Early-Age Test Methods for Fiber-Reinforced Shotcrete

by Stefan Bernard

The ability of a fiber-reinforced shotcrete (FRS) lining to stabilize ground depends on its strength and toughness, among other things. Toughness is at least in part influenced by the compressive strength of the shotcrete matrix, so concrete strength is doubly important for ground control. In time-critical environments such as heading development in mines and most tunnels, the cost of excavation is often strongly influenced by the overall rate of progress; this, in turn, is influenced by the time to safe reentry. The minimum period of time that must elapse before it is safe to reenter under freshly shotcreted ground is directly related to the rate of strength gain in the shotcrete matrix.

While a FRS lining seldom fails in compression, the compressive strength of the matrix can provide a guide to the strength in bending and shear, which are the more common modes of failure. The compressive strength of the shotcrete can be measured using various indirect methods including soil and needle penetrometers, beam fragment testers, and Hilti guns. These methods, however, often yield conflicting results. It is not yet clear what minimum strength of shotcrete is required to guarantee safe reentry. The present paper examines recent work in Australia to determine the most suitable method of measuring early-age strength gain and identify the minimum shotcrete strength required before it is safe to reenter under freshly sprayed ground.

Early-age Compressive Strength Tests

Several methods of measuring the indirect and direct early-age compressive strength of the shotcrete are generally available. These are: use of a soil penetrometer, needle penetrometer, ASTM C 116-based beam end crusher, and Hilti Gun. Each of these tests is described below.

Soil Penetrometer

A soil penetrometer is generally a proprietary device consisting of a sprung flat-ended steel plunger calibrated to indicate the approximate compressive strength of the soil/concrete when forced into the surface a distance of approximately 1/4 in. (6 mm) (Fig. 1). The device is used at approximately six to ten locations across the surface of freshly sprayed shotcrete at each age of testing. Readings are taken at 10 to 20 min intervals until the shotcrete strength exceeds 190 psi (1.3 MPa).

The advantages of this test are that it is easy and cheap to perform, virtually nondestructive, and the test equipment can be readily carried around by operatives. The disadvantages are that the device overestimates compressive strength by a significant margin and the results are strongly affected by the presence of aggregate and fibers. Estimating the correct depth of penetration can also be difficult on a rough surface.

Needle Penetrometer

The Meynadier Needle Penetrometer consists of an 1/8 in. (3.0 mm) diameter steel needle at the end of a spring that is forced into the surface of setting concrete (Fig. 2). The force required to drive the needle to a depth of 0.6 in. (15 mm) is used to determine the approximate compressive strength with the aid of a calibration chart. This method is suitable for determining compressive strengths up to 175 psi (1.2 MPa). This type of needle penetrometer should not be confused with Vicat needle penetrometers and other types of needle penetrometers that are widely used to assess setting times for conventionally cast concrete.

The advantages of the needle penetrometer are that it is a readily portable device that is quick and easy to use. The disadvantage is that results are influenced by the presence of fiber and aggregate particles getting in the way of the needle. Also, the requirement to drive the needle steadily into the surface of the shotcrete is often difficult to

Fig. 1: Soil penetrometer

achieve. Driving the needle into a drying shotcrete surface can also lead to overestimates of strength, and use of the calibration chart is a time-consuming nuisance.

Beam End Tester

The ASTM C 116-based beam end tester (Morgan 1998) is the only early-age strength testing device that involves direct compressive failure of shotcrete samples. Beams measuring 3 x 3 x 16 in. (75 x 75 x 400 mm) are produced by spraying shotcrete into an open-ended mould (see Fig. 3, other sizes can be used if desired). The absence of ends helps to prevent rebound getting caught inside the mould. After spraying and cutting back to size, the beams are left to harden and can be extracted from the mould and tested when the strength exceeds about 73 psi (0.5 MPa) (as measured using the needle penetrometer). Portions of the beams are subjected to direct compression between the platens of the test device and the compressive strength is worked out on the basis of the area of the platens. Approximately three to four tests can be obtained using each beam (Fig. 4).

Extracting the beams from the mould can be difficult at early ages, so use of pressed metal inserts is recommended. The metal inserts (Fig. 3) sit in the mould during spraying and are then removed with the beam inside. The fresh shotcrete beam remains in the pressed metal insert (made using approximately 0.02 in. [0.5 mm] thick steel sheet) until it is time to test, whereupon the mould is "peeled off" the beam like a wrapping. In most cases, the beam survives this process without breaking, even if it is only 20 to 30 min old. Use of inserts also liberates the rigid steel mould for use in producing further beams by spraying so that numerous sets of beams can be produced in a short period of time.

