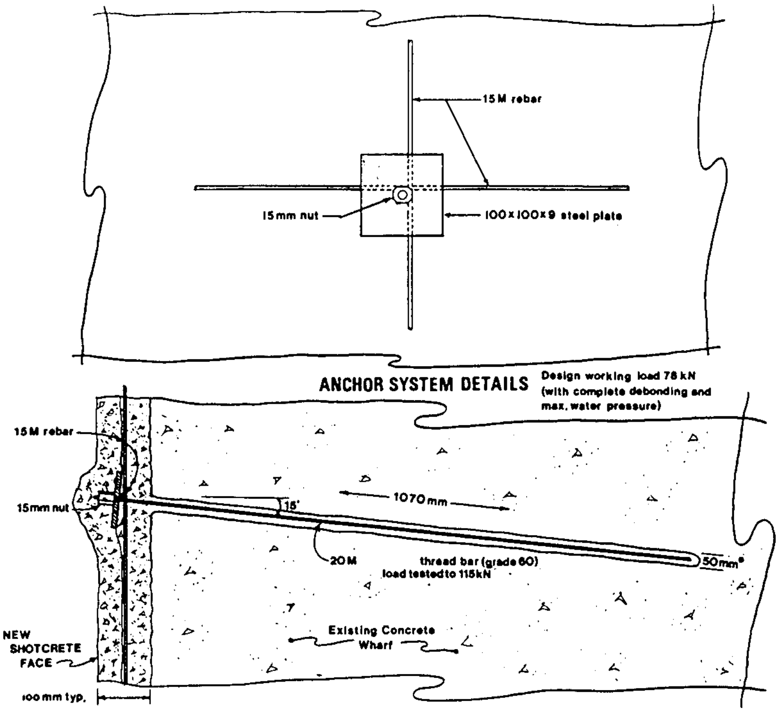


Figure 5: Detail of anchor system used.

Table 1: Wet mix, steel fiber-reinforced silica fume shotcrete mixture design

Material	Material mixture proportions
	kg/m^3
Normal portland cement (Type 10)	400
Silica fume	56
10 mm course aggregate (SSD)	460
Concrete sand (SSD)	1100
Water	180
Water-reducing admixture	2 L
Superplasticizer	7 L
30 mm steel fiber	60
Air-entraining admixture	As required for
Air content (in place)	7 ± 1%
Totals	2265
Slump	80 ± 20 mm
Minimum 28-day compressive strength	40 MPa

Figure 6: View of shotcrete being applied to berth face from floating barge.

Table 2: Results of compressive strength, flexural strength, and ASTM C 1018 toughness index test during regular quality control testing

Date shot	Fiber type	Fiber dosage	Compressive strength			Flexural strength		Toughness Index			
			7 days	28 days	56 days	7 days	28 days	I_5 7 days	I_5 28 days	I_{10} 7 days	I_{10} 28 days
87-06-24	D	60	40.4	49.0	62.7	8.4	9.6	6.2	5.6	12.7	10.1
87-08-20	D	60	37.5	42.1	55.2	3.8	6.9	5.2	6.0	10.0	13.7
87-06-22	D	60	42.1	46.6	57.8	7.4	8.5	5.5	5.5	11.1	9.5
86-11-07	X	65	35.7	46.8	52.9	6.0	8.0	4.3	3.9	8.2	6.3
86-11-07	X	62.5	39.3	50.9	53.4	4.7	8.4	4.5	6.4	8.1	11.0
86-10-29	X	65	34.4	52.3	66.2	6.2	8.1	3.7	3.4	7.5	5.4
86-09-10	X	60	40.9	43.0	—	6.7	7.7	3.2	4.3	4.5	6.3
86-09-03	X	60	35.7	41.0	—	5.7	6.8	3.8	3.9	6.1	5.7
86-07-17	X	60	—	—	—	5.6	9.3	—	—	—	—
86-07-04	X	60	—	—	—	5.0	9.2	—	—	3.1	3.6
86-05-26	X	60	—	—	—	4.0	7.0	4.9	—	9.5	—

Shotcrete Evaluation

A comprehensive preconstruction testing program was undertaken to:

- Evaluate the ability of different local ready-mix concrete suppliers to produce shotcrete conforming to the project specifications;
- Establish time-dependent changes in the properties of the fresh shotcrete during silica fume addition, transport, steel fiber addition, pumping, and shooting;
- Optimize the dosage of air-entraining, water-reducing, and superplasticizing admixtures required to produce the required in-place shotcrete quality;
- Evaluate compressive strength, flexural strength, and toughness value of the hardened shotcrete; and
- Determine the freezing and thawing durability of shotcrete prisms using the ASTM C 666-Procedure A (“Rapid Freezing and Thawing in Water”).

These preconstruction tests indicated that both suppliers could provide wet-mix, steel fiber-reinforced, silica fume shotcrete conforming to the project specifications. In particular, the freezing and thawing durability tests provided relative durability factors from 95 to in excess of 100% after 300 cycles.

