Compatible Shotcrete Specifications and Repair Materials

By William Clements and Kevin Robertson

Concrete repair projects can often be completed using a variety of different repair materials and methods, though in some cases, the specific performance requirements of a project may dictate use of a specific material or method. Shotcrete is often used as a repair method to replace other methods such as form-and-pour to reduce labor costs and accelerate the construction schedule. Shotcrete is the best method when access to the repair area is limited in location and availability (Fig. 1). In selecting a repair method, a repair material must then be selected that is compatible with the concrete substrate, durable in the expected exposure conditions, and meets the structural requirements detailed by the design professional responsible for the repair. Ideally, these important criteria would be evaluated by the design professional and incorporated into the project specification to address the specific requirements of the project based on the expected service life of the repair. However, some design professionals, in developing their project specifications, are not well informed about the specific details for quality shotcrete placement and may miss or overlook important repair criteria.

Fig. 1: Remote dam repair using dry-mix shotcrete and a cofferdam[1]

The service life of any repair depends on the repair material's successful bond to the substrate, resistance to the exposure conditions, and crack resistance while in service. Even if the repair material exhibits excellent durability properties, if cracks develop either in the repair material or around the perimeter of the repair area, they allow easier ingress of corrosive agents such as water and chlorides to the embedded reinforcing steel. Thus, when considering these factors, the repair material must be as compatible as possible with the substrate to reduce the potential for cracking.[2]

SPECIFICATIONS

As with most specifications in the construction industry, concrete repair specifications typically use either a prescriptive specification or a performance specification. Prescriptive specifications either reference the actual repair product(s) by name or the constituents or characteristics of the repair material. In contrast, a performance specification outlines the performance requirements of the repair material after placement in accordance with applicable standards. In general, there is currently a trend towards performance specifications, but in North America, both ACI 318[3] and CSA A23.1/A23.2[4] still use a hybrid method of both prescription and performance when classifying concrete.[5] There are cases where contractors prefer to submit an "or equal" alternative to prescribed products based on past experience. The contractor may propose the shotcrete method in lieu of form-and-pour. It can be simpler for a contractor to submit shotcrete placement for a performance specification, as the contractor and manufacturer simply need to display compliance with the project specification through the appropriate submittals to obtain approval. This process does become much more difficult however, when the project specification presents a product or certain performance criteria that do not match the typical test methods applicable to shotcrete. ACI 506.2-13, "Specification for Shotcrete"[6] includes mandatory provisions for the commonly tested performance characteristics such as compressive strength and flexural strength, noting that any hardened test samples must be produced from sprayed test panels. Unfortunately,

Table 1: Test Methods for Repair Mortars Compared to the Corresponding Method for Shotcrete

Property	Repair mortar test method	Repair mortar specimen type	Shotcrete test method	Shotcrete specimen type
Compressive strength	ASTM C109/ C109M[8]	Cast cube (2 x 2 in.)	ASTM C1604/ C1604M[7]	Core (3 in. Ø)
Flexural strength	ASTM C348[9]	Cast beam (1.5 x 1.5 x 6.5 in.)	ASTM C78/C78M[10]	Sawed beam (6 x 6 x 21 in.)
Splitting tensile strength	ASTM C496/ C496M[11]	Cast cylinder (4 x 8 in.)	ASTM C496/C496M[11] (modified)	Core (3 in. Ø)
Slant shear bond strength	ASTM C882/ C882M[12]	Cast cylinder (3 x 6 in., -30-degree incline)	ASTM C1583/C1583M[13] (Pulloff bond strength)	Tensile bond of core (3 in. Ø)

Note: 1 in. = 25 mm

it is common to see specifications or even technical data sheets from manufacturers of shotcrete materials showing results for test methods applicable to repair mortars and not for shotcrete. For example, the compressive strength of shotcrete should always be evaluated in accordance with ASTM C1604/C1604M,[7] but it is typical for manufacturers to present data in accordance with ASTM C109/C109M.[8] ASTM C109/C109M involves manually consolidating shotcrete mortar into cube molds, as opposed to being shot, and is not representative of the in-place shotcrete that is compacted by high-velocity impact. An example of commonly specified test methods in a shotcrete repair specification compared to the corresponding applicable test method for shotcrete is presented in Table 1.

