State-of-the-Art Specifications for Shotcrete Rehabilitation Projects

by Jean-François Dufour, Simon Reny, and Daniel Vézina

The Ministry of Transportation of Quebec's (MTQ's) shotcrete specification document has evolved over the 40 years since it was first introduced and has changed dramatically over the past 10 years. Today, this specification for shotcrete rehabilitation remains a source document (mostly when durability is the leading parameter) for a large number of major authorities/owners and engineering firms in the Province of Quebec, Canada.[1,2]

MTQ's Engineering Structural Department, together with other industrial partners—government authorities, cement producers, shotcrete manufacturers, admixture producers, and contractors—has been involved in Laval University's Industrial Chair on Shotcrete and Concrete Repairs since 1995.[3] During these years, this Industrial Chair has worked on various applied research projects covering a wide variety of dry- and wet-mix shotcrete topics such as durability of shotcrete,[4-6] fundamentals of shotcrete, shotcrete rheology (rebound, build-up, aggregate gradation, and reinforcing bar encapsulation),[7] surface preparation, mixture designs, finishing, curing, and investigation of various powder and liquid admixtures.

As a result of the MTQ staff's active participation and involvement, they have been able to put their research findings to practice. Combined with their experience in the field, they have been adapting and updating their concrete rehabilitation specification documents almost yearly. In addition, they follow the latest cutting-edge technology in an effort to improve the quality of repairs and practices in the field.

This article provides a summary of MTQ's shotcrete performance specification and focuses on the use of shotcrete for rehabilitation of deteriorated concrete structures. It can also be of value for any other type of shotcrete in civil applications, such as slope stabilization and new construction.

Method Selection—Dry-Mix Versus Wet-Mix

MTQ's shotcrete performance specification treats both dry- and wet-mix processes as methods of placing concrete and recommends which process is best suited for each application. It leaves the ultimate decision, however, to the contractor. The rational is that both methods offer similar performance. The only limitation is that MTQ does not allow wet-mix shotcrete to be used in an overhead orientation. In fact, MTQ will not even recognize ACI certification for overhead wet-mix applications. MTQ has taken this stand because, in most cases, overhead wet-mix applications require the use of accelerators to avoid fallouts. Recent MTQ/Industrial Chair research has indicated that most accelerators available in the Quebec market have a negative effect on shotcrete rheology and long-term durability.[8]

Although this specification is performance based, each process demands a specific mixture design and material requirements. Durability and structural behavior remain the leading parameters when rehabilitated structures are exposed to extreme freezing-and-thawing cycles in the presence of deicing salts. All rehabilitation projects throughout the province require mixture design submittals, technical data sheets, and raw material documentation for approval.

Requirements for both dry- and wet-mix processes are as follows:

- All aggregate must comply with Canadian Standards CSA A23.1/A23.2, which includes an alkali-aggregate reaction evaluation;
- Aggregate gradations must comply with ACI 506R, "Guide to Shotcrete," Gradation No. 2;[8]
- Synthetic fibers must be made of polypropylene, have a tensile strength of 40,000 to 60,000 psi (275 to 415 MPa), measure 1/2 to 3/4 in. (12 to 20 mm) in length, and must be hydrophobic (no water absorption) with a density between 0.9 and 0.92;
- Reports of the air-void distribution characteristics are required for each mixture submittal; and
- Mixing water must be clean and free from substances that may be injurious to concrete or steel.

Dry-Mix Process

- Only aluminate-based, rather than carbonate-based, set accelerators in powder form are approved for application on MTQ projects.[5]

They may only be used in specific situations such as cold temperature applications (over 41 °F [5 °C]) or when traffic lanes need to be reopened quickly to withstand structure vibration. Set accelerators can only be used when prepackaged in ISO-registered manufacturing facilities. They are prohibited from volumetric batching systems; and

- Blended portland cements or Type HE (Type 3) must comply with Canadian standard CAN/CSA A3000-03.