The successful ready-mix shotcrete bidder supplied shotcrete to the project throughout the 1986 and 1987 construction seasons (May to October). Regular quality-control testing was conducted throughout the project and included:

- Testing for slump, air content, and 7- and 28-day compressive strengths by the supplier at the batch plant (prior to steel fiber addition);
- Testing after steel fiber addition for slump, air content, compressive and flexural strength, and ASTM C 1018 I_5 and I_{10} toughness index values at 7 and 28 days. Test specimens were prepared by the owner’s forces and tests were conducted by an independent testing laboratory; and
- Extraction of cores from the in-place shotcrete for visual examination of the quality of consolidation of the shotcrete and shotcrete to existing bond. Good quality bond was generally indicated by extracted cores fracturing in the existing concrete interface. Cores were tested for compressive strength at 28 days, boiled absorption, and parameters of the air voids system (air content, specific surface, and spacing factor of the hardened concrete).

Typical results from routine quality-control testing are given in Table 2 and 3.

Compressive and Flexural Strength

Seven- and 28-day compressive strengths on 150 mm-diameter cylinders cast at the job site from shotcrete discharged from the transit mixers typically averaged 37 and 47 MPa, respectively. Cores of 100 mm diameter extracted from the in-place shotcrete and tested at 28 days, by contrast, had compressive strengths on average of about 58 MPa. This substantially greater in-place strength is attributed primarily to the reduced air content of the in-place shotcrete compared with the as-delivered shotcrete. The air content of fresh concrete in the as-cast shotcrete cylinders was typically in the range of 8 to 11%, whereas the air content of shotcrete shot into the air pressure meter base was typically in the range of 4.5 to 7%; that is, some 3 to 4% points of air content are lost as the shotcrete is sprayed and consolidated on the receiving surface.

Table 3: Quality control testing for air content in plastic shotcrete and absorption and parameters of the air voids system in hardened shotcrete

Date shot	Air content in plastic shotcrete, %	Air content in hardened shotcrete, %	Specific surface, mm^3/mm^2	Spacing factor, mm	Absorption, %
87-06-24	10.0	6.8	22.3	0.209	8.3
87-08-20	5.2	—	—	—	5.7
87-06-22	4.5	3.7	39.3	0.162	7.6
86-11-07	6.6	7.6	24.7	0.196	5.1
86-11-07	5.4	8.3	22.3	0.204	3.5
86-10-29	6.0	5.0	27.3	0.211	5.9
86-10-29	6.5	5.2	34.2	0.166	6.9
86-09-10	6.8	4.8	23.4	0.262	—
86-09-10	6.8	4.8	23.4	0.262	—
86-09-03	7.1	6.3	25.8	0.198	—
86-07-17	4.5	3.3	15.6	0.328	—
86-05-26	4.5	2.4	16.8	0.389	—

Flexural strengths of cast shotcrete beams tested in accordance with ASTM C 1018 averaged about 6 and 8 MPa at 7 and 28 days, respectively.

Toughness Index

Seven-day I_5 and I_{10} toughness index values averaged about 4.0 and 6.8, respectively, for the mixtures with the 38 mm-long corrugated steel fiber, and 5.6 and 11.2, respectively, for mixtures with the 30 mm hooked-end steel fibers. Twenty-eight-day I_5 and I_{10} toughness index values averaged about 4.2 and 6.3, respectively, for the mixtures with the 38 mm-long corrugated steel fibers, and 5.7 and 11.2, respectively, for the mixtures with the 30 mm-long hooked-end steel fibers. Clearly, for equivalent fiber content, the higher aspect ratio hooked-end fiber provides higher toughness index values. An appreciation of the relative performance of this wet-mix shotcrete compared to dry-mix steel fiber-reinforced shotcrete and wet-mix steel fiber-reinforced shotcrete, on other projects, can be obtained from reference 3. In short, the overall toughness index can be considered as good.

Freezing and Thawing Durability and Air Void Parameters of Hardened Concrete

Examination of the data in Table 4 shows that the Canadian Standards Association recommendation for a spacing factor not exceeding 0.20 mm will generally be achieved provided the air content of the as-shot shotcrete is kept in the range of 5.5 to 7%. If the air content drops down to 4.5%, then the spacing factors are likely to exceed 0.30 mm.

Table 4: Quality control testing for air content in plastic shotcrete and absorption and parameters of the air void system in hardened shotcrete

Date shot	Air content in plastic shotcrete, %	Air content in hardened shotcrete, %	Specific surface, mm^3/mm^2	Spacing factor, mm	Absorption, %
87-06-24	10.0	6.8	22.3	0.209	8.3
87-08-20	5.2	—	—	—	5.7
87-06-22	4.5	3.7	39.3	0.162	7.6
86-11-07	6.6	7.6	24.7	0.196	5.1
86-11-07	5.4	8.3	22.3	0.204	3.5
86-10-29	6.0	5.0	27.3	0.211	5.9
86-10-29	6.5	5.2	34.2	0.166	6.9
86-09-10	6.8	4.8	23.4	0.262	—
86-09-03	7.1	6.3	25.8	0.198	—
86-07-17	4.5	3.3	15.6	0.328	—
86-05-26	4.5	2.4	16.8	0.389	—

Note: Plastic air content measured as shot into air pressure meter base.

