Determination of Early-Age Compressive Strength for FRS

by Stefan Bernard and Christian Geltinger

The strength of the concrete matrix at early ages is an important factor in successful ground control using fiber-reinforced shotcrete (FRS). For this reason, many specifications for FRS intended for overhead applications, such as the Austrian guide to shotcrete,[1] have minimum requirements for strength development as a function of age after spraying. This is based on field evidence that compressive strength is related to the ability of the lining to stick to the substrate, support itself, and ultimately stabilize the ground and carry imposed loads. The safety of operatives under newly sprayed FRS is strongly dependent on the ability of a fresh lining to support itself and at least small areas of loose ground. While the exact mechanism by which FRS helps to support the ground at early ages remains only partially understood, many methods exist for testing the direct or indirect compressive strength of this material.

Test methods for FRS at early ages were previously reviewed by Bernard[2] with evidence that alternate methods often result in conflicting estimates of compressive strength for a given concrete. At a given age, estimates of the compressive strength of FRS will typically differ if measured using a soil or needle penetrometer, beam end tester, Hilti Gun, or conventional cores. These discrepancies have sometimes caused confusion among users and specifiers of shotcrete, so the methods that yield true and valid estimates of the compressive strength must be determined. The present investigation was initiated in response to this challenge. It has involved a large number of tests on early-age FRS using each of the methods listed previously to determine empirical correlations between results and identify the most accurate and effective among the alternatives available.

Early-Age Compressive Strength Tests

Several methods of measuring the indirect and direct early-age compressive strength of shotcrete are generally available. Some of these were described in detail by Bernard[2] but will briefly be reviewed here. All of the methods involve portable equipment that does not require preplacement of inserts in the shotcrete (such as Lok-test inserts commonly used for cast concrete[3]) because such methods are impractical for shotcrete.

Soil Penetrometer

A soil penetrometer is generally a proprietary device consisting of a sprung flat-ended steel plunger that is 0.25 in. (6 mm) in diameter. This is calibrated to indicate the approximate compressive strength of the soil/concrete when forced into the surface a distance of approximately 0.25 in. (6 mm) (Fig. 1). The device is used at approximately six to 10 locations across the surface of freshly sprayed concrete at each age of testing, and readings are taken at 10- to

Fig. 1: Soil penetrometer

Fig. 2: Needle penetrometer

20-minute intervals until the concrete strength exceeds 145 psi (1 MPa). This test has the advantages that it is easy and cheap to perform, virtually nondestructive, and the test equipment can be readily carried around by operatives.

Needle Penetrometer

A needle penetrometer consists of a 0.12 in. (3 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 claimed suitable for determining compressive strengths up to 145 psi (1 MPa). 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, and the requirement to drive the needle steadily into the surface of the concrete is often difficult to achieve.

Beam End Tester

The ASTM C 116-based beam end tester,[4] described by Morgan,[5,6] is the only early-age strength testing device that involves direct compressive failure of concrete samples. Beams measuring 3 x 3 x 16 in. (75 x 75 x 400 mm) are produced by spraying shotcrete into an open-ended mold (refer to Fig. 3; other sizes can be used if desired). The absence of ends helps to prevent rebound getting caught inside the mold. After spraying and cutting back to size, the beams are left to harden and can be extracted from the mold and tested. 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.

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 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 that if a significant difference in temperature exists between shotcrete within the lining and beams, then the rate of strength gain will be affected.

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 concrete 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 concrete. Only a DX450 Hilti gun can be used for this purpose (Fig. 4), and the pull-out 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-place 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 gun does not always fire the fastener into the concrete correctly.

Rebound Pendulum

A rebound pendulum is a device occasionally used to estimate the early-age compressive strength of concrete floors and walls. It consists of a hammer on a pendulum that rebounds off the concrete surface after swinging from a preset position (Fig. 5). The distance that the hammer rebounds off the surface is related to the strength of the concrete. The device is supplied with a chart that indicates the compressive strength for a given rebound distance. The advantage of this test is that it is quick and simple to execute and is completely

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

Fig. 4: Hilti gun

Fig. 5: Rebound pendulum

nondestructive. The disadvantage is that a smooth horizontal or vertical surface is required for the calibration charts to be correct.

Cores

Cores are the traditional means of determining in-place FRS strength. This method is well known and proven, and numerous standards exist for extraction and testing of cores (that is, AS1012 and ASTM C 1604), but cores cannot be extracted before the compressive strength reaches at least 700 psi (5 MPa). Its usefulness at early ages is therefore limited to providing a control against results obtained using the other methods at relatively late ages (several hours to days after spraying).

