

THE USE OF SHOTCRETE AS A REPAIR PROCESS FOR STRUCTURAL CONCRETE REPAIR

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The shotcrete process has been around since its inventor, Carl Akeley, first came up with the idea of pneumatically conveying a cementitious mortar over 100 years ago. While it has been regarded by many simply as another method of placing concrete, the shotcrete process in the context of concrete rehabilitation is much more than that. The benefits derived from modern shotcrete technology have provided forward-thinking contractors with an economic advantage over their competitors, and specifiers have also recognized that the shotcrete process can provide a durable, long-term repair solution that other repair procedures simply can't match.

To understand the true benefits of the shotcrete process, it is important to first understand what shotcrete is. As defined in ACI 506R, "Guide to Shotcrete,"¹ shotcrete is "Mortar or concrete pneumatically projected at high velocity onto a surface." In other words, shotcrete is not a product; it should be considered a process for placing concrete. So when evaluating the benefits of a concrete repair,

the same properties should apply to a repair whether the repair material is hand-troweled, cast-in-place, or applied at high velocity using the shotcrete process (Fig. 1).

DRY VERSUS WET

There are two distinct processes when placing shotcrete. Using the dry process, concrete is conveyed through a hose in an air stream at high velocity. Water is added at the nozzle to produce plastic material on impact. Mixing of water and the dry material occurs at the nozzle and on the receiving surface. Using the wet process, concrete is pumped through a hose and air is added at the nozzle to accelerate the mixture to a high velocity. The key common ingredient for both processes is "velocity." Without high velocity, usually measured at 100 ft (30 m) per second, a pneumatically placed concrete or mortar cannot be described as shotcrete. Compaction achieved when concrete hits a surface at high velocity provides many of the key properties that make the shotcrete process unique as a concrete placement procedure.

When selecting a shotcrete process for a concrete rehabilitation project, it is usually best to leave that decision up to the contractor. Both wet- and dry-process shotcrete can be equally effective; however, some contractors are better suited (because of crew experience, equipment options, access to material, or other factors) to successfully complete a shotcrete repair using one process over the other (Fig. 2).

ENVIRONMENTAL CONDITIONS

Cold-Weather Application: Shotcrete specifications should outline limitations for the placement of shotcrete under varying environmental conditions. When faced with cold temperature conditions, it is best practice to follow the recommendations in ACI 306R, "Guide to Cold Weather Concreting."² In addition, the following precautions should be considered:

- Do not apply shotcrete if air temperature is 40°F (4.4°C) and falling unless protective measures taken;
- Do not apply shotcrete on frozen surfaces;
- Keep mixture temperature above 50°F (10°C);



Fig. 1: Concrete (shotcrete) pneumatically projected at high velocity to repair area

- Protect shotcrete from freezing until it has reached at least 500 psi (3.4 MPa) in compressive strength; and
- Use warm mix water.

The use of concrete mixtures with high early cement and/or accelerators can also expand cold temperature parameters; however, approval should first be obtained from the project engineer. It is also important to note that accelerators should always be added using controlled dosing methods. Too much accelerator can be detrimental to the quality of the concrete.

Hot-Weather Application: When faced with hot temperature conditions, it is best practice to follow the recommendations in ACI 305R, “Guide to Hot Weather Concreting.”³ In addition, the following precautions should be considered:

- Keep shotcrete mixture temperature as low as possible;
- Do not apply shotcrete when ambient temperature exceeds 100°F (38°C) unless precautions are taken;
- Use cool water in mixture;
- Use shades where possible; and
- Use fogging/misting for cooling and controlling evaporation.

SURFACE PREPARATION AND BOND

Understanding that structural designs require the existing concrete and repair material to perform as a single element, the bond between these two components becomes critical. Without a durable bond interface between the existing substrate and the new concrete, a concrete repair can be subject to a high degree of failure.

