

Shotcrete Testing— Who, Why, When, and How

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Who Needs It?

If you are an architect or engineer (A/E) who routinely uses shotcrete in your projects, you likely already know why, when, and how to specify shotcrete. Sorry, this article probably won't be giving you much new information; but it should be a great refresher.

There are many examples of construction team professionals, however, who may not be as knowledgeable in specifying testing of shotcrete and should find this article of distinct interest.

Are you one of these?

- The specifying A/E involved in a new project where the owner has suggested shotcrete or industry standard designs include something called “shotcrete”; or
- An A/E responsible for the field administration of an existing project and the contractor have suggested the value engineering use of shotcrete instead of cast concrete for some of the structural components of the job; or
- You are a design-build contractor and one of your subcontractors is using shotcrete in his portion of the project; or
- An owner who is concerned about the quality and durability of your project; or
- A shotcrete contractor and neither the owner nor the specifier has included testing in the project.

Thus, the short answer to the question “Who needs it?” is everyone involved in designing, producing, placing, and evaluating shotcrete in a concrete structure.

Why Test Shotcrete?

So why do we want to test shotcrete? The primary goal of any testing is to confirm that the shotcrete placed meets the project requirements. This is a quality control (QC) issue for the material supplier and contractor and a quality assurance (QA) issue for the owner and A/E.

But isn't shotcrete just concrete that is placed at a high velocity using air pressure? Don't the usual concrete tests work? The answer is yes and no, and the answer depends on whether we are using dry- or wet-mix shotcrete and whether we are evaluating hardened shotcrete in-place or using a sample for lab testing.

In wet-mix shotcrete, the concrete mixture is either batched and delivered by a ready mix

concrete supplier or maybe mixed on site and fed directly to the shotcrete pump. The concrete is then pumped to the nozzle at the end of the delivery hose where air pressure “shoots” the material out of the hose and onto the structure. With wet-mix shotcrete, testing of the fresh concrete material after batching would certainly follow the same testing requirements as cast-in-place concrete. This would include items such as slump, air content, unit weight, and temperature. Further, it may be advisable to take several test cylinders of the batched concrete to have a representative sample of the concrete as delivered.

Dry-mix shotcrete is an entirely different process where air pressure is used throughout the length of the delivery hose to convey a dry mixture of cementitious material and aggregate to the nozzle. Water isn't added to the dry mixture until it enters the nozzle at the end of the shotcrete delivery hose. Immediately after passing by the water jets in the nozzle, the dry-mix shotcrete is shot onto the structure surface. Thus, there is no batch of fresh, wet concrete material to test for the routine concrete tests.

When and How Do We Test?

There are three distinct times that shotcrete testing is needed:

- Preconstruction;
- During construction at the time of placement; and
- After hardening and appropriately cured and aged.

Preconstruction Testing

Many projects use preconstruction test panels when the project has heavy, congested reinforcing in the structural sections to be shot (refer to Fig. 1). The test panels are fabricated to mirror the types of congestion that are to be expected in the project. They are used to qualify three different aspects of the shotcrete: 1) the material being shot; 2) the equipment used for shooting; and 3) the nozzleman doing the shooting. Thus, for test panels to accurately reflect each aspect, the actual shotcrete mixtures, equipment, and nozzlemen for the project must be used.

Separate test panels should be used for mixture proportion evaluation and for nozzleman qualification. ACI 506R-05 recommends mixture

proportion test panels measuring 24 x 24 x 3-1/2 in. (610 x 610 x 90 mm) with flared sides and no reinforcement. The nozzleman qualification test panels should be large enough to simulate the actual project conditions with a minimum size of 30 x 30 x 3 in. (760 x 760 x 75 mm) and use reinforcing that models the size and complexity of reinforcement to be shot on the project. The orientation of the panels (horizontal, vertical, or overhead) should also match the orientation of the work on the project (refer to Fig. 2). Once the shotcrete has sufficiently hardened and aged, both types of test panels are then cored to provide 3 in. (75 mm) diameter cores (refer to Fig. 3) for evaluation of the quality of encasement or for further laboratory testing. The unreinforced cores should be tested for compressive strength. ACI 506.2-95, "Specification for Shotcrete," lists contractor requirements for testing.

Preconstruction test panels may also be used to provide architectural "mockups" of the completed shotcrete color and surface finishes. Architectural panels would need to be shot with the same mixture proportions (including admixtures) and then finished with the same techniques to be used on the project. A minimum size of an architectural mockup panel should be 30 x 30 x 3 in. (760 x 760 x 75 mm). Different sizes may be needed, however, to give the full effect of a particular surface treatment. An architectural mockup helps the owner, A/E, and contractor agree on what the final product will look like before it is used on a project.

