Determination of Early-Age Compressive Strength of Shotcrete

by Roland Heere and Dudley R. Morgan

There has long been a need for a reliable, simple-to-use means of determining the early-age rate of strength gain in shotcrete. During approximately the first 24 hours after shotcrete has been placed, its compressive strength is typically too low to measure using standard core-extraction and testing procedures. Monitoring the rate of early-strength development in shotcrete is important in tunneling, mining, and other applications such as the underpinning of structures. Recent studies by the authors have demonstrated that there is a simple, direct method for determining the early-age compressive strength development of shotcrete. It involves the shooting of a set of beams in a standard steel mold and testing the beams after stripping, using an adaptation of ASTM C 116, "Standard Test Method for Compressive Strength of Concrete using Portions of Beams Broken in Flexure." This "Technical Tip" describes a procedure for determining the compressive strength of shotcrete beams and presents results of tests conducted with plain and accelerated shotcretes produced by both the wet- and dry-mix shotcrete processes.

Background

In shotcrete, for ground support in tunneling (particularly NATM), mining, and underpinning of structures, it is necessary to know the rate of early-strength development. This is particularly true for accelerated shotcretes, where the shotcrete may have a measurable compressive strength as soon as 15 min after application. Frequently, it is not realistic to extract core specimens from a shotcrete test panel, ship them to a testing laboratory, and condition and test them in such a short time frame. Furthermore, the extraction of cores from standard shotcrete test panels before the shotcrete has reached a compressive strength of approximately 10 MPa (1450 psi) is not recommended, as cores tend to ravel, resulting in unreliable strength-test data. Similarly, attempts to diamond saw-cut cubes from shotcrete test panels are problematic, because of raveling and breaking during cutting.[1-3]

A variety of different methods has been used by the Europeans and others in an attempt to determine the rate of early-strength development in the range of 0.5 to 10 MPa (70 to 1450 psi). These methods include the use of impact hammers, penetrating pins, and pullout devices. All of these methods, however, provide only an indirect measure of compressive strength and are thus only as good as their calibration to compressive strength measured by other means. As such, they have their limitations.

In 1995, the first author observed compressive-strength testing being done at the University of Innsbruck in Austria on dry-mix shotcrete shot into small, 25 x 25 x 100-mm (1 x 1 x 4 in.) wooden

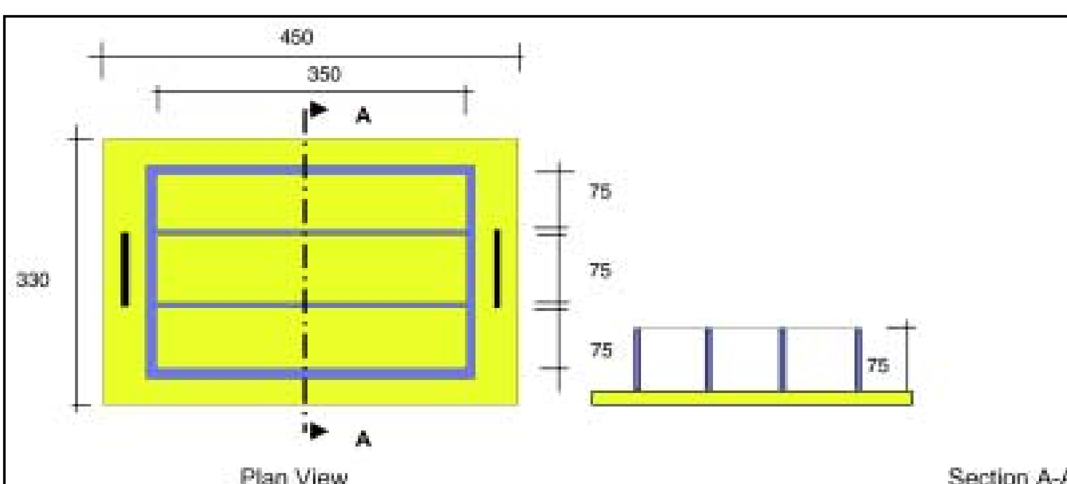

Figure 1: Sketch of ganged three-beam steel mold.