In addition to these performance requirements, one of the most important performance criteria for durability remains the determination of air-void distribution as per ASTM C 457. The in-place, hardened shotcrete requires an average air-void spacing factor of under 0.0118 in. (300 µm), with no individual results over 0.0125 in. (320 µm).

Figures 1 and 2 illustrate air entrained versus non air-entrained dry-mix shotcrete microstructures, and Figures 3 and 4 represent the corresponding deicing salt scaling performance[4] as per ASTM C 672. These photos demonstrate that air entrainment in dry-mix shotcrete offers increased durability performance when shotcrete repairs are exposed to freezing and thawing in the presence of deicing salts. The industry standards limit salt scaling surface loss to a maximum of 0.2 lb/ft^2 (1 kg/m^2).

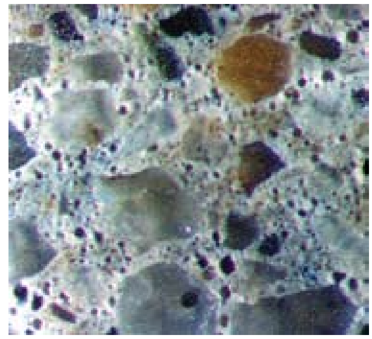

Fig. 1: Air-entrained shotcrete microstructure; spacing factor: 0.004 in. (101 µm) (60× magnification)

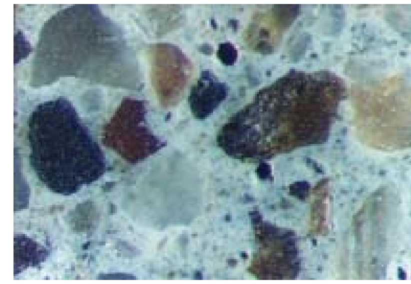

Fig. 2: Non air-entrained shotcrete microstructure spacing factor: 0.016 in. (415 µm) (60× magnification)

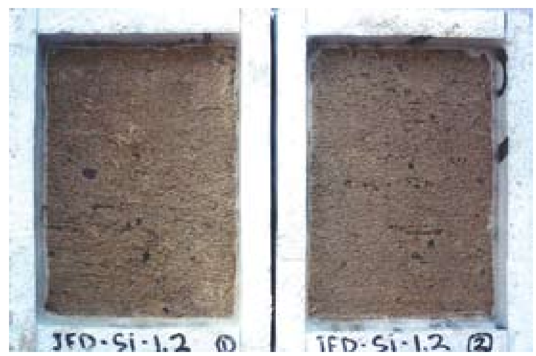

Fig. 3: Resistance to deicing salt scaling—air-entrained; surface loss: 0.23 lb/ft^2 (0.11 kg/m^2)

Fig. 4: Resistance to deicing salt scaling—non air-entrained; surface loss: 1.8 lb/ft^2 (8.81 kg/m^2)

Shotcrete Material Suppliers

Material may either be supplied in prepackaged bags of 66 or 2205 lb (30 or 1000 kg) bulk bags from ISO-registered manufacturing facilities, or by volumetric batching systems such as mobile truck mixers. In the case of mobile mixers, suppliers must be BNQ[10] certified to be approved for MTQ projects.

Shotcrete Equipment

The specification documents state that dry-mix shotcrete equipment must meet ACI 506R, "Guide to Shotcrete."[9] The documents also specify the use of a predampener or hydronozzle. As shown in Figure 5, a hydronozzle consists of a special prewetting and mixing nozzle with a water ring inserted approximately 10 ft (3 m) from the nozzle tip, or premixing nozzle. This type of nozzle produces longer mixing action, which helps to reduce dust and rebound when predampeners are not available.

Water-booster pumps are also specified to deliver consistent water pressure at the water ring. Water pressure at the water ring must exceed the material conveying hose pressure by at least 15 psi (100 kPa).