A common misconception when it comes to current shotcrete specifications for repair projects is where “low-velocity mortar spray” or “low-pressure mortar spray” is somehow considered equal to high-velocity dry-mix or wet-mix shotcrete. As noted in Table 1, the adapted ASTM test methods for compressive strength, flexural strength, and other test methods differentiate shotcrete from mortar. Low-velocity spraying involves pumping at a lower pressure and air flow than conventional wet-mix shotcrete, resulting in a much lower velocity placement. The main difference between both methods is the velocity at which the material is shot into place. Shotcrete has been characterized to travel at speeds of 45 to 78 mph (72 to 125 km/h), which produces a high impact force and fully consolidates the concrete in-place. Conversely, low-velocity mortar spray was developed and is essentially a method to replace hand-troweling of a repair material.[14] Low-velocity mortar spraying simply lacks the velocity required to fully encapsulate reinforcing steel and even wire mesh in most cases. In some of North America’s construction markets, the shotcrete method has been given a bad reputation because the specifications have been written around low-velocity mortar spraying that was considered to be “as equal” to shotcrete. Both methods have their place in the repair industry depending on the type of repairs to be completed. When designing repairs that use wire mesh or reinforcing steel, high-velocity shotcrete must be used to have the ability to properly encapsulate the embedded reinforcing steel and not create voids behind the steel.

The shotcrete process selected can impact the mixture design of the concrete materials being shot. Wet-mix shotcrete materials must be pumped through the delivery pipe and hose prior to spraying. Wet-mix shotcrete commonly contains an air-entraining admixture to either provide durability in freezing-and-thawing environments, or to improve the pumpability of the material using the “high initial air content concept”.[15] Using a high initial air content ranging from 10 to 20%, the “high initial air content concept” has been proven to increase the slump and pumpability of shotcrete during pumping, and due to high velocity impact of the shotcrete produce an in-place air content of 3 to 5% in place after shooting. In the case of dry-mix shotcrete where water is added at the nozzle, it is impossible to ascertain the air content because the concrete materials are not mixed to form the cement paste until water is added at the nozzle. Therefore, any test results presented for the mechanical and durability properties of a shotcrete repair material, whether wet-mix or dry-mix, should be from as-shot samples.

ADAPTING TEST METHODS TO THE SHOTCRETE PROCESS

The International Concrete Repair Institute (ICRI) technical data sheet protocol established in ICRI Guideline No. 320.3R,[16] provides a thorough list of both mechanical and durability parameters that should be provided on the technical data sheet of any repair material. Although the guideline details which ASTM standard test method should be followed for mortars and which methods should be followed for concrete, some adaptations are required when applying the protocol to a shotcrete material. Considering most of the test methods described in ICRI Guideline No. 320.3R and noted in Table 1 reoccur in concrete repair specifications from the industry, KING enlisted Laval University to execute a testing program for the required parameters using a silica fume-enhanced dry-mix shotcrete (KING MS-D1). All of the samples tested were obtained from coring or sawing conventional test panels (Fig. 2), spraying shotcrete onto previously cast concrete sections, or by