When using any of the methods previously described other than beam end testers, it is important to recognize that they all suffer relatively high variability and that it is therefore 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 approximately 10-minute intervals for set accelerated shotcrete and 20- to 30-minute intervals for nonset accelerated shotcrete. When the needle penetrometer indicates that a compressive 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 145 psi (1 MPa) is reached. The beam end tester will continue to be useful up to approximately 725 to 1450 psi (5 to 10 MPa) depending on how large a hydraulic ram is included in the press. Finally, cores can usually be extracted approximately 1 day after spraying without excessive ravelling 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 age after spraying (that is, 1 or 2 hours) or the time until a minimum strength is achieved (commonly 145 to 290 psi [1 to 2 MPa]). It is recommended practice to obtain strength estimates at ages well beyond the required minimum to increase confidence in the interpolated values (Fig. 6).

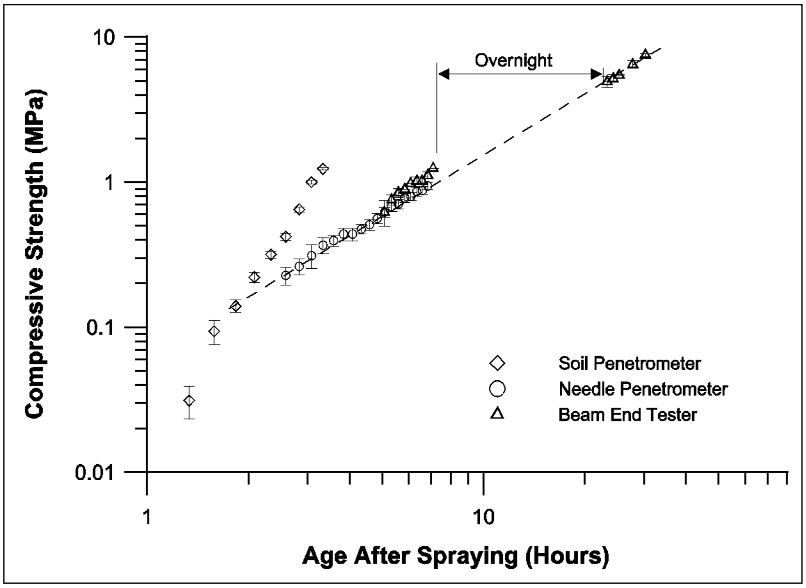

Fig. 6: Typical history of compressive strength development as measured using a soil and needle penetrometer, and then a beam end tester

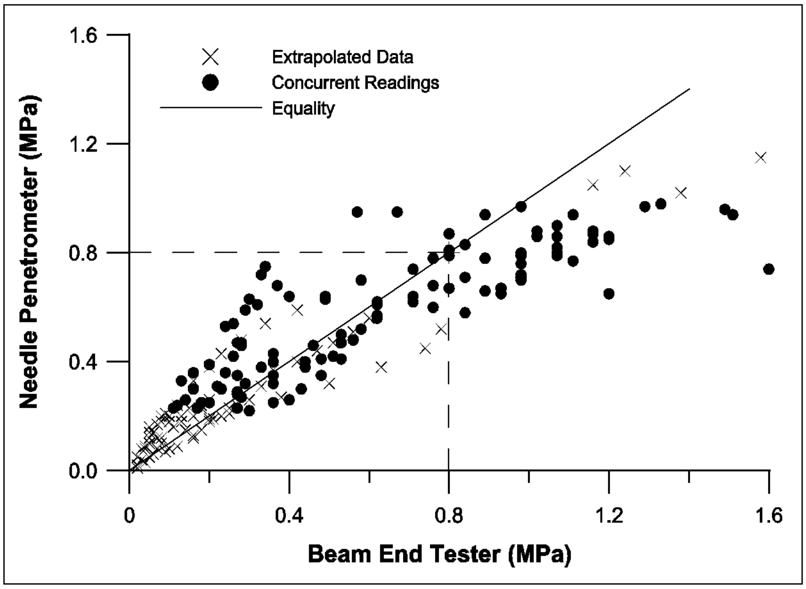

Fig. 7: Indirect compressive strength as measured using a needle penetrometer compared with results obtained using the beam end tester. Solid points indicate tests done at same age and crosses indicate extrapolations in which only one of the tests were actually performed. Lines indicate equality and curve-fit to data

Correlations between Test Results

Conducting alternative early-age strength tests at the same time on the same sample of concrete indicates that the various methods often do not produce the same estimate of compressive strength. To help identify correlations in results obtained for the various instruments, over 1000 tests were performed on approximately 30 sprayed and cast batches of shotcrete. Most were sprayed without set accelerator, but several also included accelerator. The results are presented in the following correlations.