Fig. 5: Hydronozzle (water ring inserted 10 ft [3 m] from nozzle tip)

Wet-Mix Process

- Set time accelerators are not approved, as recent research findings indicate that most accelerators available in the Quebec market have a negative effect on shotcrete rheology and long term durability;[8] and

Table 1: MTQ Dry-Mix Shotcrete Performance Requirements

Minimum 28 day compressive strength, psi (MPa)	Minimum weight of cement, lb/yd³ (kg/m³)		Maximum water-cementitious material ratio*	Minimum proportion by weight of 3/8 in. (10 mm) aggregate, %	Air content (plastic and hardened states), %	Minimum weight of synthetic fiber, lb/yd³ (kg/m³)
	Type GUb-SF (Type 1 with silica fume)	Type HE (Type 3)				
5000 (35)	760 (450)	775 (460)	Based on consistency† (~0.40)	10	3.5 to 7.0	1.5 (0.9)

* Water-cementitious material ratio is not verified, given the nature of dry-mix shotcrete.

† Plastic consistency is evaluated and monitored (refer to Shotcrete Placement section).

Table 2: MTQ Wet-Mix Shotcrete Performance Requirements

Minimum 28-day compressive strength, psi (MPa)	Minimum weight of cement,* lb/yd³ (kg/m³)	Maximum water-cementitious material ratio	Minimum proportion by weight of 3/8 in. (10 mm) aggregate, %	Air content,† %	Slump,‡ in. (mm)	Minimum weight of synthetic fiber, lb/yd³ (kg/m³)
5000 (35)	690 (410)	0.40	25	10 to 15	4 ± 1 (100 ± 30)	1.5 (0.9)

* Binary Type GUb-SF (Type 1 with silica fume), Ternary Types GUb-F/SF (Type 1 with silica fume and fly ash), and GUb-S/SF (Type 1 with silica fume and slag).

† Air content is measured after the addition of high-range water-reducing admixture, if required, before pumping.

‡ Slump is measured after the addition of high-range water-reducing admixture. The tolerance specified is noted for quality control purposes only.

- Blended portland cements have to comply with the Canadian standard CAN/CSA A3000-03.

As with the dry-mix process, one of the most important performance criteria in wet-mix shotcrete is the determination of the air-void distribution as per ASTM C 457 (refer to Table 1). As presented in Table 2, the concept of a high initial volume of air[11] is used to ensure proper air-void distribution of the in-place wet-mix shotcrete. Therefore, the air content of the fresh concrete (before pumping) is targeted between 10 to 15%. The hardened shotcrete requires an average air-void spacing factor of under 0.009 in. (230 μm), with no individual results over 0.01 in. (260 μm).

Concrete/Shotcrete Material Suppliers

Concrete plants, like mobile truck mixers, must be BNQ[9] certified to be approved for MTQ projects.

Shotcrete Equipment

The specification documents state that wet-mix shotcrete equipment must meet ACI 506R, "Guide to Shotcrete."[9]

Concrete Demolition

Concrete structure rehabilitation requires proper removal of deteriorated concrete to get a sound concrete substrate before the surface preparation takes place. Qualified personnel determine the damaged area by sounding the deteriorated concrete to mark surfaces. To prevent further damage to the sound concrete and to ensure long-term performance of the repair, MTQ requires the following equipment for partial demolition:

- Pneumatic jackhammers
  - ♦ Maximum weight of 35 or 65 lb (15 or 30 kg) to remove the first layer of concrete down to the first row of steel reinforcing bar;
  - ♦ Maximum weight of 15 or 35 lb (7 or 15 kg) to remove concrete under or on the side of the steel reinforcing bar;
  - ♦ For thin or elongated structural elements (beams, columns, and diaphragms), use a maximum weight of 35 lb (15 kg) to remove the first layer of concrete down to the first row of steel reinforcing bar. Use a maximum weight of 15 lb (7 kg) to remove concrete under or on the side of the steel reinforcing bar;
  - ♦ 60 joule or less hydraulic jackhammers can be used to replace 65 lb (30 kg) pneumatic ones; and
  - ♦ The use of 200 joule jackhammers can be accepted for demolition more than 17.5 in. (450 mm) deep on massive structural elements like abutments, piles, or thick slabs.
- Hydrodemolition is the preferred concrete demolition method, as it is most effective in preventing the concrete substrate from damage such as microcracking.[12] It is specified that the contractor conduct representative testing before the project begins to calibrate the pressure of the equipment and to obtain desired results.