A strong, durable bond starts with proper surface preparation. After removal of loose and deteriorated concrete, the resultant sound concrete surface should be pre-wetted using a high-pressure water spray (Fig. 3), leaving a saturated surface-dry surface. Free-standing water should not be left on the surface because excess water will create a higher water-cementitious materials ratio (w/cm) in the shotcrete mixture and result in a reduction in bond strength at the interface between the shotcrete and the existing concrete.⁴

Testing has indicated that in a concrete repair application, the shotcrete process often achieves a stronger and more durable bond than other placement methods.⁵ This is due to the principles of the shotcrete process and lead back to the previous statement referencing the importance of velocity. In the case of both wet- and dry-process shotcrete, bond quality can be attributed to the high energy transfer that occurs when the shotcrete material impacts the existing concrete surface.

As the stream of plastic concrete initially makes contact with the surface at high velocity, much of



Fig. 2: (a) Dry process shotcrete gun versus (b) wet process shotcrete pump



Fig. 3: High-pressure cleaning of the prepared concrete substrate prior to shotcrete application

the fine and coarse aggregate bounce away from it as “rebound,” leaving an accumulation of fine cement paste. As the layer of cement paste builds, fine and coarse aggregates embed into the cement paste and the amount of rebound material is

reduced. This layer of cement paste acts as a bonding agent for the shotcrete material, and even without the use of traditional bonding agents, direct tensile bond strengths of shotcrete repairs can generally reach 200 psi (1.4 MPa).⁶

It has been stated many times by shotcrete experts around the globe that bonding agents are NOT required when concrete is placed using the shotcrete process.⁷ Bonding agents interfere with the shotcrete's natural bonding mechanism and often create an unreliable and unpredictable bond, or bond breaker.

SHOTCRETE MATERIALS AND MIXTURE DESIGN

The plastic and hardened properties that are essential for a conventional concrete mixture design also apply to the shotcrete process. For example, air entrainment may not be critical when the concrete is exposed to an environment with little or no freezing-and-thawing exposure, such as Arizona, but if the concrete is used to repair a bridge in the northeast, where exposure to freezing-and-thawing conditions and road salt is prevalent, air entrainment is extremely important.

As in conventional cast-in-place concrete, almost all cement types, admixtures, and types of fiber can be used in shotcrete mixtures. A shotcrete mixture design should be developed to meet the required properties of the project. Hardened property testing should be conducted on core samples, representative of the in-place shotcrete, extracted from the repaired structure or test panels.

Air Entrainment: In areas where exposure to deicing salts and freezing-and-thawing cycles is a concern, the most important performance durability criteria is the air-void spacing factor per ASTM C457/C457M, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete."⁸ In-place hardened shotcrete, whether applied by the dry or wet process, requires an average air-void spacing factor of under 0.0118 in. (300 μm), with no individual results over 0.0125 in. (320 μm).⁹

In a wet-mix shotcrete application, air content can be measured in two ways: the "as-batched" air content, which is measured at the concrete truck, and the "as-shot" air content, in which the shotcrete material is collected after shooting and measured in an air meter. An air-entrained wet-process shotcrete mixture design will typically have an acceptable as-batched air content of 7 to 10% and an as-shot air content of about 3 to 5%. These air content values will generally provide good durability performance in areas exposed to freezing-and-thawing conditions and deicing salts.

In a dry-mix shotcrete application, air-entraining admixture should be added in powdered form and

pre-blended with other components in prepackaged materials. The shotcrete material manufacturer should have a proven track record producing prepackaged, air-entrained, dry-mix shotcrete and should be able to provide ASTM C457 test data that reflects the recommended air-void spacing factor for dry-mix shotcrete. For the dry process using bulk materials, the addition of an air-entraining admixture is not recommended due to variability in dosage, which can affect strength and durability.

Typically, for the dry process, air content is not tested with an air meter due to the stiffness of the material as shot. The air meter reading is not representative of the air content. The only accurate procedure to evaluate the air content is on a hardened shotcrete sample with the ASTM C457 test method. For both dry and wet processes, the air content on a hardened sample should generally be 4 to 8%.

Silica Fume: Silica fume is a highly pozzolanic admixture (Fig. 4(a)) that improves both the plastic and hardened properties of concrete placed using the shotcrete process. In markets where silica fume is readily available, it is commonly used to improve the shooting characteristics. The use of silica fume in shotcrete will increase adhesion to the bonding surface and cohesion within the shotcrete, consequently allowing thicker placement of shotcrete before sloughing (especially in overhead applications). Although there is no standard test method to measure attainable thickness in one pass, testing has proven that the addition of silica fume has been beneficial in overhead and vertical repair applications.¹⁰

In terms of hardened concrete properties, silica fume provides increased concrete compressive strength and decreased permeability, which improves resistance to aggressive chemical attack and reduces the potential for chlorides to migrate into the concrete and accelerate the corrosion of reinforcing steel. In areas where exposure to chlorides is prevalent (areas with exposure to deicing salt or seaside areas exposed to salt water), silica fume can improve the durability of concrete repairs.