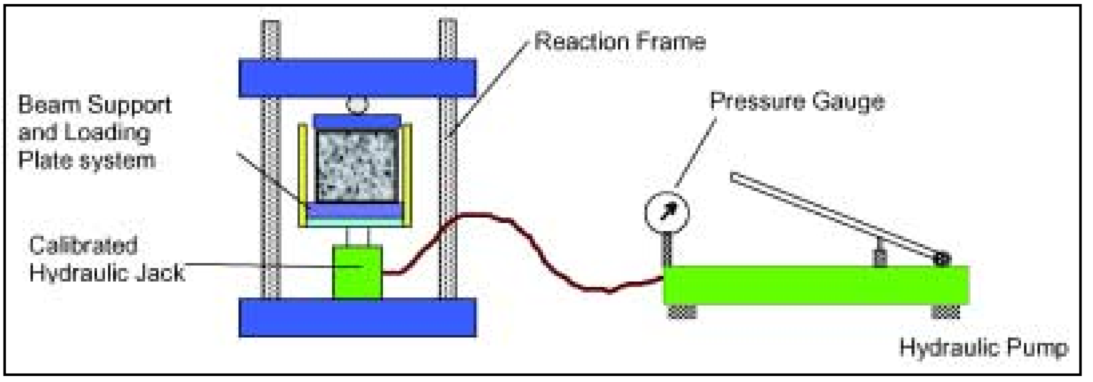

Figure 2: Portable compression-testing machine.

beam molds. The authors decided to investigate whether this method could be adapted to full-scale testing of accelerated shotcrete in the field, for shotcrete applied with either hand-nozzling or remote-control, manipulator-arm nozzling for both the wet- and dry-mix shotcrete processes. Research conducted in Canada, field studies on a tunneling project in Canada, and mining projects in the USA and Australia have demonstrated the suitability of this test method for determining the early-age compressive-strength development of shotcrete. Using this test method, the authors have been able to reliably measure the compressive strength of accelerated shotcrete when the compressive strength of the shotcrete varied from as low as 0.5 to as high as 20 MPa (70 to 2900 psi), and higher, 24 hours later. A description of the test method, as adapted by the authors for the evaluation of various accelerated dry- and wet-mix shotcretes, is given as follows.

Description of Test

Equipment

The test method is suitable for use with standard shotcrete-placing equipment and shotcrete with a 10-mm (3/8 in.) maximum aggregate size. For the production of the beam specimens, a set of three ganged steel molds was mounted on a common base plate. The internal dimensions of each individual mold are 75 x 75 x 350 mm (3 x 3 x 14 in [see Figure 1]).

A portable compression-testing machine was used by the authors to field-test the specimens. It consisted of a manual hydraulic pump, a calibrated pressure gage, a 10-ton hydraulic jack, a stiff reaction frame, a spherical seat-loading head, and suitable hydraulic pressure hoses and connectors. If there is ready access to a testing laboratory, a universal testing machine may be used in lieu of the portable compression-testing machine. Figure 2 provides a simplified view of the testing apparatus.

During testing, the beam was supported on two support plates as shown in Figure 3. A top-loading plate with the dimensions 75 x 75 x 20 mm (3 x 3 x 3/4 in.) transmits the load from the loading head to the specimen. The loaded section of the beam specimen is supported by a 75-mm-long (3 in.), 80-mm-wide (3.2 in.), and 20-mm-deep (3/4 in.) bottom plate. The bottom plate has vertical guides to enable easy alignment of the top and bottom plates with the beam section to be tested. Figure 3 shows the loading plates. Note the 75-mm (3 in.) gap between the 75-mm-long (3 in.), 80-mm-wide (3.2 in.), and 20-mm-deep (3/4 in.) bottom loading plate and the 200-mm-long (7.9 in.), 80-mm-wide (3.2 in.), and 20-mm-deep (3/4 in.) bottom support plate. This gap is important in preventing failure in the beam during the compression test from the external load propagating outside the effective 75-mm (3 in.) cube area and thus affecting the geometry of the fracture.