Any concrete sections to be repaired must be saw cut (feather edging is prohibited). The saw cut perimeter exposes the repair area and separates it from sound concrete. It also determines the minimum thickness of the repair. The minimum depth of the saw cut must be 3/4 in. (20 mm). If the concrete cover is less than expected, the surface profile of the repair is increased from the structure's original profile. If reinforcing steel is damaged during concrete demolition, it must be replaced.

MTQ also specifies a minimum of 1 in. (25 mm) clearance behind the exposed reinforcing steel. This eliminates any chloride-contaminated concrete from having contact with the reinforcing steel and also provides additional mechanical anchoring of the new repair material.

Surface Preparation

Recent research has demonstrated that bond strength between the concrete substrate and concrete repair (whether it is shot or cast in place) is directly related to the quality of the surface preparation.[12] Good surface preparation requires correct concrete demolition practices and properly cleaned surfaces.

MTQ specifies, in its documents, that any products of corrosion covering the reinforcing steel must be removed completely, and that epoxy-coated reinforcing bar must be cleaned by removing all delaminated epoxy.

It also specifies that all exposed concrete surfaces and shotcrete construction joints must be cleaned with a high-pressure water blast (see the following details) or with wet sandblasting (dry sandblasting can be a safety hazard in some areas). This statement does not apply in the case of the hydrodemolition surface preparation method because this method provides the same result.

It is important to note that the MTQ differentiates between high-pressure water blasting and normal-pressure water washing. Although the high-pressure water blasting characteristics are not detailed in the MTQ specification, they are considered as effective as wet sandblasting. Normal high-pressure water blasting requirements are defined as follows:

- Pressure: 2200 psi (15 MPa);
- Flow: 5.3 gal./min. (20 L/min.);
- Application: Circular nozzle jet motion; and
- Shooting distance: 6 to 8 in. (150 to 200 mm) from the receiving surface.

These (normal) pressure water blasting requirements are mandatory for the last cleaning procedure even when hydrodemolition is used. Although this procedure may seem redundant, it is a crucial step to ensure good quality bond between the substrate and the shotcrete repair by removing any microfractured concrete, dust particles, debris, and loose sand.

Fig. 6: Mesh installation—Île-aux-Tourtres Bridge

In addition to the cleaning procedures, MTQ specifies that adequate prewetting of the concrete substrate be performed before shotcreting. Concrete substrates should be in a saturated surface-dry (SSD) condition immediately prior to the shotcrete application.

Mesh Installation

Although the type of welded wire mesh specified in MTQ documents does not serve any structural purpose, it is used mainly to minimize cracking due to drying shrinkage and thermo-volumetric deformation. The use of mesh also provides additional mechanical anchorage during shotcrete application (Fig. 6).

The specification calls for the following welded wire mesh requirements:

- Plain welded wire connected mesh;
- Galvanized (ASTM A 641, Clause 3);
- Meets CSA G30.5 or ASTM A 185, identified as W1.4 2 x 2; and
- Dimension criteria:
    - Spacing: 2 x 2 in. (50 x 50 mm); and
    - Gauge: 0.134 in. (3.5 mm);

The welded wire mesh must be installed at a minimum of 1 in. (25 mm) from the desired repair profile and must be installed in accordance with the concrete surface cover specified by the engineer. Guide wires (or other means) are therefore recommended to obtain the profile requirements.

