The Evolution of Shotcrete Evaluation and Testing

By George Seegebrecht

The versatility of concrete is truly impressive. Changing the concrete aggregate type, gradation, or removing a portion of aggregate can change common concrete to become lightweight, heavyweight, or pervious concrete, to list a few types. Using today's admixtures, concrete can be accelerated, retarded, or suspended in its setting behavior, allowing wider possibilities in concrete placement.

Changing placement methods from concrete truck chute, bucket, or pumping allows placement of concrete over longer distances, at greater elevation changes, or on steep slopes, and in extreme climates.

Shotcrete enhances the creativity and versatility of concrete. The dry-mix shotcrete process (originally trade-named gunite) pneumatically propels concrete materials under pressure to the nozzle at the end of the hose, where water is added to the materials stream. The wet-mix shotcrete process pumps fully mixed concrete through the hose, where at the nozzle, air flow is used to produce high velocities that compact the materials on impact. Also referred to in Europe as "sprayed concrete," shotcrete is conveyed under pressure at high velocity so consolidation is achieved instantly upon impact. The shotcrete process allows concrete to be placed without forms, into complex shapes, vertically, and overhead. Shotcrete has been the construction tool of choice for pools, tunnels, domes, tanks, foundation walls, soil stabilization, and a wide range of repairs in easy-to-reach or seemingly inaccessible locations.

To determine if this rapid placement process is successful, testing is necessary to verify that the shotcrete applied is of good quality, both strong and durable. Differences between shotcrete and form-and-pour concrete are primarily in the placement method and, to a degree, in the concrete materials and admixtures. Like other unique concretes, testing specific to shotcrete was needed to provide assurance that the applied materials will perform the intended function and exhibit durability for the design life required.

SHOTCRETE EVALUATION AND TESTING THROUGH THE YEARS

Before progress can be made in testing a material, an accepted name had to be established. Formed in 1904, the American Railway Engineering Association (AREA) adopted the term "shotcrete" circa 1930 to encompass the many proprietary names generated for the dry-mix process that had appeared in addition to "gunite," such as: guncrete, blastcrete, jetcrete, spraycrete, spritz-beton, and so on.

In 1942, the American Concrete Institute (ACI) formed Committee 805, "Recommended Practice for Pneumatically Applied Mortar." ACI 805-51, in the introduction (excerpted in the following paragraph), established a consistent term in the interest of clarity. The term "shotcrete" was set by the committee as the nomenclature for the remainder of the document.

"To avoid the cumbersome term 'pneumatically-placed mortar' the word 'shotcrete' is used to refer to this material in the remainder of this report."

This helped standardize the use of the term in the United States. By contrast, Europe and other parts of the world adopted the term "sprayed concrete."

ACI Committee 805 was retired after completion of the Practice Recommendation, but in 1957, ACI Committee 506, Shotcreting, was created, and in 1960 organized to revise and update the recommended practice for shotcreting. ACI 506 Chair Thomas J. Reading stated in the preface to publication SP-14, *Shotcreting*, that the committee quickly found there was a scarcity of engineering data on shotcrete, its properties, and performance. Also, that there was an obvious need for better guidance for field personnel who apply shotcrete and for the designer as to what can reasonably be expected of the material. The committee sought out the shotcrete-related input of committee membership including most knowledgeable engineers, shotcrete contractors, equipment manufacturers, general contractors, admixture manufacturers, federal and local government representatives, port authorities, and the Portland Cement Association to address this deficiency in guidance.[1-3]

ACI Committee 506, Shotcreting, has since sponsored many ACI symposia and seminars, and produced numerous documents to aid those working with shotcrete in the recommended practice and specifications and use of shotcrete in a variety of above-ground and underground applications.

RAPID IMPROVEMENTS IN SHOTCRETE

According to George D. Yoggy in his "History of Shotcrete" series,[1] the years following World War II saw rapid change and improvements. The shotcrete industry was introducing new technology and producing the first significant equipment changes since the original invention in 1907.

In 1957, the rotary gun was introduced and not only enabled easier operation but could also incorporate larger-sized aggregate into the mixture. The "continuous feed" guns made a significant change in the industry, allowing for the successful delivery of relatively higher production rates. Many are still in use today, incorporating various batching, mixing, and feeding mechanisms.

Rapid growth frequently comes with growing pains. After shotcrete's first 40 years of outstanding growth and success, the dry-mix process improvements and wider industry acceptance drew many into the industry. Was the growth so fast that it was uncontrolled? Did the new machine developments make operation so easy that training seemed no longer necessary? A period of poor workmanship soon followed in the 1970s, resulting in damage to the reputation of shotcrete as a reliable process.

