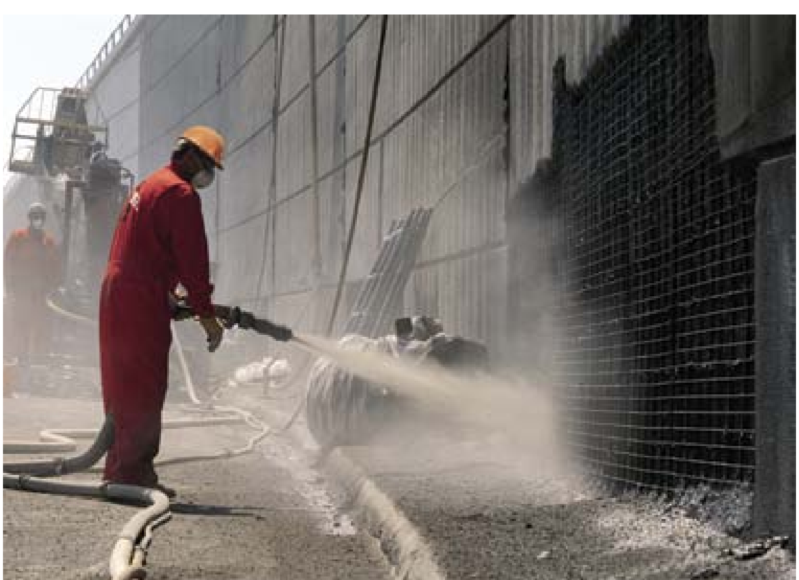
The Use of Shotcrete as a Repair Process for Ontario Bridge Structures

By Joe Hutter and Mahaish Singh

For the past 25 years, King Packaged Materials Company has worked closely with the technical personnel at the Ministry of Transportation of Ontario (MTO) to assist in the development of the shotcrete specifications currently used by MTO. This article has been written from the perspective of the shotcrete materials manufacturer and covers the history of the shotcrete process as it has been used for the rehabilitation of Ontario's bridge structures.

MTO is responsible for the maintenance and repair of over 2720 bridges within the highway system of the province of Ontario. This maintenance ranges from snow removal during the winter months to the repair and rehabilitation of those bridges after years of exposure to freezing-and-thawing cycles and the damaging effects of deicing salts. Ontario's winter climate requires the use of significant quantities of road salt to ensure that Ontario's roads are safe all year. Unfortunately, the 550,000 to 660,000 tons (500,000 to 600,000 metric tons) of salt that are used annually take a toll on reinforced concrete structures through corrosion-induced damage.


MTO is responsible for the maintenance and repair of over 2720 bridges in the province of Ontario

The Early Days of Shotcrete

MTO began using shotcrete as a repair method in 1980, preferring to use a latex-modified product for its low permeability values. The specifications in 1980 provided the option of using the dry- or wet-mix process, although local practice usually favored dry-mix because it was generally considered to be more suitable for smaller repairs. There were no requirements for the use of preblended or prepackaged materials, as there were few manufacturers capable of producing these types of mixtures. A typical mixture proportion (by weight) of latex-modified shotcrete was as follows:

- 1 part Type 10 portland cement;
- 3.5 parts fine aggregate;
- 1/3 parts latex (47.5% solids by weight); and
- Water/cement ratio (*w/c*) of 0.35 (approximately).

The MTO specification called for a minimum application thickness of 1 in. (25 mm) and a maximum thickness of 2 in. (50 mm). The decision to limit the maximum thickness of 2 in. (50 mm) was based on the poor cohesive properties of the mixture. Material applied at greater thicknesses would generally sag, separate, and de-bond, leaving the shotcrete contractor with no choice but to reshoot the material. If areas to be shot had thicknesses greater than 2 in. (50 mm), additional layers of shotcrete were placed until the shotcrete repair reached the required thickness. There was no strength requirement before applying a second layer of shotcrete. The specification, however, called for the base material to reach final set. The specification also required that any accumulated rebound or foreign matter be removed.

One of the challenges associated with the use of latex-modified shotcrete was finishing. The "sticky" consistency of the plastic material made it difficult, if not impossible, to finish the surface of the shotcrete patch. In fact, the specification required that hand finishing be minimized so that the surface material would not tear away from the rest of the patch. After reaching initial set, any excess material was cut from around the perimeter of the patch, leaving the remainder of the repair with a gun finish.