During its installation, both the mesh and reinforcing bar must be anchored and attached correctly to avoid movement or vibration during shotcrete application. Otherwise, the energy produced may adversely affect the bond of freshly applied shotcrete to the reinforcing and adjacent substrate, particularly for overhead surfaces.

The specification requires that both the mesh and reinforcing bar must be attached to structural anchor bolts spaced at a regular pattern of 16 in. (400 mm) center to center using galvanized ties. Bracing must be verified before shotcrete application. Additional details on structural anchor bolts and installation procedures can be found in MTQ's documents but are not covered in this paper.

Fig. 7: Portable penetrometer measuring plastic dry-mix shotcrete consistency

Shotcrete Placement

Before the inception of the ACI Shotcrete Nozzleman Certification Program, MTQ had designed its own certification program. Since 2001, they have required that any individual applying shotcrete must be certified by the American Concrete Institute as outlined in ACI Certification Publication CP-60. MTQ's amendments to the existing ACI Shotcrete Nozzleman Certification Program are as follows:

- Certification for the wet-mix process in the overhead position is not required because MTQ does not allow the wet-mix process for overhead shotcrete applications; and
- The certification is only valid for 3 years rather than the 5 years stated in the ACI Committee C 660, Shotcrete Nozzleman Certification, program policies.

Recent research programs related to the rheology of dry-mix shotcrete indicate that concrete shot at its "wettest stable consistency" will provide good reinforcing bar encapsulation when proper craftsmanship is followed.[9,13] In most cases, "wet" consistencies correspond to the water-cementitious material ratios (*w/cm*) varying from 0.40 to 0.45, which is controlled by the nozzleman. Physical properties of the in-place material, such as compressive strength, shrinkage, permeability, and others, are all related to the *w/cm*, for a given mixture design.

The specification documents require that dry-mix shotcrete be applied at a sufficiently "wet" consistency, enough to achieve complete reinforcing bar encapsulation, to provide reduced dust and rebound levels, and increased finishability. The *w/cm*, however, should be minimized to avoid sloughing, as a high *w/cm* will adversely affect both plastic and hardened shotcrete properties.

Because the correct consistency at which the shotcrete should be placed is subjective, portable penetrometers were developed as a result of research projects undertaken by the Industrial Chair. This apparatus objectively measures the penetration resistance, and thus the consistency, of the dry-mix shotcrete immediately after placement.[13] Such penetrometers (Fig. 7) are calibrated and used by MTQ inspectors/lab technicians on shotcrete rehabilitation projects to monitor shotcrete consistencies for quality control purposes.

Previous experience indicates that most nozzlemen using the dry-mix process have a tendency to shoot quality control test panels at a drier consistency (lower *w/cm*) to obtain higher compressive strength results. MTQ's shotcrete quality control program (which will be described in the next section) requires the use of portable penetrometers to assess the consistency of the as-shot shotcrete of both the test panels and the actual repair to ensure parallel assessment throughout the project. Various consistency readings are obtained between the as-shot shotcrete in test panels and on the structure and should corroborate within ±70 psi (0.5 MPa).

Regarding the consistency of wet-mix shotcrete, the slump, as the measure of workability, is taken before pumping operations and is specified at 4 ± 1 in. (100 ± 30 mm). As stated previously, the *w/cm* shall not exceed 0.40 and the desired workability shall be obtained through the use of admixtures (water-reducers and/or plasticizers). Portable penetrometers can also be used to assess the as-shot consistency on the structure only; however, it is not specified.

During shotcrete application, MTQ requires the following for single- and multi-layer applications:

- Layers of fresh material shall not exceed their plastic shear resistance to avoid the risk of fallouts. The build-up thickness will vary depending on mixture designs, repair area, and vertical versus overhead positions;

- Multi-layering is permitted and each layer shall be applied within 120 minutes. Then all loose, uneven, or excess material, glaze, laitance, overspray, and rebound should be removed by brooming, scraping, or other means; and
- The minimum shotcrete repair thickness shall be 2.5 in. (60 mm) because the use of ACI 506R, "Guide to Shotcrete," Gradation No. 2, is specified.

