Curing Silica Fume Shotcrete with Wet-Sprayed Cellulose

by Medhat Shehata and Tom Klement

Chloride-induced corrosion is the primary cause of deterioration in many concrete bridges in Canada and the northern United States. For corrosion to take place, the chloride ions permeate through the interconnected pores of the concrete toward the embedded steel reinforcement and attack the passive layer that forms around the steel during the hydration process of concrete. Once this passive layer is destroyed, corrosion proceeds, resulting in a reduction in the structural integrity of the structure in addition to the onset of spalling of the concrete cover. To restore the serviceability of the structure and extend its service life, the deteriorated concrete is usually removed, the reinforcement is replaced if necessary, and the concrete is replaced with a durable repair material that has high resistance to chloride ion transport. In the province of Ontario, Canada, partially deteriorated concrete bridge soffits are typically repaired with shotcrete containing silica fume.

Silica fume shotcrete is being used because it significantly improves the shotcrete bonding. Further, its adhesive properties minimize rebound, particularly important in overhead work. Equally important, deep repairs can be built up faster than with conventional shotcrete. However, due to silica fume self-desiccation property coupled with the low water-binder ratio of shotcrete, adequate curing of the repair material is even more essential to reduce shrinkage cracking and achieve a product of low permeability and high durability. Shrinkage cracking is common with improperly cured concrete, and even more of a problem with concretes containing silica fume.

The Ontario Ministry of Transportation (MTO) specifies fog mist spray for a minimum of 24 h, followed by 72 h fog misting or continuously moist burlap treatment for shotcrete repairs. After moist-curing the shotcrete surface, it is coated with a curing compound. Occasionally, when the above specified curing is physically impossible to achieve, a shorter curing interval may be specified. Moist curing of bridge soffits is difficult and costly. It is hard to keep burlap attached to the soffit and continuously wet. Also, continuous misting over highways may require daytime lane closures, costly traffic control, or enclosure. As a result, moist curing is often not a practical option on the underside of busy freeway bridges. The application of curing compound or sealing the repair area using plastic sheeting maintains the moisture already present in the concrete by preventing further evaporation, but does not provide any additional water to the concrete, which is required to maintain a level of relative humidity within the concrete high enough to achieve a high degree of hydration and reduce shrinkage cracking. To improve the performance of the silica fume shotcrete, the MTO decided to look for an alternative curing method.

Through its 2002 Highway Infrastructure Innovation Funding Program, the MTO contributed funding to a research project to investigate the feasibility of using wet-sprayed cellulose to cure shotcrete. The project was assigned to a research team from Ryerson University in Toronto led by Dr. Medhat Shehata.

The Project

Twelve wooden panels were sprayed with shotcrete in an overhead position simulating bridge soffits (Fig. 1 and 2). The panels (39 x 39 x 5 in. [1000 x 1000 x 130 mm]) each, were reinforced in two directions (15M reinforcement at 6 in. [150 mm] and 12 in. [300 mm] in each respective direction), and topped by a layer of wire mesh. The same panel configuration has been used by MTO for years to prequalify nozzlemen for MTO work. The trial took place on July 9, 2003, at St. Catharines.

Shotcrete Materials

The material used in this project was ready-to-use bagged silica fume shotcrete from a commercial supplier. As an independent test, three of the panels were shot with shotcrete containing polypropylene fibers and an aluminate-based accelerator. One of these panels had the 5 in. (130 mm) depth built up in one continuous process.

Application of Shotcrete

The shotcrete was applied to the pre-wetted panels using the dry-mix process. Except for one panel as mentioned above, shotcreting was performed in two lifts adding up to a total thickness of about 5 to 5.5 in. (130 to 140 mm), with the surface "as-shot" (without screeding). The time lag between the first and second lift was about 5 to 8 h. Shotcrete application was carried out during the night to emulate a typical work environment and to maximize the time available for cellulose application, should unexpected problems arise.

Curing

After completing the shotcrete process, each panel was cured following a predetermined curing regime. To provide a basis for comparison, one panel was air cured, two were cured with a curing compound, and two were mist-cured for 4 days followed by the application of a curing compound. The seven remaining panels were sprayed with a nominal 2 in. (50 mm) of wet cellulose about 1 h after completion of shotcreting. All panels were suspended for 28 days, after which the cellulose layers were scraped off and cores were taken from each panel for testing.

Of a large number of invited companies, only two cellulose producers/applicators chose to participate in the project, contributing materials and an application crew. Both companies used cellulose material (Fig. 3) and adhesives more or less in configurations in which they use them in acoustic and thermal industrial applications.

Application of Cellulose

The cellulose curing was applied to the surface of the test panels in a manner similar to that of shotcrete application (Fig. 4), in a nominal 2 in. (50 mm) layer (Fig. 5). Fibers were propelled by compressed air and were mixed at the nozzle with a mixture of water and adhesive. The finished cellulose surface was sprayed with a layer of adhesive to seal it, to limit moisture evaporation.

Observations

One of the cellulose applicators experimented with the amount of adhesive used and it took him a while to improve the process. In the initial attempts, the cellulose mat failed, essentially peeling off the shotcrete surface and falling to the ground under its own weight. Cellulose applied to the last panel adhered properly to the shotcrete and remained intact for 28 days. The other cellulose product adhered properly to the surface of the three trial panels for the 28-day trial period.