Aggregates: Appropriate aggregate selection and specifications are often the neglected aspects of the shotcrete mixture design. Generally, specifiers tend to rely solely on ACI 506R, and use either the recommended Gradation #1 or Gradation #2 for combined aggregates (Fig. 4(b) and (c)). However, to ensure optimum durability, including resistance to freezing-and-thawing conditions and alkali aggregate reaction, concrete aggregates should meet the minimum requirements outlined in ASTM C33/C33M, "Standard Specification for Concrete Aggregates."¹¹

When addressing aggregate gradation in a concrete repair application, thickness of the repair will influence the selection of the ACI 506R gradation.



Fig. 4: (a) Silica fume; (b) coarse aggregate; and (c) fine aggregate

The minimum thickness of a shotcrete application should always be a minimum of three times the maximum diameter of the largest aggregate. Taking into consideration that a shotcrete mixture containing a nominal maximum aggregate size of 3/8 in. (12.7 mm) in length, the minimum thickness at which the shotcrete mixture should be placed is 1-1/2 in. (38 mm). The use of larger-sized aggregates in shotcrete will also promote an in-place composition as close as possible to that of cast-in-place concrete.¹² This compatibility (between the repair material and the existing concrete) is a crucial factor in achieving a long-term durable repair.

The use of larger coarse aggregate in shotcrete will also have a positive effect on the shootability of a shotcrete mixture. In the case of dry-process shotcrete, it has been proven that the transportation of dry material through a shotcrete hose is more efficient when the mixture contains coarse aggregates. This efficiency can be attributed to the “cleaning effect” that coarse aggregates provide when traveling through the hose. The abrasion of coarse aggregate against the inside lining of the hose reduces the cement buildup and improves material flow. Accordingly, a coarser aggregate

gradation will allow the use of longer transportation hoses and reduce plugging.

CURING

Curing is critical, especially for concrete repair applications where the repair areas are often thin and exposed to rapid evaporation. Curing will promote the hydration process to optimize hardened concrete properties and improve durability. Proper curing will ensure that the potential for plastic and drying shrinkage will be reduced.

After finishing operations, the fresh concrete is sensitive and must be protected from surface evaporation. 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. In some critical areas exposed to high heat and wind, fogging could be necessary during the finishing operation and prior to curing.

Vertical surfaces, and other non-overhead shotcrete surfaces, should be wet cured using white synthetic fiber burlap, saturated with water, and covered with a polyethylene plastic sheet to avoid surface evaporation (Fig. 5). Wet curing must be continuous for a minimum period of 7 days.



Fig. 5: Curing a vertical shotcrete repair area using a curing blanket

Overhead shotcrete surfaces should be cured using a curing compound that complies with ASTM C309, “Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete.”¹³ The application rate must comply with the manufacturer’s recommendations and form a continuous surface film thick enough to protect the entire surface exposed.

QUALITY CONTROL/QUALITY ASSURANCE

For shotcrete repair applications, the primary goal of a QC/QA program is to assure and verify that the in-place shotcrete achieves the minimum

hardened properties outlined in the project specifications. The type and extent of the QC/QA testing required will vary depending on the shotcrete process (wet versus dry).

For wet-mix shotcrete placement, testing of the fresh concrete material after batching is a simple process that follows the same testing requirements as cast-in-place concrete. Testing criteria for plastic properties include slump, air content, unit weight, and temperature. Hardened property testing such as compressive and flexural strength, rapid chloride permeability, and air-void system analysis would be completed in a laboratory environment using cores extracted from the repaired structure or test panels.

For dry-mix shotcrete, the nature of the process eliminates the need to conduct plastic property testing. As in wet-mix testing, hardened property testing would be completed in a laboratory environment, also using cores taken from the repaired structure or test panels.

