

Use of Dry-Mix Shotcrete to Repair a Lighthouse Structure

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This paper presents a description of the repair work carried out in 1996 at the Haut-Fond Prince lighthouse structure located in the St. Lawrence River, 8 km (5 mi) from the coast of Tadoussac, Quebec, Canada. The damaged section of the structure in the tidal zone was repaired using dry-mix shotcrete. Due to the particular field conditions (freezing-and-thawing cycles, ice erosion and impact, submersion of the repair zones only minutes after the application of shotcrete, etc.), the mixture used contained high early strength cement, silica fume, steel fibers, a liquid air-entraining admixture, and a powdered set-accelerator admixture. Removal of deteriorated concrete, preparation of the surface, replacement of the reinforcement, specifications for the shotcrete produced, as well as the application procedures are described in this article. A certification session was held to verify the skills of the nozzlemen. Only those qualified were authorized to apply shotcrete on the structure.

Introduction

This article describes the repair work carried out at the Haut-Fond Prince structure located in the St. Lawrence River at the confluence of the Saguenay and the St. Lawrence rivers, 8 km (5 mi) from the coast of Tadoussac, Quebec, Canada (Fig. 1).

The structure foundation of the Haut-Fond Prince lighthouse was constructed in 1962 in a dry dock at Lauzon near Quebec City and towed to the site. The upper part of the structure was built on the spot and was finished in 1964. The diameter of the structure ranges from 30 m (120 ft) at the base to approximately 20 m (80 ft) for the upper part.

Situated in the tidal zone of the river, the repaired section of the structure showed damage on the steel laps and the concrete forming the pier base. This damage was caused by the high pressure of ice grinding against the surface. The covering made of steel plates 12 mm (0.5 in.) thick was deteriorated and the concrete was damaged by ocean currents, ice movement, and freezing-and-thawing cycles. Some sections of the concrete were deteriorated up to 1.5 m (5 ft) deep. Figure 2 shows a section of the Haut-Fond Prince Lighthouse in its deteriorated state before its rehabilitation.

For both technical and economic reasons, the Canadian Coast Guard, owner of the lighthouse, chose shotcrete to repair the structure. The repair work consisted of removing the damaged steel plates, removing the deteriorated concrete, and applying shotcrete to reinstate the structural integrity of the lighthouse. The repair work was carried out during Fall 1996.

Design of the dry-mix shotcrete

Technical demands and severe exposure conditions for the shotcrete led the designer (S.E.M. Inc.) to develop a dry-mix shotcrete especially adapted for this project. As the repair sections were located in the tidal zone, several constraints had to be taken into account, such as the washout of the surface caused by ocean currents on the structure and the submergence of the concrete in salt water only a few minutes after its application, the water temperature (approximately 4 C [39 F]), and, owing to the tide cycles, short working periods to complete the repair work. The dry-mix process was required because of the restricted access to the repair site. All the shotcreting equipment was secured on a barge that was moored adjacent to the structure.

Table 1 presents the proportions of the different components of the dry-mix shotcrete. To provide better protection against washout of the shotcrete at the surface, Type 30 high-early-strength portland cement and a powdered set-accelerator



Figure 1: Location of the lighthouse structure in the St. Lawrence River.

admixture were used to obtain a high initial strength within a short period of time.

Adding silica fume produces a shotcrete that is better able to resist chloride penetration and therefore provides better protection against corrosion of the steel reinforcing bars. Silica fume is also used in shotcrete for rheological purposes.¹ It increases the paste viscosity, which decreases the amount of the rebound and increases the maximum build-up thickness achievable.²⁻⁴

To reduce the damage done by salt water penetrating into cracks, 30 mm (1.2 in.) long hooked steel fibers were used to provide better control of any cracking that occurs as a result of stresses caused by ice movement against the structure.

A powdered set-accelerator admixture was added to the mixture to provide enhanced resistance to washout of the shotcrete on the structure because the fresh shotcrete was typically in contact with sea water within 20 min after the completion of shooting operations. This mechanical resistance is quickly achieved when the set-accelerator admixture dosage is adequate and the concrete temperature at the outlet of the nozzle is higher than 25 C (77 F). To reach this temperature, the dry materials were kept in the hold of the barge where the temperature was maintained at approximately 30 C (86 F). In addition, hot water was used during shooting to produce shotcrete with an adequate temperature in place.

Because of the severe freezing-and-thawing conditions, a liquid air-entraining admixture was added to the mixing water to produce a frost-resistant shotcrete with an air-void spacing factor lower than 300 µm (0.012 in.).

Nozzlemanship certification

In the specifications produced by S.E.M. Inc., the nozzle men proposed by the contractor for the project had to possess the necessary skills to properly apply the shotcrete. To verify such skills, a certification session was held a few weeks before the repair work commenced.