The beam end tester has been taken to represent the true compressive strength based on close agreement with cores for compressive strengths greater than 725 psi (5 MPa). Sources of error are also relatively minor for the beam end tester, thus the validity of readings obtained using this instrument are less variable or subject to doubt than for the other devices.

The compressive strength of FRS according to the needle penetrometer has been plotted against values obtained using the beam end tester in Fig. 7. In comparing the correlation data against the inclined solid line (representing equality), it is apparent that the needle penetrometer slightly overestimates compressive strength up to approximately 87 psi (0.6 MPa) but underestimates strength thereafter. Indeed, the results at the higher end of the scale indicate that the needle penetrometer is not particularly accurate beyond 116 psi (0.8 MPa) as relatively constant results are obtained with this device despite the strength increasing according to the beam end tester. The differences between the needle penetrometer and beam end tester are not statistically significant up to 116 psi (0.8 MPa), hence compressive strength according to the needle penetrometer can be taken to be reasonably accurate up to this level.

In Fig. 7 to 9, the solid circles represent samples for which both tests were undertaken, while the crosses represent samples in which one set of data was obtained by extrapolating data obtained at other ages. The extrapolated points were only obtained when a trend in data points for the missing instrument was believed valid. Such a trend exists, for example, in Fig. 6 for the needle penetrometer in the range 2 to 3 hours after spraying.

The spread in data in Fig. 7 is due, at least in part, to differences in temperature and degree of hydration experienced by beams compared with in-place FRS. While the beam end tester has the advantage that it involves direct compression, the needle penetrometer actually measures in-place concrete. Given that the needle penetrometer has been established to be accurate up to 116 psi (0.8 MPa), comparisons with the soil penetrometer at the low end of the scale can help to determine the accuracy of this latter device.

The correlation data in Fig. 8 and 9 indicate that the soil penetrometer substantially overestimates the compressive strength of shotcrete compared with a needle penetrometer or beam end tester. As in Fig. 7, the solid points represent samples for which both tests were undertaken, while the crosses represent samples in which one set of data was obtained by extrapolating data obtained at other ages. This extrapolation was frequently necessary when using the needle penetrometer because results effectively could not be obtained for this device when the compressive strength was less than 29 psi (0.2 MPa). In correlating results, emphasis has been placed on the concurrent data due to the uncertainty inherent to extrapolated points.

The correlations between the soil penetrometer and needle penetrometer or beam end tester clearly exhibit considerable variability, suggesting that estimates of strength obtained using the soil penetrometer are not as accurate as can be obtained using alternative devices. Although the precision of the soil penetrometer is poor, its repeatability for a given mixture is quite satisfactory. Based on the results obtained in this investigation, the soil penetrometer can be considered a useful instrument for FRS of up to 29 psi (0.2 MPa) compressive strength (which is equivalent to approximately 73 psi [0.5 MPa] according to the soil penetrometer). Even within this envelope, however, the error in readings can exceed 100%.

In comparing the results of the soil and needle penetrometer, it was noticed that the estimates of strength based on the soil penetrometer were almost always greater than those obtained using the needle penetrometer. When plotting the ratio of strength estimates based on the soil penetrometer