As it is today, quality assurance was a key aspect of MTO's shotcrete practice. The contractor was required to shoot two test panels (one vertical and one overhead) using the same equipment and nozzleman used on the project. Cores were taken from the panel at an age of 4 days and tested for compressive strength at 7 and 28 days (the 7-day requirement was 3600 psi [25 MPa] and the 28-day requirement was 4400 psi [30 MPa]). The cores were also checked for voids, as full encapsulation of the steel was required by MTO. If the cores were deemed to be satisfactory and they met the 7-day compressive strength requirement, the contractor was allowed to proceed with the shotcrete placement.

Although there was no provision for taking cores from the repaired area for strength testing, four cores were taken from the repair area after 28 days so that rapid chloride permeability testing could be conducted. A maximum value of 1500 coulombs was specified; however, there was no provision for rejection of the shotcrete for failure to meet the test criteria.

The use of latex-modified shotcrete continued to be used on MTO projects up until the late 1980s, at which time the many problems associated with this material led MTO to look at alternative methods of repair. The key problems related to the use of latex-modified shotcrete were:

1. Finishing—The "sticky" consistency of the latex-modified material prevented traditional finishing, leaving the patch with a rough gun finish. This was believed to be detrimental to the long-term durability of the patch because an "unfinished" surface would have higher absorption potential. Also, the aesthetics of the patch were less than desirable.
2. Mixture consistency—Until 1989, the MTO specification allowed for site mixing, which often led to inconsistencies in the mixture proportions. Mixtures were proportioned volumetrically, usually using shovelfuls of bulk sand and 88 lb (40 kg) bags of Type 10 portland cement. There was no method to ensure that the 1 to 3-1/2 parts ratio specified by MTO was being followed accurately; understanding that compressive strength was the only pass/fail criteria, contractors would often use too much cement, causing higher shrinkage and contributing to cracking. Stockpiling of sand near the mixing station also led to variations in moisture content, especially during periods of wet weather.
3. Surface cracking—Although the bond of most latex-modified shotcrete patches was acceptable, extensive shrinkage cracking was a common concern. Although it was difficult to pinpoint the exact cause of the cracking, potential causes were inconsistencies in the mixture, higher-than-required cement content, less-than-favorable aggregate gradation (stockpiled sand meant no coarse aggregate was used), and difficult curing conditions (especially when repairing bridge soffits).

The specification for latex-modified shotcrete required that hand finishing be minimized, leaving the repair with a gun finish

Until 1989, the MTO specification allowed for site mixing, which often led to inconsistencies in mixture proportions. Inconsistent cement contents would often lead to high shrinkage values, which contributed to cracking and debonding

The Golder Study

In early 1989, MTO enlisted the services of Golder Associates Ltd., a Toronto, ON, Canada, area engineering consulting firm, to conduct a study to determine if their shotcrete repair practices could be improved. The study was carried out in several phases, which included a literature study, limited laboratory evaluations of trial mixtures, and a field evaluation of shotcrete mixtures using test panels in both vertical and overhead orientations.

Eleven different mixtures were chosen for the field trials, all placed using the dry-mix process. The variables included aggregate gradation (mixtures with and without coarse aggregate), surface preparation (with and without bonding agents), and varying dosages of silica fume and the use of latex, steel, and synthetic fibers. A local contractor experienced in the application of dry-mix shotcrete was selected to shoot the test panels, and all mixtures were supplied, pre-bagged, and proportioned under controlled factory conditions to ensure consistency.

Panels were constructed with dimensions of 39 x 39 in. (1 x 1 m) and a 2 in. (50 mm) concrete base was poured to allow for an acceptable substrate on which the shotcrete could be placed. The concrete surface was roughened to produce a surface that would be similar to a typical repaired surface. Six parallel 0.5 in. (13 mm) diameter steel reinforcing bars were placed in one corner of the panel at a distance of 2 in. (50 mm) above the concrete surface. The spacing between the bars ranged from 2 to 6 in. (50 to 150 mm) and an 18 x 18 in. (450 x 450 mm) piece of 2 in. (50 mm) square wire mesh was secured to the reinforcing steel.

All mixtures were shot by the same experienced nozzleman to ensure consistency. Each mixture was shot in a vertical and overhead orientation and then moist-cured for a period of 7 days. Cores were extracted after 10 days and returned to Golder's laboratory for storage in the moist-curing room with a relative humidity of 100% at 73°F (23°C).