During the certification session, the nozzle men shot the same dry-mix shotcrete proposed for use in the repair work into wood panels with steel reinforcing bars. Other skill parameters analyzed during the certification session were nozzling technique, distance, and angle of the nozzle from the receiving surface, and consistency of the freshly applied shotcrete mixture. A few days later, the shotcrete panels were cored and sawed to evaluate the following characteristics:

Reinforcing bar encasement: The evaluation of the reinforcing bar encasement was based on the "Core Grade System" in ACI 506.2-95.

Homogeneity of the shotcrete: Any shotcrete surface of 25 x 25 mm (1 x 1 in.) on the three sawed faces of the panel had to include visible aggregate of nominal diameter of 2.5 mm (0.1 in.) (the first



Figure 2: View of the structure before the repair work.

20 mm [0.80 in.] from the bottom of the wood panel was not considered in this evaluation because of coarse aggregate rebound in the first bedding layer of the shotcrete).

Presence of major voids:

A maximum allowable area of voids was fixed at 150 mm² (0.23 in.²) on the three sawed faces of the panel.

Compressive strength: Performed on three cores at 7 days according to ASTM C 42: minimum of 30 MPa (4350 psi).

Air void spacing factor: Maximum of 300 µm (0.012 in.) according to ASTM C 457.

To be recognized as a certified nozzleman, the craftsman had to succeed in every category listed above. The three nozzle men proposed by the contractor were qualified.

Demolition and Preparation of the Surface

At first, the repair work consisted of preparing the surface of the structure to make it suitable for application of shotcrete. The steel facing plates



Figure 3: Removing deteriorated concrete.

Table 1: Dry-shotcrete mixture composition

Component	Percentage of dry materials by mass, %
Type 30 cement	20.0
Silica fume	2.5
Sand (0 to 5 mm [0 to 0.2 in.])	61.0
Coarse aggregates (2.5 to 10 mm [0.1 to 0.4 in.])	14.8
Set-accelerator	1.0
Steel fibers	1.7

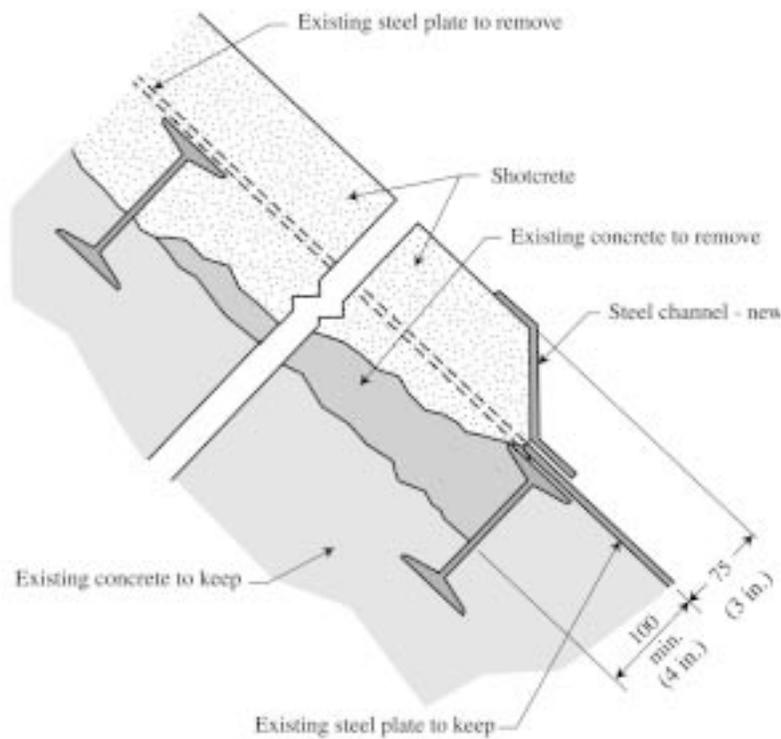


Figure 4: Details of the repair work.

were removed and afterwards, the contractor used pneumatic chipping equipment to remove damaged concrete (Fig. 3). The equipment mass was limited to 27 kg (59.5 lbs) to prevent damage to the concrete forming the shotcreting surface. Heavier tools could have induced additional cracks in the concrete base of the structure, which could have adversely affected the quality of bond between the old concrete and the shotcrete.

The specifications required the removal of the deteriorated concrete until sound concrete was exposed. The minimum demolition depth was fixed at 100 mm (4 in.) from the surface of the

structure to ensure a sufficient shotcrete thickness to obtain an adequate anchorage of the shotcrete to the structure. At different places, concrete deterioration was observed from as much as 1 to 1.5 m (3.3 to 4.9 ft) deep.