Finally, in the preconstruction period, the wet-mix shotcrete mixture proportions may be tested. Concrete mixture designs are often provided from previous experience of the concrete supplier or the testing laboratory doing the mixture design. When new components are used in a shotcrete mixture, however, such as new suppliers for supplementary cementitious materials (SCMs) or different combinations of admixtures (such as retarders, high-range water-reducing admixtures [HRWRAs], and accelerators), it may be prudent to evaluate the mixture before testing on site. Test batches of a proposed mixture may be cast in standard cylinders or forms and then tested at the appropriate age. The mixture proportioning tests may include simple 28-day compressive strength or more advanced properties such as set time, very-early-age strength (for example, 8-hour strength has been used in some tunnel work) or drying shrinkage potential.

Testing during Construction at Time of Placement

One of the most important times to test shotcrete is during construction at the time of placement. At this time in the construction work,



Fig. 1: A typical preconstruction test panel with congested reinforcement



Fig. 2: Overhead shooting



Fig. 3: Coring of a test panel



Fig. 4: A typical shotcrete test panel being shot during construction

we are most interested in the fresh shotcrete properties. It is also the time we produce test panels for subsequent testing of the hardened shotcrete properties.

Testing of fresh shotcrete helps to confirm that important aspects of the specified mixture proportions have been met and the temperature of the shotcrete does not exceed the specified maximums. This testing generally does not verify the amount of cementitious materials or aggregates in the mixture. Thus, it is highly recommended that each delivery of concrete include on the delivery ticket a record of water, admixtures, cement, SCMs, and aggregates used in producing that specific batch and not just repeating the theoretical mixture design. Any water added on site should also be noted on the delivery ticket by the driver.

For wet-mix shotcrete, where the concrete is batched before pumping, sampling of the concrete before pumping would include these fresh concrete properties:

- Slump (ASTM C143);
- Air content (ASTM C231 or ASTM C173);
- Concrete temperature (ASTM C1064/C1064M); and
- Density (ASTM C138).

These fresh concrete properties are readily tested using current ASTM standards. These tests can also be performed on concrete created with prebagged shotcrete mixtures that are mixed on site.

Also, during shotcrete placement, test panels will be made for determining the hardened shotcrete properties after appropriate curing and aging of the panels. Test panels will be produced for each mixture, each nozzleman, and each work day or for every 50 yd³ (38 m³) of shotcrete placed, whichever results in the most panels. These test panels should be at least 16 x 16 in. (400 x 400 mm) with a depth of at least 3 to 5 in. (75 to

125 mm) and are generally shot in a vertical orientation (refer to Fig. 4), unless the project needs to dictate shooting in another orientation.

Even though shotcrete test panels will be produced for either wet- or dry-mix shotcrete to determine hardened shotcrete properties, it would also be advisable to periodically prepare standard cylinders (6 x 12 in. [150 x 300 mm] or 4 x 8 in. [100 x 200 mm]) for each concrete mixture as delivered before pumping. These cylinders should be field cured on site. The cylinders do not need to be tested and could be considered as an insurance policy. They can be invaluable if shotcrete problems arise on the project and one must try to determine whether the problem was caused by the concrete materials, the ready mix supplier, or some flaw in the shotcreting application.

After Hardening and Appropriately Cured and Aged

Hardened shotcrete properties are normally determined by laboratory testing. Usually, samples are extracted from the previously prepared test panels. Cores may also be extracted from the in-place structure for testing. Care must be exercised, however, in taking cores to be sure no critical reinforcement is severed in the coring process or the compressive capacity of the cored member is significantly decreased.

The most common test on hardened shotcrete is the compressive strength at 28 days of cores taken from the test panels (ASTM 1604/C1604M). Some applications also require particular compressive strengths at less than the 28-day period. This is common in underground applications and in some structures with early post-tensioning requirements. The compressive strength is considered adequate if the average of the three cores from a test panel or from in-place shotcrete exceeds 85% of the specified compressive strength and no single core is less than 75% of the specified compressive strength.

Bond strength testing may be required when shotcrete is required to adhere to a previously existing material. Bond strength is tested using the provisions of ASTM C1583/C1583M. Common acceptance criteria for bond strength is that the average of the bond strength of the specified number of cores should exceed the specified minimum strength and no single core bond strength should be less than 75% of the specified strength.

Flexural properties are usually only required for fiber-reinforced shotcrete (FRS). When FRS is specified, flexural strength is evaluated using beams sawed from test panels tested in accordance with ASTM C1609/C1609M and for residual strength in accordance with

ASTM C1609/C1609M or ASTM C1399/C1399M. For toughness, tests should be in accordance with ASTM C1550.