Any excess material cut during finishing, fallouts, or rebound must be rejected and must not be reintroduced into the mixture when shooting or finishing.

The MTQ specification states that shotcrete may be placed only when the ambient temperature and the substrate temperature is above 41°F (5 °C). Temperature of the as-shot shotcrete must be between 50 and 77 °F (10 and 25 °C). These limitations are specified to keep the new material at a minimum of 41 °F (5 °C) for 7 days. It is not acceptable to begin or continue shotcrete application when exposed to rain or water runoff. Repaired areas must be protected from rain until shotcrete has reached its final set. The MTQ specification documents also cover hot and cold weather shotcreting in more detail.[1]

The MTQ specification documents also require that shotcrete operations be suspended under the following inclement weather conditions:

- High winds preventing proper application procedures;
- Temperatures approaching freezing where the work can't be protected; and
- Rain causing washouts or sloughing of the plastic shotcrete.

Therefore, construction joints must be used at the end of the day and/or when the shotcrete process stops. Work can be stopped, for example, due to equipment problems and unfavorable environmental conditions. Square construction joints are prohibited in the specification, as they form a trap for rebound and overspray. Construction joints must be constructed at a 45-degree angle. Before applying additional shotcrete, the entire joint should be thoroughly cleaned and wetted and allowed to dry to a saturated surface-dry condition (SSD), as indicated in the Surface Preparation section.

Shotcrete Quality Control Program

Shotcrete, as a method of placing concrete, requires particular attention to detail. Strict quality control procedures were developed by MTQ to ensure good quality mixture design, mixture components, placing equipment, and placement. These procedures were designed to increase the life expectancy of the shotcrete repair.

The MTQ's quality control procedures monitor concrete delivery on site at a frequency of one test sample per nozzleman per mixture each day, for both dry- and wet-mix shotcrete. These procedures are described as follows:

Fig. 8: Mechanical spinning trowel with a high-density rubber disk

- Air content of the fresh dry-mix shotcrete is measured on a regular basis by shooting in an air meter before test panels are shot. Although the air content measured is not as accurate as when measured in the hardened state, the results provide a means to determine if air-entrainment admixture is present in the mixture. As for wet-mix, the air content is also measured with an air meter before pumping;
- Test panels are shot to assess compressive strength at 7 and 28 days (1 core and 2 cores, respectively), and air-void distribution (air content and spacing factor, upon request). Performance requirements are described in the Method Selection section;
- The test panel bottom is 12 x 12 in. (300 x 300 mm) with side walls angled at 135 degrees to a minimum depth of 5 in. (125 mm);
- Final surface finishing is achieved with a wood float (refer to the Surface Finishing section);
- The samples remain on site for 24 ± 4 hours at temperatures between 50 and 77 °F (10 and 25 °C) and are wet cured as per MTQ's specification. (Curing is described in the Curing section);
- Samples are then brought to an independent laboratory and placed in a curing chamber at 100% relative humidity;
- 3 in. (75 mm) diameter cores are extracted within 3 to 5 days after the sample is shot and are kept in a 100% relative humidity chamber until testing;
- Cores are prepared in accordance with CSA A.23.3-14C. Both ends of the cores must be sawed to achieve parallel surfaces. A minimum of 3/4 in. (20 mm) of the bottom end of the cores must be removed, as a lack of homogeneity may occur in that section. Capping compound is then applied on both ends;
- The ratio length/diameter of cores must be between 1.0 and 1.1. The measured compressive strength is then corrected by multiplying by a factor of 0.87; and

Fig. 9: Curing system already in place while shotcreting

Fig. 10: Synthetic fiber burlap, saturated with water, covered with a polyethylene plastic sheet

- Temperatures of the fresh shotcrete are monitored during the dry-mix process and just before pumping for the wet-mix process.