It is important to note that the platens of the compression loading device must be free to swivel so that load can be applied uniformly to the specimen following adjustment of the platens when first applying load (Fig. 4). The beams can have sides that are not quite parallel, and eccentric application of load can greatly diminish the apparent strength of the concrete. The beams should always be tested on their sides so that the smooth off-mould surfaces contact the loading plattens. About 0.4 to 0.8 in. (10 to 20 mm) of beam should protrude from each end of the loading platen during testing; this will ensure an adequate amount of shotcrete exists to resist the load but precludes development of significant confining stresses.

The beam end tester has the advantage that direct compressive strength is obtained. No calibration against other methods of measurement is therefore necessary, indeed, the indirect methods

Fig. 2: Needle penetrometer in use

Fig. 3: Beam end tester (right) with mould and sheet steel inserts

Fig. 4: Beam end tester in use

are calibrated against data obtained using this test. The disadvantage of this method is that the beams are produced and stored separately from the lining. So, if a significant difference in temperature exists between shotcrete within the lining and ambient air, then the rate of strength gain will be affected. Measures can be taken to ensure the results are relevant, for example, by storing the beams under cover immediately adjacent to the lining so that the heat of hydration from the lining keeps the beams warm. Another disadvantage of the beams is that rebound can be trapped in the mould and incorporated into the beam if spraying is not performed carefully.

Hilti Gun

The Hilti gun method involves firing a steel fastener into the surface of shotcrete, measuring the depth of penetration, and then using a separate device to pull the fastener out of the shotcrete surface. The force required to pull the fastener out is combined with the depth of penetration using a calibration chart to determine the strength of the shotcrete. Only a DX450 Hilti gun can be used for this purpose, and the pullout device is also a proprietary Hilti item.

The advantages of this method are that strengths in the range 290 to 2600 psi (2 to 18 MPa) can be determined, and the strength measured is the actual in-situ strength between 0.8 and 2 in. (20 and 50 mm) through the thickness of a shotcrete lining. The disadvantages are the high cost of the equipment and fasteners, the fact that explosive cartridges are used, and the relatively long length of time required to conduct the measurements. Moreover, the guns do not always fire the fastener into the concrete correctly.

When using any of the previously described methods, it is important to recognize that they all suffer relatively high variability; therefore, it's necessary to conduct many tests at each sampling time before calculating the mean. Measurements should start soon after spraying is completed using either the soil penetrometer (if very low strengths are of interest) or the needle penetrometer. Conduct tests at about 10 to 15 min intervals for set accelerated shotcrete, 20 to 30 min intervals for non-set accelerated shotcrete. When the needle penetrometer indicates that a strength of approximately 73 psi (0.5 MPa) has been reached, then the beam end tester should be used together with the needle penetrometer for several sampling intervals before 175 psi (1.2 MPa) is reached. The beam end tester will continue to be useful up to approximately 725 to 1160 psi (5 to 8 MPa) depending on how large a hydraulic ram is included in the press. Finally, cores can usually be extracted about 1 day after spraying without excessive unraveling of the shotcrete.

Plotting the results on a graph against the logarithm of time will permit easy interpolation to determine the strength at a required time after spraying (for example, 1 or 2 hours) or the time until a minimum strength is achieved (commonly 145 psi [1 MPa]). It is recommended practice to obtain strength estimates at ages well beyond the required minimum to increase confidence in the interpolated values.

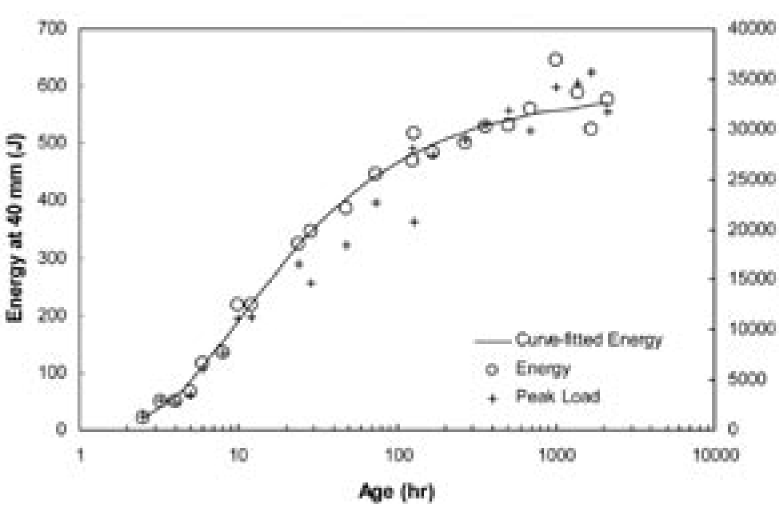

Fig. 5: Development of toughness with age from 2 h to 91 days for a mixture reinforced with 16 lb/yd^3 (10 kg/m^3) Barchip HT48 fibers