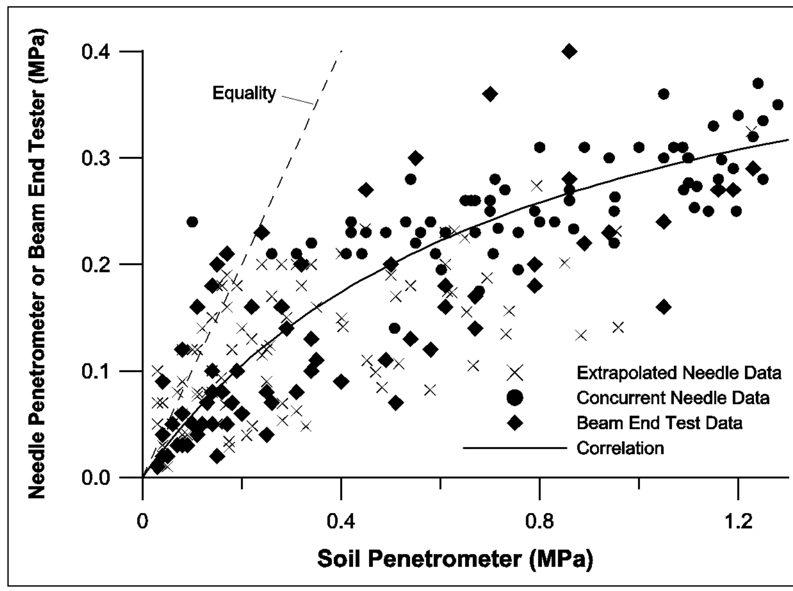

Fig. 8: Indirect compressive strength as measured using a needle penetrometer compared with results obtained using a soil penetrometer. Solid points indicate tests done at same age and crosses indicate extrapolations in which only one of the tests were actually performed

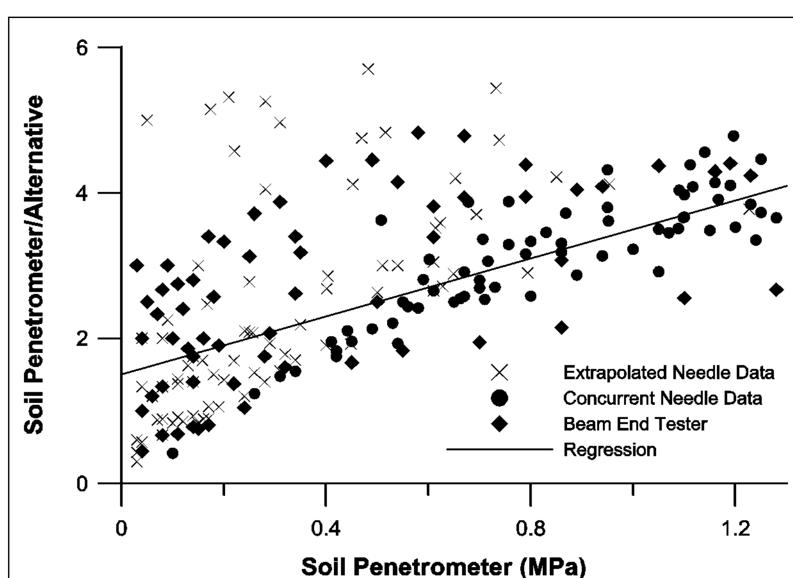

Fig. 9: Ratio of indirect compressive strength as measured using a soil penetrometer over results obtained using either the needle penetrometer or beam end tester plotted as a function of results according to the soil penetrometer. Solid points indicate tests done at same age and crosses indicate extrapolations in which only one of the tests were actually performed

over estimates obtained with the needle penetrometer or beam end tester against strength obtained using the soil penetrometer (Fig. 9), it was necessary to commence at a ratio equal to at least unity despite the existence of data showing lower ratios. Based on the trend in Fig. 9, the soil penetrometer effectively overestimated the strength of the concrete by a factor of between 1.5 and 4.1 across the range of strengths valid for this instrument.

Using the linear regression plotted in Fig. 9, the true compressive strength of the concrete matrix σ_C (that is, the value according to the needle penetrometer or beam end tester in MPa) can be estimated from readings obtained using the soil penetrometer σ_S (in MPa) as

$$\sigma_C = \frac{\sigma_S}{1.5 + 2\sigma_S} \quad (1)$$

This relation has been plotted as the solid line in Fig. 8. If using a soil penetrometer to estimate the compressive strength of FRS, the values indicated by the device should be substituted into Eq. (1) to obtain the true compressive strength.

Comparisons between the Hilti gun, pendulum hammer, and beam end tester are shown in Fig. 10 and 11. These figures reveal that both the Hilti gun and pendulum hammer overestimate compressive strength, especially at the lower end of the scale. While the Hilti gun data appears to be related to the beam end results by a consistent (in this case, power-based) function, the pendulum hammer results are poorly related and grossly overestimate strength in the 435 to 1160 psi (3 to 8 MPa) range. Relative variability in the Hilti gun data is comparable with results obtained using the needle penetrometer. The systematic error in the pendulum hammer results suggests that a recalibration of this device is necessary because the data underlying the published calibration chart was based on tests performed on cast concrete.

The Hilti gun suffers the problem that numerous types of explosive cartridges and fasteners are available for this device, and power settings on the gun can be varied. This makes it difficult to be certain tests are executed under the same conditions from site to site. A serious problem inherent to the pendulum hammer is the requirement to hold the device exactly vertical or horizontal during tests. This can be very difficult to achieve in a mine or tunnel environment due to the absence of reference surfaces. This problem effectively diminishes the value of this instrument for field work involving most shotcrete.