All data collected during quality control testing is grouped in a detailed report and provided to MTQ for their review. When a "noncompliance" occurs, the degree of the noncompliance is evaluated for further action.

Surface Finishing

As described in the Shotcrete Placement section, cutting and/or screeding operations are necessary to remove the excess material of both dry- and wet-mix shotcrete. To facilitate cutting of vertical and horizontal surfaces, levels and guide wires (or other means) must be used to bring the surface of the shotcrete to the profile of the original concrete.

It is well documented that shotcrete, unlike conventional concrete, has little excess water to provide the particle lubrication required for effective finishing. Finishing operations for MTQ projects are therefore performed in two segments. First, MTQ specifies the use of a mechanical spinning trowel (finishing machine), with a high-density rubber disk (Fig. 8) for preliminary finish. This operation provides the following advantages:

- Increased ability to seal surface capillary pores;
- Improved work crew efficiency and productivity; and
- Less labor intensive.

The second finishing procedure is to finish the surface with a wood float, which leaves a final uniform finish with a granular texture. Guide wires are removed during this segment.

These procedures must be completed without adding more water to the surface, as it will be detrimental to the quality and durability of the shotcrete repair.

The finishing tolerance of the shotcrete patch repair profile specified must not exceed 5/8 in. (15 mm) over 10 ft (3 m) linear.

Curing

After finishing operations, the fresh material is weak and cracks may develop. The tensile strength of the shotcrete, however, increases with time, which reduces the possibility of new cracks forming. It is more likely that existing cracks will widen than new ones will develop. To prevent crack initiation from occurring, it is important to reduce the time delay between finishing and curing operations. Therefore, the curing program should be available and ready prior to shotcreting (Fig. 9).

MTQ therefore requires that proper curing practices be performed as soon as possible after shotcrete finishing. Curing must be continuous for a minimum period of 7 days. Curing will promote the hydration process to optimize hardened properties and improve durability. Proper curing will also ensure that the potential for plastic and drying shrinkage will also be reduced.

Non-Overhead Surfaces (Dry- and Wet-Mix Shotcrete)

Non-overhead shotcrete surfaces must be wet cured using white synthetic fiber burlap,[2] saturated with water, and covered with a polyethylene plastic sheet to avoid surface evaporation. This evaporation protection system must be properly anchored to prevent the shotcrete from coming in contact with air (Fig. 9 and 10).

Overhead Surfaces (Dry-Mix Shotcrete Only)

Overhead shotcrete surfaces must be cured using a curing compound that complies with ASTM C 309. Although three curing compound products are on MTQ's list of approved products for curing concrete, only one is accepted for shotcrete,[2] which must be a membrane formulated as a dissipating type cure (fugitive dye). The application rate must comply with the manufacturer's recommendations and form a constant surface film, thick enough to protect the entire surface exposed.

Inspection

After 7 days, the shotcrete repair areas must be inspected to verify the integrity of the hardened material, and are normally sounded with a geological hammer. When voids are detected, the entire perimeter is increased by 6 in. (150 mm) and is marked for further repair. The area must then be demolished and rebuilt, according to the specifications.

Conclusions

Concrete research has allowed the development of stringent technical requirements, which make the shotcrete process an excellent, versatile, and reliable method of placing concrete for concrete rehabilitation projects. The overall performance and history of shotcrete on MTQ concrete structures over the last decade demonstrate that shotcrete repair applied in accordance with MTQ's specifications provides increased durability and increases the life expectancy of its rehabilitated structures.

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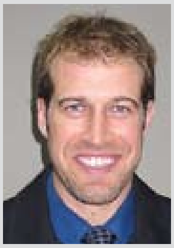

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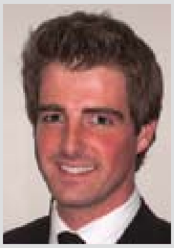

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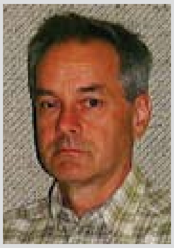

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