Table 2: Adapted Test Methods for Shotcrete using ICRI Guideline No. 320.3R

Property	Test method	Sample type	Result (28 days)
Flexural strength	ASTM C78/C78M	Sawed beam (6 x 6 x 21 in.)	1088 psi (7.5 MPa)
Splitting tensile strength	ASTM C496/C496M	Core (3 in. Ø)	645 psi (4.45 MPa)
Direct tensile strength	CRD-C 164[17]	Core (3 in. Ø)	500 psi (3.45 MPa)
Modulus of elasticity	ASTM C469/C469M[18]	Core (3 in. Ø)	4.2 x 10^6 psi (29.0 GPa)
Pulloff bond strength	ASTM C1583/C1583M	Tensile bond of core (3 in. Ø)	420 psi (2.9 MPa)
Slant shear bond strength	ASTM C882/C882M	Core (3 in. Ø-30-degree incline)	3335 psi (23.0 MPa)
Length change	ASTM C157/C157M[19]	Sawed beam (3 x 3 x 11.25 in.)	50% RH: -0.0494% 100% RH: +0.0122%
Coefficient of thermal expansion	CRD-C 39[20]	Core (3 in. Ø)	6.5 x 10^{-6}/°F (11.7 x 10^{-6}/°C)
Freezing-and-thawing	ASTM C666/C666M[21]	Sawed beam (3 x 3 x 11.25 in.)	100% durability factor
Salt scaling	ASTM C672/C672M[22]	Sawed slab (72 in.^{2} surface)	0.04 lb/ft^2 (0.2 kg/m^2)
Chloride ion penetrability	ASTM C1202[23]	Core (4 in. Ø)	500 Coulombs

Note: 1 in. = 25 mm; 1 MPa = 145 psi

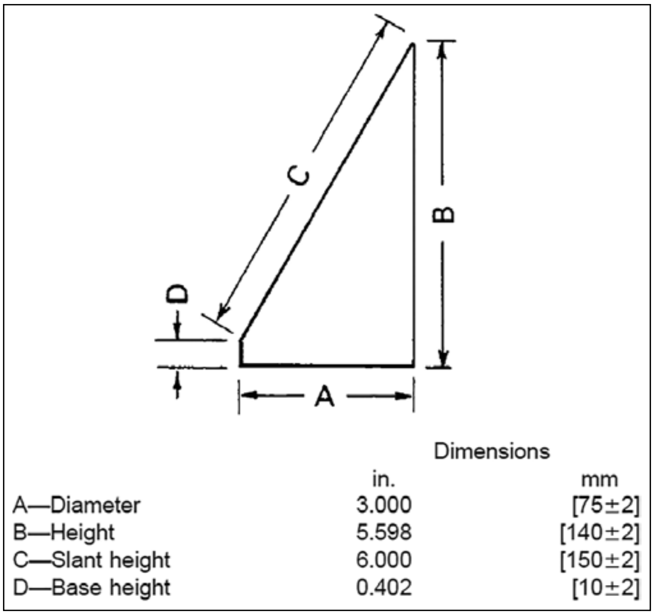
spraying oversized test samples for durability testing and then sawing the edges around the perimeter of the samples to remove sections of rebound and overspray.

The Slant Shear Bond Strength test (ASTM C882/C882M) was originally developed to test the bond strength of epoxy between two cast mortar sections. The concrete repair industry has since adopted a modified version of the test, wherein the concrete repair material is placed onto the hardened mortar dummy (Fig. 3) and then the composite cylinder is tested in compression.

The resulting load on the cylinder is divided by the area of the ellipse, resulting in a shear bond strength along the 30-degree plane of the bonding surface. To modify the test method to the shotcrete process, a concrete section was cast using the appropriate angle (Fig. 4), and then shotcrete was sprayed onto the concrete section. Cores were taken perpendicular to top surface of the composite sample to model the shotcrete being cast onto the mortar dummy as per the standard (Fig. 5).

Following the completion of the test program, it is apparent that most test methods for concrete materials can be adapted to the shotcrete process, although in some cases execution is more complicated. Table 2 presents the results of the testing program. When compared to typical requirements for concrete, it can be seen that dry-mix shotcrete is an excellent concrete repair material. Notably, the bond strength exhibited by the ASTM C882/C882M test samples were very high, and two of the five cores tested at 28 days

Fig. 2: Conventional square shotcrete test panels used for obtaining cores



Dimensions	in.	mm
A—Diameter	3.000	[75±2]
B—Height	5.598	[140±2]
C—Slant height	6.000	[150±2]
D—Base height	0.402	[10±2]

Fig. 3: Schematic of slant shear dummy section (ASTM C882/C882M)

failed with multiple vertical cracks as opposed to failing along the bond line.