Other Factors Affecting Reentry Time

Other parameters apart from strength can also be used to assess the safety of reentry under fresh shotcrete. The stickiness and cohesion of shotcrete have a direct influence on safety under freshly sprayed ground. Stickiness is a measure of the ability of fresh shotcrete to adhere to a solid surface, whereas cohesion is the ability of the material to adhere to itself. Highly sticky and cohesive shotcrete will exhibit a lower tendency to fall and injure operatives than shotcrete displaying poorer cohesive characteristics. Stickiness and cohesion can be assessed using simple techniques such as overhead spraying to determine the maximum build-up thickness before collapse occurs, and by spraying onto vertical walls followed by floating using a wooden float to subjectively determine how cohesive a mixture is. Cohesiveness can also be assessed by observing whether shotcrete that detaches from overhead failed internally or whether it suffered an adhesion failure at the surface of the rock.

Toughness also plays a role in preventing cracked FRS falling onto operatives, even at very early ages. ASTM C 1550 round panels can be used very effectively to assess the toughness and strength of shotcrete at early ages (Fig. 5), provided a suitable test rig is available close to the spraying site. The load at first crack can also be used to determine the flexural strength of the shotcrete

(Bernard 2004). It is presently unclear what minimum level of toughness is required to ensure a lining can "hold itself up" in the absence of adequate adhesion to the ground surface.

Correlations Between Test Results

Conducting alternative early-age strength tests at the same time on the same sample of shotcrete indicates that the various methods do not necessarily produce the same estimate of compressive strength. The data in Fig. 6 and 7 indicate that the soil penetrometer substantially overestimates the compressive strength of shotcrete compared to needle penetrometers and the beam end tester. Current preliminary research has shown that the ratio between strength results obtained using the soil and needle penetrometer lies between 2 and 4 depending on the strength of the shotcrete. The needle penetrometer results are similar to those obtained using the beam end tester in the region of overlap (73 to 175 psi [0.5 to 1.2 MPa]), and the beam end tester results are very similar to core results for the same shotcrete (725 to 1160 psi [5 to 8 MPa]). Due to the superior compatibility of results for these latter three methods, it is recommended that the needle penetrometer, beam end tester, and cores form the basis of a reliable quality control system for measuring early-age compressive strength. It must be acknowledged, however, that soil penetrometers are much more sensitive to variations in the strength of the shotcrete at the low end of the range (less than 30 psi [0.2 MPa] by the needle penetrometer). This is evidenced by the gentle slope of the trend line in Fig. 8. If data

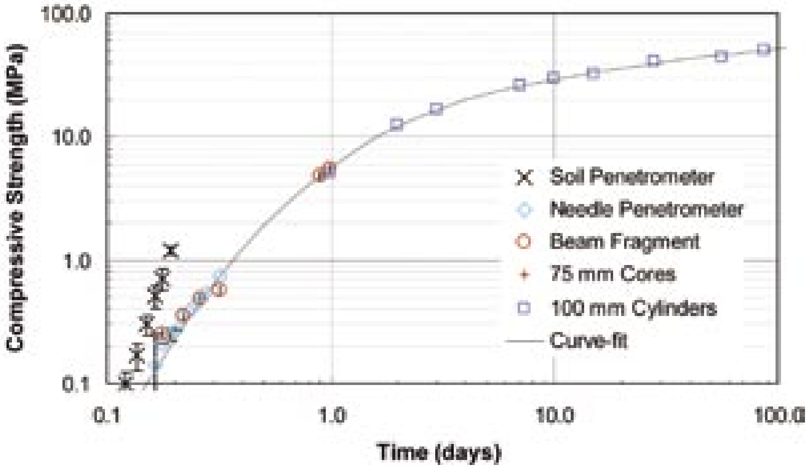

Fig. 6: Development of compressive strength using direct and indirect measurement methods for a non-set accelerated fiber-reinforced shotcrete