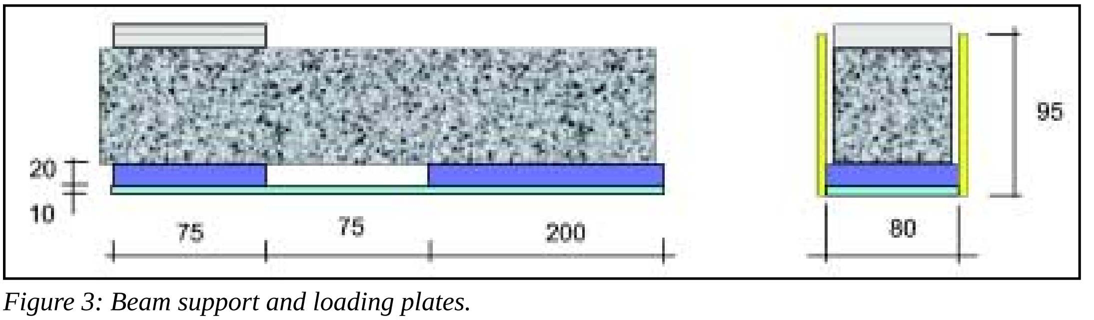

Figure 3: Beam support and loading plates.

Procedure

One set of three ganged beam molds per shotcrete mixture was assembled and oiled slightly. The mold is then securely placed in a near-upright position (about 70 ± 5 degrees inclined from the horizontal). Shotcrete is applied using standard nozzling procedures. Take care to employ the same shooting technique and equipment settings as would be used in regular shotcrete work. The bottom end of the molds needs to be filled first to avoid entrapment of the rebound. The molds should be slightly overfilled. In addition to the molds, one standard test panel per mixture should be shot to determine the setting time. Immediately after shooting, the molds were brought into a horizontal position and struck off with a trowel to remove the excessive material. The exposed surface was then finished to a plane, smooth condition.

Determine the setting time of the separate test panels according to ASTM C 1117, "Standard Test Method for Time of Set of Shotcrete Mixtures by Penetration Resistance." After the final set occurs, the beams can be demolded and placed on a stiff, flat surface in a secure area where they are exposed to the same curing conditions as the in-situ shotcrete.

At suitable times after demolding, place a test beam in the testing machine. Turn the beam at 90 degrees to the direction as shot about the longitudinal axis, so that the smooth sides come in contact with the loading plates. The top and bottom platen should be aligned carefully with the beam, leaving a minimum of 25 mm (1 in.) of any beam end protruding to avoid testing any flawed material that is more likely to be found near the beam ends. The guide plates by the bottom platen enable easy centering of the beam.

The beams should be loaded at a rate of approximately 1 to 2 kN (224 to 448 lb*f*) per second and tested to destruction. Conduct the tests after final set has occurred, at ages suitable for demonstrating the rate of strength development of the particular shotcrete mixture. Typically, X-shaped fracture modes similar to those found in testing conventional concrete cube specimens are observed on the broken specimens. Two tests should be conducted for each mixture and age. The test can be used to measure strengths up to approximately 20 MPa (2900 psi) (depending on the capacity of the testing machine), but is best suited to testing shotcretes with compressive strengths in the 1 to 10-MPa (145 to 1450 psi) range—that is, when strengths are too low for extraction and testing of cores.

Examples of Field Test Results

Figures 4 and 5 shows the results of some early-age compressive-strength tests on wet- and dry-mix shotcretes, respectively. The rate of strength development varied considerably depending on the mixture design, accelerator types, and addition rates used. Strength differentials were most pronounced at early ages (up to approximately 10 hours). By 24 hours, the differences in strengths between the different shotcretes were much less pronounced.

Extensive testing in the field using this test method has demonstrated that the rate of early-strength development is strongly influenced by:

1. The mixture design, including the particular type and brand of cement used;
2. Whether supplementary cementing materials, such as fly ash, silica fume, or blast-furnace slag are used;