Field Trial Observations (Plastic Properties)

The nozzleman reported that the easiest mixtures to shoot were the silica fume mixtures, primarily because they made it easier to fully encapsulate the reinforcing bars and to place thicker passes. By comparison, in some cases, mixtures without silica fume collapsed within several hours of shooting a second lift. Also, rebound values of mixtures produced with silica fume were significantly lower than those produced with latex.

Field Trial Observations (Hardened Properties)

To properly assess the hardened properties of each mixture, testing included compressive strength, bond strength, rapid chloride permeability, and boiled absorption. The test results varied with each mixture with the lowest compressive strength attributed to the plain mixtures (mixtures without silica fume) and the highest to mixtures with silica fume. Results of tensile bond strengths were also lowest with latex mixtures and highest with silica fume mixtures. Rapid chloride permeability tests were lowest (less permeable) with the silica fume mixtures and highest with the plain mixtures. Boiled absorption values were lowest with the latex-modified mixtures and highest with the plain mixtures.

After weighing the value of each set of test results, Golder recommended that a full-scale field trial involving the repair of an MTO structure be undertaken using a shotcrete mixture enhanced with silica fume and with an aggregate gradation closely matching ACI 506 Gradation No. 1. The trial should include sections shot in both overhead and vertical orientations.

Full-Scale Field Trial—Magnetawan River Bridge

Early in 1990, MTO issued a request for bids to repair the Magnetawan River Bridge, located approximately 186 miles (300 km) north of Toronto. Constructed in 1959, it was the last new open-spandrel concrete arch bridge constructed in the King's Highway System. The required repairs included rehabilitating the underside of the bridge deck (soffit) and sections of the concrete arches that spanned the Magnetawan River.

The bidding closed in the spring of 1990 and the contract was awarded to a Toronto-area contractor with experience on MTO structures. For the first time, the MTO specification called for a prepackaged shotcrete mixture following the recommendations in the Golder Associates report. Over 39 yd^3 (30 m^3) of deteriorated concrete was chipped from the structure and replaced with a silica-fume-enhanced, dry-mix shotcrete material with gradation meeting ACI 506 Gradation No. 1. Initial quality control testing produced an average compressive strength of 6800 psi (47 MPa) and an average rapid chloride permeability value of 557 coulombs. Both results were well within the limits set by MTO. Subsequent visits to the site (the latest of which was made at the time this article was authored) showed that there was no evidence of de-bonding or failure in any of the 21-year-old shotcrete patches and no indication of any corrosion or further damage to the repaired areas.

The success of the Magnetawan River Bridge project led to the development of the current MTO specification, which was most recently updated in July of 2009. Since that project was completed, approximately 65 MTO structures have been repaired using the prepackaged silica-fume-enhanced shotcrete mixture.

After 21 years, there was no evidence of debonding or failure in any of the shotcrete patches of the Magnetawan River Bridge structure

The success of the Magnetawan River Bridge project led to the development of the current MTO shotcrete specification

Current MTO Shotcrete Nozzleman Approval System

For the first several years after MTO adopted the new shotcrete specification, contractors were typically required to have their nozzlemen shoot test panels before starting any shotcrete work on a contract. The original specification simply stated that "A nozzle operator approved by the Owner (The MTO) shall be provided for the application of the shotcrete. Approval may require the evaluation by the Owner, of test panels prepared by the nozzle operator doing the work."

In 1994, however, MTO implemented a testing program in which nozzlemen would be "certified" by a program that was administrated by MTO personnel. This program, which continues to operate today, required that nozzlemen shoot both vertical and overhead test panels using the equipment and materials that were to be used on the project. Applicants who fail to meet the acceptance requirements on the first attempt are permitted one additional attempt during the same calendar year.

Nozzlemen approved through this process for the first time are permitted to place shotcrete on any MTO project during the same calendar year in which the approval is granted. If a nozzleman is approved a second time, the nozzleman is approved for a period of two calendar years. After the second approval, a nozzleman is approved for three calendar years, provided their previous approval was for 2 years, the minimum rating for each of the 24 cores is 2, and the minimum compressive strength of each core is 4350 psi (30 MPa) at 7 days.