Proper cellulose adhesion is essential to ensure not only curing, but more importantly, to prevent wind-drag created by passing traffic from tearing cellulose pieces off, creating a hazard for drivers.

Shotcrete Temperature

Temperature monitoring devices (thermocouples) were installed in two panels. Results verified that the use of cellulose does not raise the temperature of shotcrete by acting as an insulator.

Fig. 1: Test panel used in the experimental program

Fig. 2: Scaffolding used to support the test panels

Fig. 3: Loose cellulose

Fig. 4: Application of cellulose

Fig. 5: Finished cellulose mat

Fig. 6: Removal of cellulose after 28 days

Removal of Cellulose

The cellulose adhered well to the surface and was still slightly damp after 28 days (Fig. 6). As a result of this moisture, it took some force to remove the cellulose from the surface. Had the surface of the shotcrete been finished prior to the spraying of the cellulose, the product would have come off more easily. Even from the as-shot surface, however, the cellulose removal was shown to be both feasible and practical. The panel surface looked uniformly grey from a distance of a few meters, with no cellulose residue visible. In applications other than overhead, with no traffic underneath, the cellulose could remain in place.

Cracking

After the 28-day trial period, the surface of the shotcrete was inspected for surface cracking. Due to the textured surface, it was not possible to determine if any hairline cracking was present in any of the panels. In the air-cured panel and the panels cured by curing compound, the shotcrete had shrunk away from the form, leaving 0.04 to 0.12 in. (1 to 3 mm) gaps. These cracks were already observed on the 15th day of the trial, during a site visit. By contrast, none of the cellulose and mist-cured panels exhibited any such cracking.

Experimental Results

Core samples were collected from each panel and tested to assess the relative efficacy of each curing method and to evaluate the properties of shotcrete material containing accelerator and fibers. Tests conducted on cores included compressive strength (ASTM C 39), rapid chloride permeability test (RCPT [ASTM C 1202]), sorptivity, mercury intrusion porosimetry (MIP) and bulk diffusion (ASTM C 1556). The only tests that were sensitive enough to differentiate between different curing methods for the panels were the MIP and sorptivity tests. Panels cured by one of the two cellulose products showed in a modified salt scaling test evidence of the presence of a 0.04 to 0.08 in. (1 to 2 mm) thick layer of weaker shotcrete at the surface.

Using MIP testing, the cellulose-treated panels had a refined pore structure comparable to shotcrete cured by curing compound or misting for 4 days. Refined pore structure results in shotcrete of low permeability and accordingly high durability. The cellulose-cured shotcrete showed lower sorptivity coefficients than shotcrete cured by curing compound. Sorptivity coefficients for cellulose-cored shotcrete were similar to, or slightly better than, shotcrete cured by misting for 4 days. In summary, cellulose curing has proven to be equivalent to, if not better than, the traditional curing methods. It is recognized that the trial was conducted under conditions highly favorable to natural curing (temperature: 22 °C; day 1 to 7 relative humidity:

73%; day 8 to 28 relative humidity: 79%; maximum wind speed: 15 km/h), and the cellulose curing effects may be even more pronounced under drier or more windy conditions. The Ryerson research team plans to conduct further tests on panels cast and cured under laboratory conditions, to investigate this aspect of the work. Table 1 shows a summary of the test results obtained under various curing regimes.

Shotcrete materials containing accelerator and fibers showed lower strength and higher permeability as determined by the compressive strength and RCPT results, respectively. This is most likely attributable to the use of an accelerator, which accelerates the early rate of strength development but may have negative effects on late strength and durability.

Recommendations

The research team recommends that a suitable bridge repair using shotcrete be selected as a full-scale pilot application for cellulose curing.

Based on the results of this research, it is anticipated that cellulose treatment will offer practical advantages over fog misting and the use of a curing compound. Cost effectiveness under many conditions may also be superior.

Weakness in the 0.04 to 0.08 in. (1 to 2 mm) outer layer of shotcrete is not considered significant in light of damage caused by mechanical cellulose removal at the end of the curing period and superior properties of the rest of the outer layer. The causes of this weak layer is currently under further investigation at Ryerson University.

Based on data from this research, MTO should not consider the use of accelerators and fiber additives in shotcrete unless it is demonstrated that none of the key shotcrete properties are adversely affected. The exception may be interim repairs of short service life.

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Table 1: Test results of panels cured under various curing regimes

Test	Curing regime		
	Curing compound	**Misting for 4 days**	**Cellulose**
Compressive strength (average of 3; *L*/*D* = 1.25, tested in an unsaturated condition)	9834 psi (67.8 MPa)	10,080 psi (69.5 MPa)	10,298 psi (71.0 MPa)
RCPT (average of 3)	313 Coulombs	282 Coulombs	302 Coulombs
MIP (total volume of intruded mercury/unit volume of sample, porosity)	0.102	0.096	0.077
MIP (average pore diameter)	0.030 μm	0.026 μm	0.025 μm
Sorptivity (coefficient of sorptivity)	0.032 mm/min$^{0.5}$	0.024 mm/min$^{0.5}$	0.021 mm/min$^{0.5}$
Bulk diffusion (coefficient of diffusion)	8.14×10^{-13} m^2/s	7.49×10^{-13} m^2/s	6.25×10^{-13} m^2/s

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