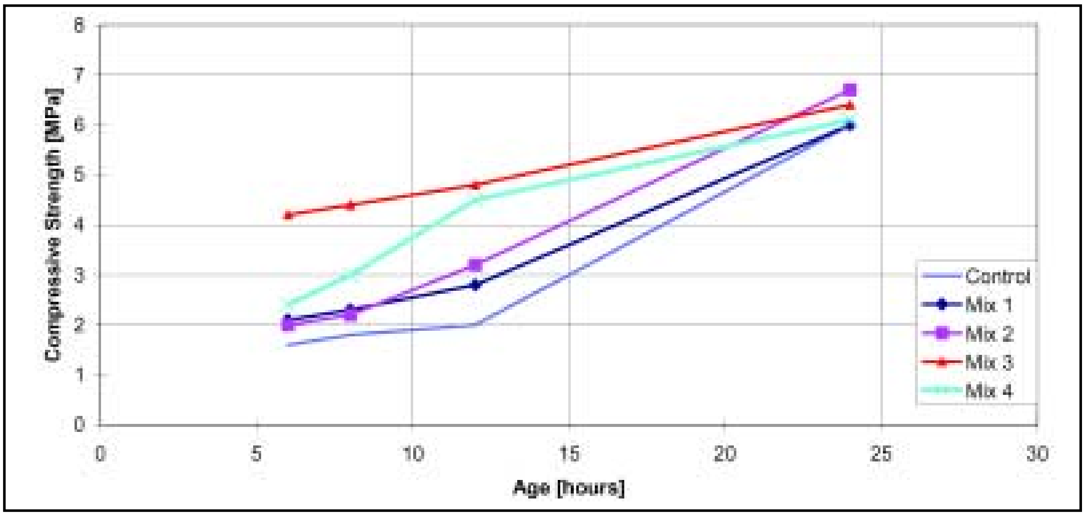

Figure 4: Early-strength development of accelerated wet-mix shotcrete.

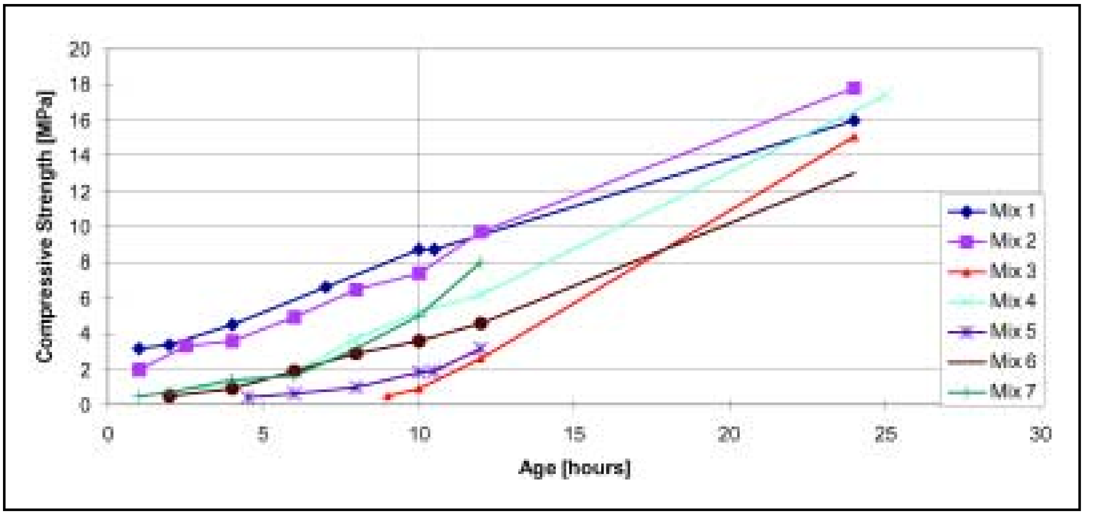

Figure 5: Early-strength development of accelerated dry-mix shotcrete.

3. The type and dosage of accelerator used;
4. Compatibility between the particular cement and accelerator used. (Some accelerators do not work well with certain types—or even brands—of cements); and
5. The shotcrete ambient and substrate temperatures at cooler temperatures, particularly as temperatures reach 5 ºC (40 ºF) or lower. Some accelerated shotcretes can be very slow in setting, hardening, and gaining strength, remaining in a state of green-set for days.

Summary

In general, shotcrete exceeding 10 MPa (1450 psi) in compressive strength can be diamond-cored; thus, the beam-test method is considered best suited for testing shotcrete at lower compressive strengths, or when timely access to coring equipment and a compression-testing machine is not available. The test method has the advantage of being robust, simple, low in cost, and readily adaptable for use in the underground environment as well as in the laboratory. It also has the advantage over other indirect, early-age shotcrete test methods (such as penetrating probes or pins, and pullout tests) of directly measuring compressive strength, and thus not requiring calibration to produce compressive-strength results.

References

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Editorial Comment

This paper was selected for the readers' interest by the editors. It is based on a paper by D. R. Morgan, N. McAskill, and R. Heere titled, "Determination of Early-Age Compressive Strength of Shotcrete," which was presented at the Third International Symposium on Sprayed Concrete in Gol, Norway, in September 1999.

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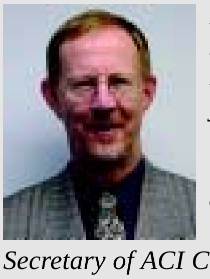

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