Those knowledgeable in the shotcrete industry knew corrections had to be made to regain the true image of the process that, when properly designed and executed, produced high-quality, durable in-place concrete. The righting of the ship was again due to the work of dedicated industry individuals who provided their experience to restore the standards the industry needed. Names of notable individuals that contributed are listed by George Yoggy in his "History of Shotcrete" article and included: Crom, Maier, Fredricks, Reading, Moore, Carroll, Truman, James Warner, Esposito, Rappa, Zynda, Lorman, and Leon Glassgold. But of course, this list is incomplete, as it continues to grow every year, including names like Yoggy, Litvin, Gebler, Rizzo, Morgan, and more recently research and testing by Jolin and Zhang.

In the 1960s, Joseph J. Shideler and Albert Litvin at the Portland Cement Association R&D Labs prepared numerous papers[4,5] detailing both wet and dry shotcrete processes covering all aspects of equipment, mixture designs, crew duties, gunning procedures, finishing, and curing.

They presented papers reporting shotcrete laboratory studies on 39 shotcrete mixtures in *Shotcreting*, an ACI Special Publication.[5] Studies reported tests conducted on test panels submitted by numerous contractors and equipment manufacturers. Tests were conducted to compare quality of shotcrete produced by various types of equipment commonly in use at the time. Test data was obtained to determine material properties of each submitted shotcrete panel and included data such as: compressive and flexural strength, modulus of elasticity, drying shrinkage, creep, absorption, freezing-and-thawing durability, and permeability.

Initially, shotcrete was tested using established cast concrete tests. ASTM standard concrete test methods for concrete were used to qualify the individual constituents of shotcrete-making materials, but there was a need for ASTM International to develop new standards specific to shotcrete materials and testing. ASTM International established a subcommittee of Committee C09, Concrete and Concrete Aggregates, in the 1990s to develop standards for shotcrete testing. (The six shotcrete-specific ASTM Standards developed by the ASTM Subcommittee C09.46, Shotcrete, are described later in this article.)

Pre-construction test panels: Used when a project has heavy, congested reinforcement in the structural sections to be shot. The test panels are fabricated with reinforcing steel to mirror the type of congestion that is to be expected in the project, and 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. Sometimes used to establish architectural texture and color of finished shotcrete.

Material test panels: Used to provide QC/QA for materials being shot on a project. ACI 506.2 specifies a panel a minimum of 16 x 16 x 5 in. (400 x 400 x 125 mm) for panels. These panels are not reinforced, and are usually shot with a frequency of every 50 to 150 yd^3 (38 to 110 m^3) or if shooting lower volumes, at least once a day. Cores for compressive strength testing or other physical properties are extracted from the panels.

Fresh concrete testing: Concrete to be shotcreted is often tested for slump, air content, concrete temperature, and density. The tests are usually run at the point of delivery—at the pump for wet-mix and at the nozzle for dry-mix.

Hardened concrete testing: 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. Cores are routinely used to test for compressive strength, but may also be used for permeability, density, or hardened air void analysis.

Compressive strength testing: The most common acceptance method for concrete. Usually measured at 28 days, but often checked other times such as 3, 7, and 14 days, to get an earlier indication of the probable 28-day strength.

Flexural and toughness testing: Flexural properties are usually only required for fiber-reinforced shotcrete (FRS), and predominately used for underground applications. When FRS is specified, flexural strength and residual strength are evaluated using beams sawed from test panels. For toughness, round panels are shot and tested in accordance with ASTM C1550.

Source: Hanskat, C. S., 2011, "Shotcrete Testing—Who, Why, When, and How," *Shotcrete*, V. 13, No. 3, Summer, pp. 8-12.

Many researchers, engineers, and contractors have conducted comprehensive testing programs to characterize shotcrete properties. It was a blessing to work at PCA's Construction Technology Laboratories (CTL) with two previous ACI 506 Chairs in Albert Litvin and Steve Gebler, who have

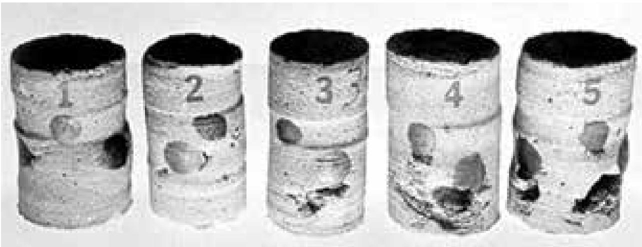


Fig. 1: When developed, the core grading system was used to judge the skill of the nozzleman to encapsulate reinforcing steel. Degree of voiding, presence of sand seams, and encapsulation of reinforcing steel were the focus of visual observations of the cores. However, the process was judged to be flawed. Many questioned the approach as too subjective and variable due to shotcrete experience of the evaluator. Significant differences between those grading cores yielded significantly different results that ranged from passing (grade 1-2-3) to failing (grade 3-4-5) results on the same set of cores. Some specified core grades that were higher than necessary for certain jobs, causing good-quality materials to be questioned or rejected when its performance would have more than met service requirements