DEVELOPING COMPATIBLE DRY-MIX SHOTCRETE

Almost all reinforced concrete structures will require some maintenance during their expected service life. The type and extent of repairs needed are a function of the structure's age, exposure conditions, original design, construction methods, and building materials used. Where possible, it is best to replace any concrete that is removed from the structure with a repair material that has physical properties similar to the substrate, such as compressive strength, modulus of elasticity, and coefficient of thermal expansion. This helps reduce potential debonding by ensuring that any physical movement, either due to loading or temperature changes in the substrate, are mirrored in the repair material. These properties do not, however, predict the inevitable volume change that a concrete repair material will undergo once in place. This volume change is a complex combination of chemical/autogenous shrinkage of the cement paste, drying shrinkage from moisture loss, and tensile creep (relaxation). Once the tensile forces of shrinkage exceed the tensile strength of the material, internal cracking can occur. If the tensile shrinkage forces exceed the bond strength of the repair material to the substrate, cracking can occur at the perimeter of the repair.

Even though shotcrete is very similar once shot to form-and-pour concrete, the shotcrete mixture design must be tailored to the process to facilitate pumping, optimize build-up while spraying, and to reduce rebound. The use of silica fume in shotcrete can greatly reduce rebound, increase build-up thickness, increase compressive strength, and reduce permeability.[24] Conversely, silica fume, with its high water demand, requires swift and proper wet curing techniques after shooting that if not followed will increase drying shrinkage and can increase the risk of cracking. To reduce the potential for shrinkage and improve compatibility, it may be beneficial to remove silica fume from the dry-mix shotcrete formulation, but the loss of productivity and efficiency due to increased rebound in the field would generally not be acceptable. Some potential techniques for reducing the shrinkage potential in shotcrete materials include the use of coarse aggregate, reducing the cementitious content, replacing portland cement with fly ash, and using polymer. To evaluate the effectiveness of these approaches to resist shrinkage potential requires a test method that captures all of the parameters noted previously as the shotcrete undergoes volume change.

Currently, the best test method for predicting the risk of cracking in a repair material is the AASHTO T 344[25] standard test method (ring test), which has recently been adapted to the shotcrete process at Laval University.[26] The method involves spraying shotcrete into a steel ring mold, which is mounted in an inclined overhead position to allow rebound to escape the mold (Fig. 6).

Following moist curing, the shotcrete ring is placed in a controlled environment at 50% (±5%) relative humidity and a temperature of 70 ± 2°F (21 ± 1°C). The stress developed

Fig. 4: Inclined precast mold for slant shear bond strength testing (ASTM C882/C882M)

Fig. 5: Composite core for slant shear bond strength testing (ASTM C882/C882M)

Fig. 6: Shotcrete being sprayed into inclined AASHTO T 344 rings

in the shotcrete ring is monitored using a data acquisition system, wherein cracking potential is then calculated as a function of the average stress developed and the age at which cracking occurs. Using a wet curing period of 3 days followed by drying, several mixture designs along with a proprietary mixture design developed by KING (HC-D1) were compared using the ring test to evaluate cracking potential.[27] The formula used and the age of cracking for each mixture design is presented in Table 3.

CONCLUSIONS

The shotcrete process can be used to achieve compatible concrete repairs offering a long service life. The combination of specifying the correct physical properties (test methods) and using the right shotcrete material helps achieve success in the field. The mechanical and durability properties of shotcrete should always be determined using samples that are shot and not cast, by adapting any applicable standards to the shotcrete process. The development of a highly

Table 3: Age of Cracking for Different Dry-Mix Shotcrete Formulas

Mix no.	Cement content (%)	Coarse aggregate (%)	Silica fume (%)	Fly ash (%)	Polymer (%)	Age of cracking AASHTO T 344 (days)
1	21	15	0	0	0	25
2	18.9	15	2.1	0	0	9
3	19.4	15	1.6	0	0	6.5
4	14.4	15	1.6	5	0	6
5	19.4	15	1.6	0	2.0	7
6 (HC-D1)	*	*	*	*	*	40

**Proprietary mixture design*
Note: The remainder of the formula consisted of sand

compatible dry-mix shotcrete with a very low cracking potential shows promise and testing of the other key properties as described in this article are currently underway.

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