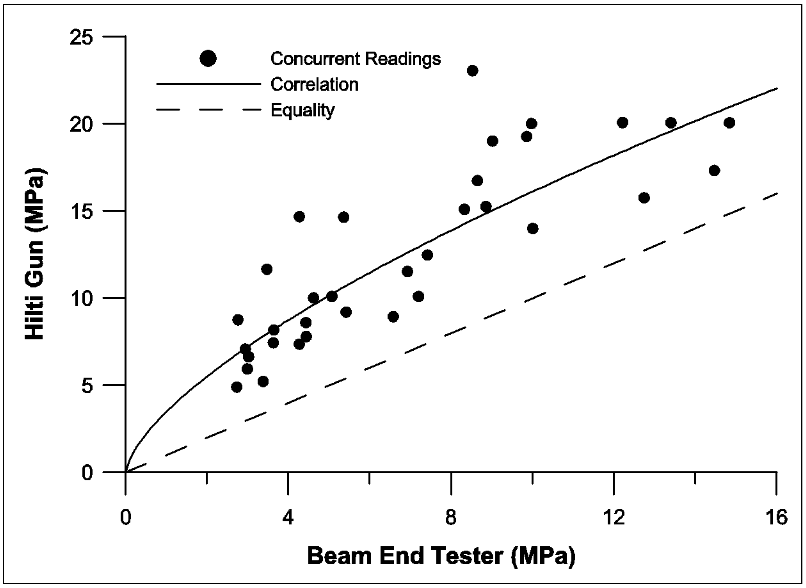

Fig. 10: Indirect compressive strength as measured using a Hilti gun compared with results obtained using the beam end tester. Lines indicate equality and curve-fit to data

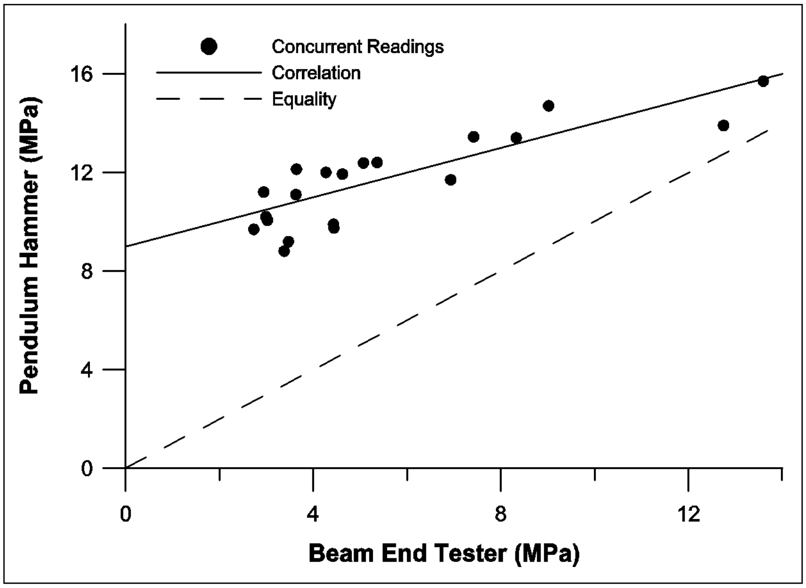

Fig. 11: Indirect compressive strength as measured using a pendulum hammer compared with results obtained using the beam end tester. Lines indicate equality and curve-fit to data

Conclusions

The beam end tester is the definitive method of obtaining early age compressive strength estimates for FRS but suffers minor problems due to temperature differences between specimens and in-place FRS, and incorporation of rebound into the specimens. The beam end tester is applicable to a very wide range of concrete strengths, and is the only device with the capacity to measure strength between 15 and 1450 psi (0.1 and 10 MPa). The needle penetrometer is the best alternative to the beam end tester but only works between 29 and 116 psi (0.2 and 0.8 MPa). The soil penetrometer is useful for very early ages and for concrete strengths up to 29 psi (0.2 MPa) but valid results are only possible after correction for systematic errors. The Hilti gun and pendulum hammer are useable for strengths in excess of 435 psi (3 MPa) but result in unconservative estimates of strength and are therefore deceptive.

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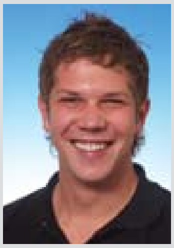

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