Fig. 2: Visual observation during shotcrete observation may note improper shooting techniques, resulting in inclusion of voids or rebound materials with low integrity where it matters most. Laboratory tests of panel cores do not address this issue, as it is related to shooting technique in this location. Visual examination for cracking patterns, supplemented by hammer sounding (ASTM C4580-12) to detect hollow/delaminated areas for closer study, and possible coring for laboratory testing where relevant properties can be determined

Fig. 3: Visual inspection of cores extracted from structures with unusual cracking or leaking can help to reveal improper shooting techniques or poor materials. All concrete has some degree of void or less than perfectly consolidated materials. Using an ACI Certified Nozzleman and crew that works well together to avoid inclusion of rebound is critical

developed and conducted many testing programs, and in my case, supervised and mentored through numerous projects.

Steve Gebler conducted many testing programs including assessments of the durability of dry-mix shotcrete and the durability of dry-mix shotcrete with rapid-set accelerator, as well as the strength, bond, and durability of shotcrete used in the repair of East Coast concrete cooling towers. He was passionate about shotcrete and wrote numerous articles regarding the core grading system, shotcrete tolerances, and shotcrete pool construction.[6-8]

When receiving field-shot test panels, they were cored in the laboratory to obtain specimens to determine properties including compressive strength, hardened concrete air voids, freezing-and-thawing performance, chloride ion penetration, specific gravity, and boiled water absorption.

The difference in the placement method is significant. For instance, with form-and-pour concrete, strength test specimens are cast as cylinders. With shotcrete placement, the impact, air flow, and production of rebound prevent representative specimens to be produced in cylinder molds. Thus, shotcrete compressive strength specimens are cored from standardized test panels.

To assure the ACI Certified Nozzleman can adequately encapsulate reinforcement configurations on a specific project, qualifying test panels are prepared and shot for subsequent coring to assess shotcrete placement around reinforcing bar and presence of voids and sand seams. Core "grading" was initially recommended in ACI 506.2-95, "Specification for Shotcrete," for evaluation of test panels, but the system has fallen out of favor due to the subjective nature in rating cores by inexperienced engineers or inspectors (Fig. 1). In our office, with our ample shotcrete experience, the core grading system worked well. On specific evaluations, the core grading was done by multiple (three) engineers independently and then averaged. If major discrepancies occurred, discussions were held, field observations added, additional cores were examined, or in extreme cases, supplemental cores were taken.

In the field, another form of testing starts with visual inspection (Fig. 2 and 3) by experienced shotcrete practitioners. Batching and mixing in the field should be observed to assure that they follow ASTM and ACI requirements for shotcrete materials. Prepackaged materials used in the dry-mix process should be pre-dampened just before use.

Inspection to visually note unintentional textural changes could signal the presence of rebound or overspray included in the work.

An engineer, inspector, or contractor experienced in shotcrete can recognize poor shooting practices during installation, such as shotcrete material buildup on reinforcing steel. On completed work, it may be possible to note suspect color changes that may signal undesirable, poorly mixed shotcrete fluctuations in water/cementitious material added to the mixture.

Such observations might next lead to hammer sounding to detect soft, punky, or delaminated shotcrete. Soundings may provide indications for locating representative cores for lab or field testing. Common tests conducted included freezing-and-thawing testing (ASTM C666), compressive strength (ASTM C1604), or in repair situations, ASTM C1583 to determine the tensile strength of concrete of concrete overlain with a repair material (Fig. 4).

ASTM Specifications Addressing Shotcrete Materials and Testing

As mentioned, shotcrete differs from form-and-pour concrete in its placement method. Most hardened properties are the same as cast concrete. Initially, shotcrete tests were conducted using existing ASTM tests for concrete with modifications as necessary because of the placement method. It became evident that shotcrete placement differs enough that these aspects must be taken into consideration when sampling and testing shotcrete to assess performance and properties. In this regard, ASTM C09.46 was established to produce testing and material standards for shotcrete that could be referenced in project specifications and in technical documents from ACI Committee 506, Shotcreting. ASTM C09.46 formalized the testing methods for preparing and sampling test panels and the extraction of cores needed for compressive strength testing and other physical properties. Tests for fiber-reinforced shotcrete and packaged/preblended materials were also addressed. ACI 506 documents including a guide, specifications, and evaluation report are used with the ASTM shotcrete tests to provide a comprehensive procedure for evaluating shotcrete quality.