Two test panels are required by each applicant—one for vertical and the other for overhead orientations. MTO is very specific about the design and construction of the test panels. As stated in the MTO document detailing the requirements for nozzleman approval:

In 1994, MTO implemented a testing program in which nozzlemen were certified by a program that was administered by MTO personnel

- The form shall be made of minimum 0.66 in. (17 mm) thick plywood, 39 x 39 in. (1 x 1 m) in size, on suitable stiffeners to prevent vibration of the form. Alternatively, the form may consist of a 39 x 39 in. (1 x 1 m) bed of precast shotcrete or precast concrete slab;
- Size 15 (No. 5) bars shall be placed 1.5 in. (40 mm) from the form at 6 in. (150 mm) centers;
- Size 15 (No. 5) bars shall be placed on and perpendicular to the first bars at 12 in. (300 mm) centers;
- If the form is constructed of precast shotcrete or concrete, it shall be abrasive blast cleaned within 36 hours and maintained in a wet condition for 1 hour prior to shooting the test panel; and
- Welded galvanized steel wire fabric of MW 5.6 x MW 5.6 (51 x 51 mm) mesh size shall be placed against and tied to the outer layer of Size 15 (No. 5) bars. The wire fabric shall be in two pieces with an overlap of one square near the center of the panel.

The applicant is required to shoot the test panels in the presence of an MTO representative to a minimum thickness of 4.75 in. (120 mm) and leave the panels in place until a designated MTO representative is available on site to witness the coring. Panels should be cured to conform to the current MTO specifications.

Twelve 3.75 in. (95 mm) diameter full-depth cores are extracted from each test panel. Six cores require reinforcing bars (at least one requires the intersection of two bars and one requires the overlap of the mesh). Six cores containing no reinforcing bars are also required.

The evaluation of the applicant is based on three criteria:

- Application;
- Visual examination of cores; and
- Compressive strength test results.

Visual examination of the cores is carried out by MTO to identify defects and the magnitude of defects, including:

- Delaminations;
- Sand pockets or lenses;
- Voids; and
- Shadows or voids behind reinforcing steel.

Each core is rated on a scale of 1 to 5 with 1 being a core with no defects and 5 being a core with one or more serious defects. To pass, the average rating of all cores requires a score of 1.5 or less. If the cores pass the visual examination, cores without steel are tested for compressive strength—two at 7 days and four at 28 days.

The minimum average strengths are 3625 psi (25 MPa) at 7 days (average of two cores) and 4350 psi (30 MPa) at 28 days (average of four cores). If any sets of cores fail to meet the minimum compressive strength requirements, the panels are considered to have failed.

The current MTO shotcrete specification allows for only prepackaged materials with performance test data verifying that the material meets the requirements of the specification

A list of approved nozzlemen is maintained by MTO's Materials Engineering & Research Office, Concrete Section, and copies of the list are provided to the Contract Management Office and the Regional Construction Offices. The list contains the nozzleman's name, date of birth, and is also supplemented with photo identification for use by field staff on MTO contracts.

Current MTO Shotcrete Specification

The current MTO shotcrete specification was originally developed from the Golder Associates Report that was commissioned in 1989. Although a number of updates have been added, much of the current specification is based on the data that was collected in that report. Key components of the specification include:

Shotcrete Material:

Only prepackaged mixtures are accepted. Materials must be supplied from an approved manufacturer—with performance test data supplied by the manufacturer or from another MTO contract—verifying that the material meets the requirements of the specification.

Nozzlemen:

Shotcrete shall be carried out by nozzlemen who have participated in the MTO Shotcrete Nozzleman Certification Program and who are on the list of approved nozzleman operators for the current construction season. Names of the nozzlemen and proof of their MTO qualification must be submitted to Contract Administrators.

Concrete Removal:

Prior to carrying out concrete removal operations, the perimeter of the removal area shall be sawn to a depth of 3/8 in. (10 mm) or to the depth of the reinforcing steel, whichever is less. The perimeter of the removal area shall have a face perpendicular to the original concrete surface for the specified depth of the removal area. Unless otherwise specified on the Contract Drawings, concrete in these areas shall be removed to a uniform depth of 1 in. (25 mm) behind the first layer of reinforcing steel. Concrete surrounding the second layer of reinforcing steel shall also be removed locally to provide a minimum clearance of 1 in. (25 mm) all around the reinforcing steel. Concrete removal beyond the second layer of reinforcing steel shall be carried out only when directed by the Contract Administrator.

Surface Preparation:

All exposed concrete that will be receiving shotcrete shall be uniformly roughened by means of scrabbling, chipping, or bush hammering. A surface profile of 0.2 ± 0.08 in. (5 ± 2 mm) shall be achieved by exposing aggregates across the entire surface. All concrete surfaces, including the reinforcing steel, shall be abrasive blast cleaned prior to the installation of wire mesh. The area to be shotcreted shall be maintained in a wet condition for a period of 2 hours prior to the placement of shotcrete.