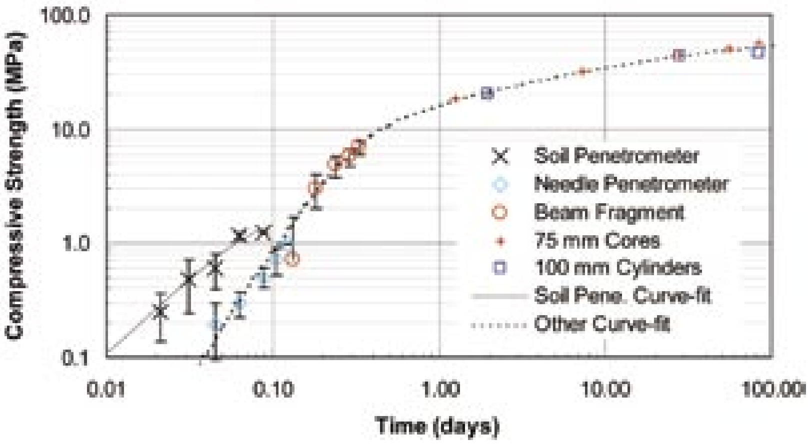

Fig. 7: Development of compressive strength using direct and indirect measurement methods for a set accelerated fiber-reinforced shotcrete

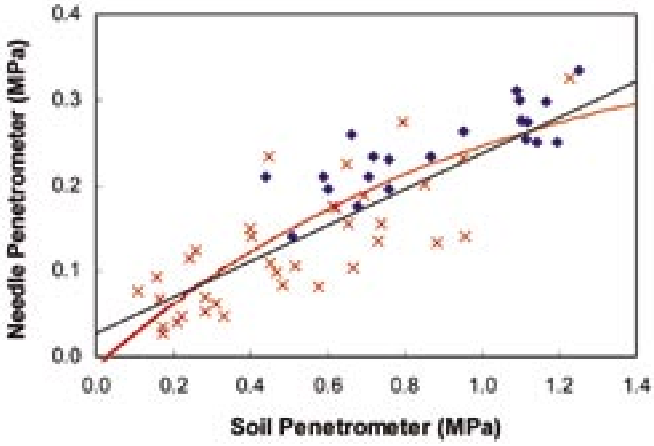

Fig. 8: Values of indirect compressive strength obtained using a needle penetrometer compared with values obtained using a soil penetrometer. Solid diamonds represent concurrent measurements, crosses represent extrapolated data (for example, lower bound for Fig. 7)

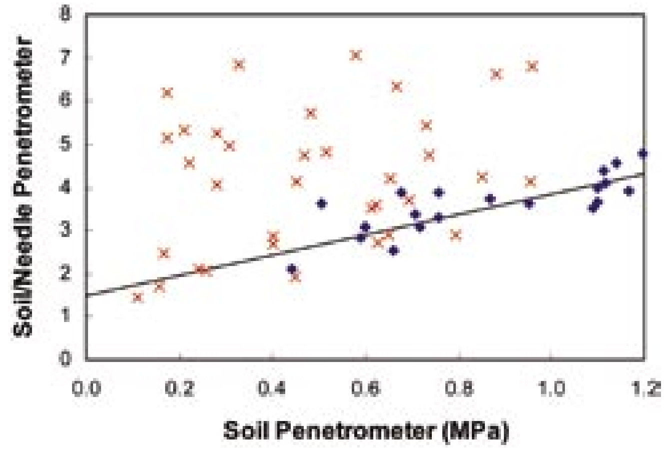

Fig. 9: Ratio of compressive strength values obtained using a soil penetrometer over needle penetrometer values expressed as a function of strength obtained using a soil penetrometer. Solid diamonds represent concurrent measurements, crosses represent extrapolated data (for example, lower bound for Fig. 7)

in this range is required, it is suggested that the soil penetrometer be used but results be reduced by a factor of between 2 and 4 to obtain the "true" strength of the shotcrete. Determination of the best factor to use is currently under investigation (Fig. 9 can be used as a rough guide for the present).

Examination of the scatter of extrapolated results in Fig. 9 indicates that the early-age strength of a mix should only be determined by direct measurement, not extrapolation of data obtained at later ages.

References

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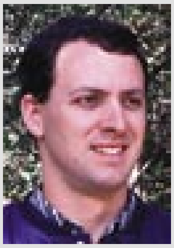

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