ASTM Subcommittee C09.46 works on the following active shotcrete standards[9]:

- ASTM C1140/C1140M-11, "Practice for Preparing and Testing Specimens from Shotcrete Test Panels"
- ASTM C1141/C1141M-15, "Specification for Admixtures for Shotcrete"
- ASTM C1385/C1385M-10, "Practice for Sampling Materials for Shotcrete"
- ASTM C1436-13, "Specification for Materials for Shotcrete"
- ASTM C1480/C1480M-07 (reapproved 2012), "Specification for Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete Application"

Fig. 4: Field testing according to ASTM C1583. Tensile bond pulloff conducted on repair using a silica fume shotcrete overlay. Setting acceptable values would be influenced by site conditions, especially the integrity of the substrate

- ASTM C1604/C1604M-05 (reapproved 2012), "Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete"

Two standards related to establishing setting time of shotcrete developed by C09.46, but withdrawn due to issues with establishing the precision statements are:

- ASTM C1117-89(1994), "Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance (Withdrawn 2003)"
- ASTM C1398-07, "Standard Test Method for The Laboratory Determination of the Time of Setting of Hydraulic-Cement Mortars Containing Additives for Shotcrete by the Use of Gillmore Needles (Withdrawn 2010)"

ASTM International also has tests that have been directly applied to use in fiber-reinforced shotcrete, including:

- ASTM C1550-12a, "Test Method for Flexural Toughness of Fiber-Reinforced Concrete (Using Centrally Loaded Round Panel)"
- ASTM C1609/C1609M-12, "Standard Test Method for Flexural Performance of Fiber Reinforced Concrete (Using Beam with "Third Point Loading)"

Shotcrete technology will continue to evolve and improve with the modification of shotcrete equipment, admixture use, and the introduction of different fibers or blends of different fiber lengths and types. Testing will need to continue to track along with modern developments to optimize designs, safety, and construction efficiency.

SHOTCRETE TESTING NEEDS FOR THE FUTURE

The outlook for the shotcrete industry is bright with the nation's repair needs ahead. Both PCA economist Ed Sullivan and the Wells Fargo's Construction Optimism Quotient (OQ) index for 2016 indicate optimism is high for general construction in the future. Just look at our deteriorating infrastructure. The American Society of Civil Engineers (ASCE) 2017 infrastructure report card rates the United States' infrastructure portfolio a dismal D+ grade. Recent years of equipment and materials improvements, along with the ACI Nozzleman Certification program, position the shotcrete industry to be a popular and dependable approach for the infrastructure repair work ahead.

Real-time maturity testing is more and more popular in conventional concrete and would benefit shotcrete as well. Hurdles may include the mixture changes inherent in the shooting process and the potential damage to maturity sensors if caught in the direct flow of shotcrete. The benefits of nondestructively monitoring strength development are obviously a plus for safety, but possibly also for monitoring efficiency of curing of shotcrete.

The benefits of shotcrete are many as it is a creative, versatile, economical, and sustainable method for the concrete construction needs ahead.

References

1. Yoggy, G. D., "The History of Shotcrete," *Shotcrete*, V. 7, No. 4, Summer 2005, pp. 26-32.

2. Glassgold, I. L., "Shotcrete in the United States: A Brief History," *Evaluation and Rehabilitation of Concrete Structures and Innovations in Design*, SP-128, American Concrete Institute, Farmington Hills, MI, 1991, pp. 289-306.

3. Glassgold, I. L., "Shotcrete," *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, STP 169C, ASTM International, West Conshohocken, PA, 1994, pp. 589-598.

4. Shideler, J. J., and Litvin, A., "Structural Applications of Pumped and Sprayed Concrete," *Research and Development Bulletin* D72, Portland Cement Association, Research and Development Laboratories, Skokie, IL, 1964, 29 pp.

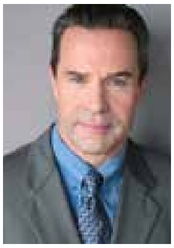
5. Litvin, A., and Shideler, J. J., "Laboratory Study of Shotcrete," *Shotcreting*, SP-14, American Concrete Institute, Farmington Hills, MI, 1966, pp. 165-184.

6. Seegebrecht, G. W.; Litvin, A.; and Gebler, S. H., "Durability of Dry-Mix Shotcrete," *Shotcrete*, V. 8, No. 2, Spring 2006, pp. 32-35.

7. Gebler, S. H., and Seegebrecht, G. W., "Confirming Shotcrete Quality on Site," *Shotcrete*, V. 7, No. 2, Spring 2005, pp. 10-14.

8. Gebler, S. H., "Durability of Dry-Mix Shotcrete Containing Regulated-Set Cement," *Concrete International*, V. 11, No. 10, Oct. 1989, pp. 56-58.

9. Hanskat, C., "U.S. Shotcrete Standards Update," *Shotcrete*, V. 15, No. 3, Summer 2013, pp. 44-46.



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