Connecting steel frames had to be replaced due to their state of deterioration; therefore, steel bars were welded to the beams to provide suitable anchorage for the shotcrete.

Figure 4 illustrates the detailed surface preparation. A new steel channel was installed on the perimeter of the repair zone. This was first used as a framework for the shotcreting operations, then later kept as protection against ice pressure due to the angle of the channel.

Shotcreting Operations

The shotcreting operations were subject to a variety of different constraints, such as tidal cycles limiting the shotcreting period, the use of an inflatable zodiac to carry the nozzleman and his helper, and the equipment being kept on the barge attached to the structure—all of which made communication between the nozzleman and the gun operator difficult.

The shotcrete gun used for the project was a barrel type gun (Aliva 240-5) with a 50 mm (2 in.) diameter and 150 m (490 ft) long hose to cover the distance between the structure and the barge. The dry materials [supplied in 1000 kg (2200 lb) bags], as well as potable water, were kept at approximately 25 C (77 F) on the barge. This high temperature was important to properly activate the powdered set-accelerator admixture premixed with the other dry materials (cement, silica fume, and aggregates). A liquid air-entraining admixture was added to the mixing water at a dosage of 20 mL/L (2% solution) of water.

The shotcreting work was completed in sectors according to the tide levels because, at the highest tides, the repair zone was completely submerged. As soon as the tide fell, a first coat of shotcrete was applied into the largest cavities [over 300 mm (12 in.) deep]. Afterwards, when the tide was at its lowest phase, the shotcrete was applied from the bottom to the top of the repair zone. Because of the careful design of the shotcrete mixture, only one pass of shotcrete was necessary to fill the whole repair zone, and this subsequently avoided the formation of cold joints between passes.

Table 2: Test results for hardened shotcrete

Sample no.	Type of curing	Compressive strength at 7 days, (MPa)*	Spacing factor, (µm)	Specific surface, (mm ⁻¹)	Scaling losses, (kg/m ²)†
1	On-site conditions	24.6	—	—	—
1	At 23 C (73.4 F) & 100% relative humidity	30.0	—	—	—
2	On-site conditions	39.1	200	35.8	1.53
2	At 23 C (73.4 F) & 100% relative humidity	38.1	—	—	—

— : Test not performed.

*Average value of three measurements.

†After 47 cycles.

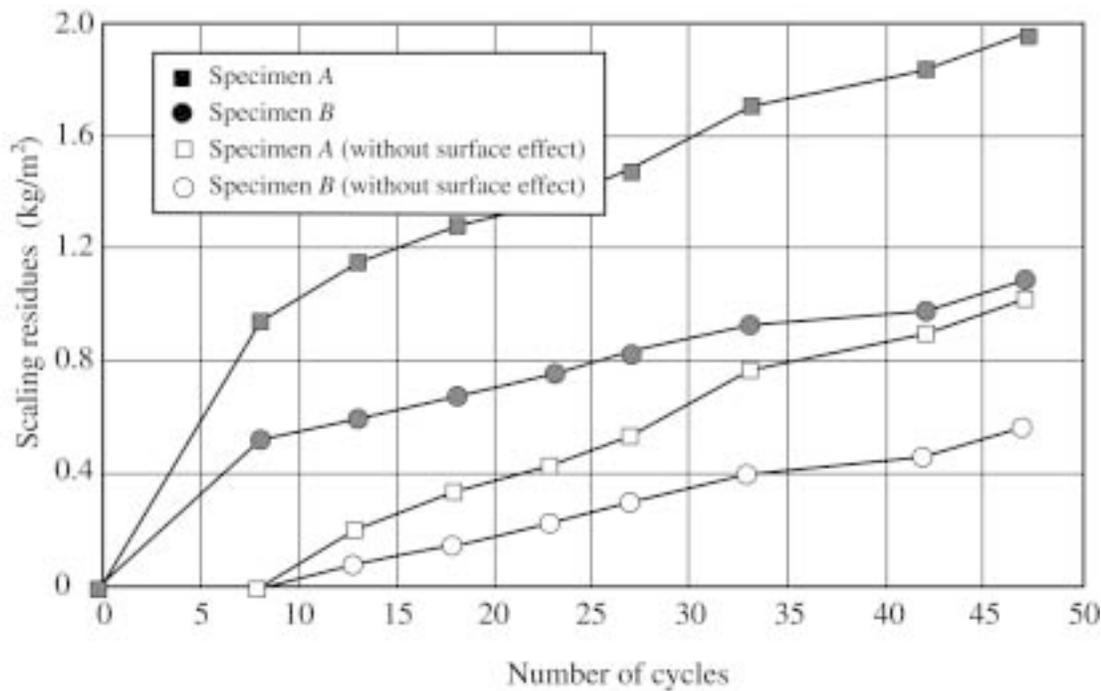


Figure 5: Scaling losses with and without the first freezing-and-thawing cycles (ASTM C 672).