Boiled absorption and the volume of permeable voids testing (ASTM C642) may be required for structures that need enhanced liquid tightness or resistance to aggressive environmental exposures. The test is sometimes used to provide an overall indication of the quality of the shotcrete mixture, particularly in dry-mix shotcrete. Many factors, however, including admixtures, aggregate, and shotcrete placing, can affect the porosity of shotcrete, so it should not be considered an absolute measure of shotcrete quality. When required, the mean average of tests on three specimens from a test panel, or from in-place shotcrete, should be less than or equal to the specified boiled absorption and/or the specified volume of permeable voids limits at the specified test age with no single test greater than the specified boiled absorption plus 1%.

Drying shrinkage of the shotcrete can be tested using general provisions of ASTM C157. Because the shotcrete is shot into a large panel and not into the relatively small mold specified by ASTM for the shrinkage test beam, it is recommended that a beam approximately 11.25 in. (285 mm) in length be sawed from a test panel. As most shotcrete uses coarse aggregate less than 1 in. (25 mm), a 3 in. (75 mm) thick panel with a 3 in. (75 mm) wide cut should approximate the ASTM requirements. The A/E should specify in the contract documents drying shrinkage limits that are appropriate for the design of the structure.

Other Testing

When problems are suspected in shotcrete placed in a structure, the evaluation of the potential deficiencies can be conducted identically to the methods used for normal cast concrete. This may include nondestructive testing such as ultrasonic pulse velocity, impact echo, impulse response, or ground-penetrating radar. A Windsor Probe may be used for evaluating in-place strength.

Also, with partial or full-depth cores, the shotcrete material may be evaluated with petrography or further chemical or physical tests. Petrography can give information on in-place air content, estimated water-cementitious material ratio (w/cm), quantity of cementitious material, presence of alkali-silica reaction (ASR), or delayed ettringite formation (DEF), as well as the evaluation of the general quality of the concrete paste and aggregate matrix. Advanced chemical analysis can yield information on potential detrimental contaminants, such as chlorides and sulfates, in

the concrete. Finally, additional physical tests for shear, tension, and compression can be conducted on cores extracted from the structure.

Resources for Specifiers and Additional Information

ACI 506 is the technical committee charged with producing standards, specifications, guides, and reports that deal with all aspects of shotcrete. Current ACI 506 documents include:

- ACI 506R, “Guide to Shotcrete”—This is a nonmandatory guide to all aspects of shotcrete design and construction. It has some excellent guidance on both materials and testing of shotcrete. A revision to the guide is under active development by the committee and is due out soon.
- ACI 506.1R, “Guide to Fiber-Reinforced Shotcrete”—This nonmandatory report focuses on the benefits and use of fiber-reinforced shotcrete.
- ACI 506.2, “Specification for Materials, Proportioning, and Application of Shotcrete”—This mandatory specification provides requirements to contractors using shotcrete on projects. Specifiers should review the document in full and determine what portions apply to their specific project. The mandatory and optional checklist items in the document provide guidance to the specifier on items that must be specified (mandatory) in the contract documents and those that should be considered (optional). Although the currently available version is from 1995, a new version of the specification should be available later in 2011 or early 2012.
- ACI 506.4R, “Guide for the Evaluation of Shotcrete”—A nonmandatory report focused on procedures used to evaluate the quality and properties of in-place shotcrete. This has some good information, although it is somewhat dated.
- ACI 506.5R, “Guide for Specifying Underground Shotcrete”—If you are specifying underground shotcrete, this should be a document you review thoroughly. It is the most current ACI 506 document and gives you great guidance on the aspects needed to specify underground shotcrete.
- ACI 301, “Specifications for Structural Concrete”—This mandatory specification provides requirements for contractors in general building construction. Although it doesn’t cover shotcrete at all, some provisions, such as mock-ups for architectural treatments and concrete testing, may be beneficial for review.

Please be aware that in developing specifications for your projects, you shouldn’t simply reference nonmandatory ACI reports and guides, as they

aren't written in enforceable language. You can, however, take provisions of those nonmandatory documents and make them mandatory in your specification. Also, in referencing ACI specifications, the following guidance should be followed:

“ACI Specification XYZ is to be used by reference or incorporation in its entirety in the Project Specification. Do not copy individual

Sections, Parts, Articles, or Paragraphs into the Project Specification, because taking them out of context may change their meaning.

If Sections or Parts of ACI Specification XYZ are copied into the Project Specification or any other document, do not refer to them as an ACI specification, because the specification has been altered.”



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