Placement of Welded Steel Wire Fabric:

The welded steel wire fabric shall be securely fastened to the exposed reinforcing steel by ties placed no more than 12 in. (300 mm) apart in a grid pattern. The minimum clearance between the existing concrete and the fabric shall be 0.79 in. (20 mm).

Shotcrete Placement:

The MTO shotcrete specification allows for the placement of either dry- or wet-mix process shotcrete. In either case, the shotcrete material must be supplied in a pre-bagged form, maintained in a dry condition up to the time of its use, and stored within a temperature range of 40 to 86°F (5 to 30°C). Continuous-feed pre-dampeners are used only when the dry-mix process is used.

Shotcreting shall not be carried out when the air temperature or existing concrete surface temperature is below 50°F (10°C) or is likely to fall below 50°F (10°C), or is above 86°F (30°C) or likely to rise above 86°F (30°C) throughout the duration of the shotcreting operation, unless protection is provided in accordance with the Contractor's submitted plan. The air in contact with the repaired surfaces shall be maintained at temperatures above 50°F (10°C) for at least 96 hours after the application of shotcrete.

Curing:

Shotcrete shall be initially moist-cured by continuous fog mist for a minimum of 24 hours. The curing shall commence as soon as the fog mist can be applied without deforming the surface of the shotcrete. After the initial 24-hour fog-misting period, moist-curing shall continue for an additional 72 hours by means of fog mist or wet burlap. Immediately after removal of moist-curing, the shotcrete surface shall be coated with a curing compound according to OPSS 904, MTO's Construction Specification for Concrete Structures.

Conclusions

Continued exposure to freezing-and-thawing cycles and deicing salt make Ontario one of North America's most challenging environments for maintenance of bridge structures. The rehabilitation of concrete structures experiencing deterioration due to corrosion often involves repairs to bridge soffits, curved concrete beams, and columns and other applications that make the use of forms a formidable challenge. The well-proven shotcrete process provides the MTO and Ontario contractors with a reliable, cost-effective option for concrete rehabilitation with a substantial extension of service life and will continue to play a vital role in the cost-effective maintenance of Ontario's highway structures.

References

1. Brown, A. W., and Yuen, C. M. K., "Improved Shotcreting Methods and Materials," Golder Associates Ltd., Toronto, ON, Canada, 1989, 60 pp.

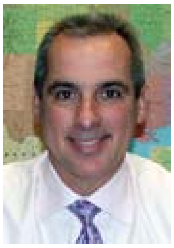
2. Dufour, J.-F.; Reny, S.; and Vezina, D., "State-of-the Art Specifications for Shotcrete Rehabilitation Projects," *Shotcrete*, V. 8, No. 4, Fall 2006, pp. 4-11.

3. "Special Provision No. 931S01," Construction Specification for Structure Rehabilitation—Shotcrete, Ministry of Transportation of Ontario, Toronto, ON, Canada, July 2007, 15 pp.

4. "Special Provision No. 109S50," Construction Special Provision for Structure Rehabilitation—Concrete Patches, Refacing, and Overlays, Ministry of Transportation of Ontario, Toronto, ON, Canada, July 2007, 19 pp.

5. "Special Provision No. 109S49," Construction Specification for Structure Rehabilitation—Concrete Removal, Ministry of Transportation of Ontario, Toronto, ON, Canada, June 2010, 14 pp.

6. "Program for Nozzleman Approval," Ministry of Transportation of Ontario, Toronto, ON, Canada, Mar. 2011, 9 pp.



*ACI member **Joe Hutter** is the Vice President, Sales, for King Packaged Materials Company, Burlington, ON, Canada. He has more than 20 years of experience in the cement/shotcrete industry. He is the current Vice President and an active member of ASA and has chaired the ASA Marketing Committee since its inception.*

***Mahaish Singh** worked with the Ministry of Transportation (MTO), ON, Canada, for over 43 years, most recently as a Senior Concrete/Materials Engineering Officer. His responsibilities at MTO included working with shotcrete, waterproofing membranes, bearings (laminated and plain), and expansion joint seals. From 1994, Singh worked closely with shotcrete contractors and materials manufacturers to advance the shotcrete process throughout the province of Ontario. His efforts to develop and administer MTO's Shotcrete Nozzleman Certification Program have contributed to the improved quality of shotcrete placed on Ontario bridge structures. Singh's career ended with MTO when he retired at the end of 2011.*