At the end of the shift or between two repair sectors, a construction joint was sometimes necessary. To enhance the mechanical anchorage between the new shotcrete and the shotcrete applied in the previous shift, steel stirrups were installed, which were properly covered with shotcrete. When anchorages were installed between two layers of shotcrete, the minimum upper shotcrete thickness was fixed at 200 mm (8 in.).

Before each shotcrete application, the old concrete surfaces to be repaired were washed with a pressurized water-jet [potable water at 1400 kPa (200 psi) minimum]. This operation aimed to remove seaweed and other impurities, as well as salt water, which could adversely affect the bond between the shotcrete and the substrate concrete.

Five sessions of shooting were necessary to fill the 16 m³ (20.9 yd³) repair zone. The contractor shot almost 23 m³ (30 yd³) of concrete, which means a loss of approximately 44% of the as-batched material due to rebound and other causes. Such a percentage of loss is relatively high but is considered acceptable in these particularly onerous field conditions.

Quality Control Program

Taking into account the particular field conditions, only two test samples were made during the repair project: one at the beginning, and one at the end. For each sample, two panels were filled [400 x 400 x 125 mm (16 x 16 x 5 in.)] with shotcrete. Two different curing procedures were utilized for each panel. One panel was cured at 23 C (73.4 F) under a damp, synthetic membrane and the other panel was stored under field conditions (ambient air) so as to represent the curing conditions of the

on-site repair material as closely as possible.

The tests performed on hardened shotcrete were compressive strength at 7 days (ASTM C 42 with two different curing procedures), scaling resistance in the presence of deicing chemicals (ASTM C 672), and measurements of the characteristics of the air-void system (ASTM C 457).

Test Results

The test results are presented in Table 2. According to the specifications, the minimum 7-day compressive strength of the shotcrete specimens (field conditions curing) was fixed at 20 MPa (2900 psi). Results obtained from both series of tests are higher than 20 MPa [25 and 39 MPa (3625 and 5656 psi)]. In the case of compressive strength tests at 7 days performed on specimens cured at



Figure 6: View of the structure one year after the repair work.

23 C (73.4 F) and 100% relative humidity, the minimum strength required was 30 MPa (4350 psi). Results indicate that both series of tests met the specifications with results of 30 and 38 MPa (4350 and 5510 psi).

Scaling resistance tests were performed only on specimens from the second sample. The surface of the specimen was gun-finished without any curing to represent, as closely as possible, the shotcrete applied to the structure. It should be noted, however, that the shotcrete on the structure is subjected to seawater curing from the tidal cycles.

The scaling test results are presented in Table 2 and the scaling loss curves are presented in Fig. 5. The results show a rapid loss in mass during the first freezing-and-thawing cycles. This surface deterioration is probably due to the lack of curing and the gun-finish surface of the shotcrete specimens. Figure 5 also shows the scaling losses without the effect of the first freezing-and-thawing cycles. It can be seen that the shotcrete produced for the repair project is durable in terms of scaling resistance.⁴

The specimens for the determination of the air-void system (ASTM C 457) were taken from the same panel as the scaling resistance test specimens (on-site conditions; second sample). The measured air-void spacing factor is 200 μm (0.008 in.), which meets the requirement of the specifications [maximum of 300 μm (0.012 in.)]. Also, the specific surface measured [35.8 mm^{-1} (909 in.^{-1})] indicates that the air-void system is formed of small air bubbles that should provide good frost resistance.

Conclusions

Four years after construction, a visual examination of the structure was performed to evaluate the behavior of the repair. The shotcrete used as a repair material showed excellent resistance to damage from freezing-and-thawing cycles, erosion, and impact from ice (Fig. 6). It is believed that the design and supply of a well-adapted shotcrete mixture, according to this repair project specification, and the quality work performed by the shotcrete crew are responsible for the success of this rehabilitation.

It is hoped that this article will promote the use of shotcrete for the rehabilitation of damaged civil structures, particularly when field conditions are not suitable for the use of cast-in-place concrete.

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Pierre Lacombe completed a master's thesis in concrete technology at Laval University in 1996. He worked for 2 years as a research engineer for the Industrial Chair on Shotcrete and Concrete Repairs at Laval University before joining the Service d'Expertise en Matériaux (S.E.M.) Inc., in July 1998. He has been working on numerous projects using shotcrete and other special concretes. He is a member of ASA's Underground and Certification/Education committees as well as ACI Committee C 660 (Certification of Shotcrete Nozzelman), ACI Committee 506 UG (Shotcrete for underground support) and 506 F (fiber reinforced shotcrete).

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