Preconstruction Testing: Preconstruction test panels (Fig. 6) remain an option for projects with heavy, congested reinforcing steel, or for architectural “mockups” to verify shotcrete color and surface finishes. For projects with significant reinforcing steel, test panels should be fabricated to mirror the types of congestion and sizes of reinforcing steel that are to be encountered during the shotcrete process. For test panels to accurately reflect each situation, the actual shotcrete mixture design, equipment, and nozzle men should be used.

Nozzle men Certification and Contractor Qualification: One of the most critical tools to

ensure a high level of quality on any shotcrete project is to specify that the nozzleman has obtained ACI certification. While ACI certification verifies that the nozzleman understands the basic theory of shotcrete placement and has demonstrated the skills required to satisfactorily place shotcrete, it does not unilaterally guarantee success.

Nozzlemen certification is only one part of the equation. An equally important aspect of the shotcrete process is the qualification of the contractor. A qualified contractor who specializes in shotcrete placement will typically have certified nozzlemen, a successful track record, equipment, crew, management capabilities, bonding capacity, and verified references that set him or her apart from less-experienced, less-qualified contractors.

To ensure a shotcrete contractor is qualified to bid and execute a contract involving shotcrete placement, the following checklist can be used as a guide:

- Verify the contractor has a long and successful business history (check references);
- Verify the contractor has successful history on similar projects (check references);
- Ask for work history of the contractor's key personnel (nozzlemen and supervisors); and
- Verify that all nozzlemen are certified for the method (dry and/or wet) and orientation (vertical and/or overhead) for which they will be shooting (verification can be obtained through ACI at www.acicertification.org/verify).

CONCLUSIONS

In most cases, the most challenging and successful shotcrete projects begin with a successful specification and continue with a committed team consisting of a knowledgeable engineer, an experienced shotcrete contractor, and a qualified material supplier. Examples of successful concrete rehabilitation projects involving shotcrete placement are plentiful and can be found across North America. Refer to a recent article published in *Shotcrete* magazine¹⁴ regarding the repair of a 60+ year-old dam and power station where the shotcrete process was successfully used in a marine environment.

REFERENCES

1. ACI Committee 506, "Guide to Shotcrete (ACI 506R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 40 pp.
2. ACI Committee 306, "Guide to Cold Weather Concreting (ACI 306R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 26 pp.
3. ACI Committee 305, "Guide to Hot Weather Concreting (ACI 305R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 23 pp.
4. Reny, S., "Surface Preparation for Shotcrete Repair," *Shotcrete*, V. 15, No. 2, Spring 2013, pp. 28-30.
5. Talbot, C.; Pigeon, M.; Beaupré, D.; and Morgan, D. R., "Influence of Surface Preparation on Long-Term Bonding of



Fig. 6: Preconstruction testing of shotcrete using a test panel

Shotcrete," *ACI Materials Journal*, V. 91, No. 6, Nov.-Dec. 1994, pp. 560-566.

6. Beaupré, D., "Bond Strength of Shotcrete Repair," *Shotcrete*, V. 1, No. 2, Spring 1999, pp. 12-15.

7. U.S. Department of the Interior Bureau of Reclamation, "Best Practices for Preparing Concrete Surfaces Prior to Repairs and Overlays," Report No. MERL 12-17, Technical Service Center, Denver, CO, May 2012.

8. ASTM C457/C457M-12, "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete," ASTM International, West Conshohocken, PA, 2012, 15 pp.

9. 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.

10. Wolsifer, J., Sr., and Morgan, D. R., "Silica Fume in Shotcrete," *Concrete International*, V. 15, No. 4, Apr. 1993, pp. 34-39.

11. ASTM C33/C33M-11, "Standard Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 2011, 11 pp.

12. Reny, S., and Jolin, M., "Improve Your Shotcrete: Use Coarse Aggregates!" *Shotcrete*, V. 13, No. 1, Winter 2011, pp. 26-28.

13. ASTM C309-11, "Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete," ASTM International, West Conshohocken, PA, 2011, 3 pp.

14. Côté, R.; Ferland, H.; and Robertson, K., "McCormick Dam & Power Station: Submerged Concrete Repairs," *Shotcrete*, V. 17, No. 1, Winter 2015, pp. 36-39.



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