Freezing and thawing tests conducted in accordance with the requirements of ASTM C 666-Procedure A for up to 300 freeze-thaw cycles resulted in relative durability factors ranging from 95 to in excess of 100%. Durability factors in excess of 80% have been considered to represent concrete (or shotcrete) with good freezing and thawing durability.[5]

Shotcrete Performance

In 1996, a paper was published by the same authors[6] reporting on the condition of the shotcrete repairs to the berth faces after up to 10 years of exposure in this harsh environment. Approximately

Figure 7: View of shotcreting in 1995, after 10 years of service with buildup of shotcrete at reinforcing steel to help alleviate restrained drying shrinkage cracks.

200 lineal m of berth face had been repaired with essentially the same shotcrete system every year from 1986 to 1995 (with the exception of 1988 and 1992).

The condition survey revealed that after 2000 cycles of freezing and thawing, the shotcrete was generally in very good condition. Compressive strengths on extracted cores averaged 57 MPa. There was no evidence of frost damage, and while some deficiencies were noted, these were estimated to constitute less than 1% of the total area of berth faces repaired. Most of these deficiencies were related to construction practice and included items such as less than adequate encapsulation of reinforcing bars (leading to localized rebar corrosion) and featheredging of construction joints (leading to localized peeling-type delaminations). Some restrained drying shrinkage cracking was encountered, but much of it had undergone autogenous healing and the conclusion was drawn that "the minor cracking in the shotcrete is not likely to affect the long term performance of the facility."

In summary, the 10-year performance evaluation of the shotcrete repairs demonstrated that overall it was providing excellent durability and the prognosis is that with a small amount of minor maintenance work, the repaired berth faces should provide many more decades of effective performance.

Acknowledgments

This abridged version of the original paper is published with the permission of CANMET/ACI.

References

1. ACI 506.1R-84, "State-of-the-Art Report on Fiber Reinforced Shotcrete," American Concrete Institute, Farmington Hills, Mich., 1984, 13 pp.

2. Morgan, D. R., *Recent Developments in Shotcrete Technology—A Materials Engineering Perspective*, World of Concrete '88, Las Vegas, NV, Feb. 7-11, 1988.

3. Morgan, D. R., *Evaluation of Silica Fume Shotcrete*, CANMET/CSCE International Workshop on Condensed Silica Fume in Concrete, Montreal, Quebec, Canada, May 1987.

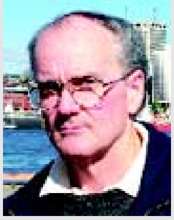
4. Sellevold, E. J., *Condensed Silica Fume in Concrete, A World Review*, CANMET/CSCE International Workshop on Condensed Silica Fume in Concrete, Montreal, Quebec, Canada, May 1987.

5. Schrader, E., and Kaden, R., "Durability of Shotcrete," *Concrete Durability—Katharine and Bryant Mather International Conference*, SP-100, V. 2, J. M. Scanlon, ed., American Concrete Institute, Farmington Hills, Mich., 1987, pp. 1071-1101.

6. Gilbride, P.; Morgan, D. R.; and Bremner, T. W., "Performance of Shotcrete Repairs to the Berth Faces at the Port of St. John," *Odd E. Gjørv Symposium on Concrete for Marine Structures*, Sponsored by CANMET/ACI, Saint Andrews-by-the Sea, New Brunswick, Canada, Aug. 4-9, 1996, pp. 163-174.

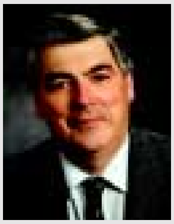
Editor's note

Portions of this article appeared in SP-109, *Concrete in Marine Environment*, the proceedings of an international conference sponsored by the Canada Centre for Energy Technology (CANMET), in association with the American Concrete Institute, U.S. Army Corps of Engineers, The Concrete Institute, and Institute for Research in Construction. This abridged article is published with the permission of the American Concrete Institute.



Paul Gilbride is the principal of Paul J. Gilbride & Associates and an associate of Portha Inc. engineering firms that specialize in marine engineering related to port and harbor infrastructure design and rehabilitation. He is a civil engineer with over 30 years' experience working on port-related projects. He is a member of ASA.

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



ACI Fellow Theodore W. Bremner, PEng, PhD, is an Honorary Research Professor of Civil Engineering at the University of New Brunswick, New Brunswick, Canada, and is Past President of the Atlantic Chapter of ACI. He received the ACI Cedric Willson Award for Research on Lightweight Concrete and is past Chair of ACI Committee 122, Energy Conservation, and 213, Lightweight Aggregate and Concrete.