Early Age Strength Testing for Shotcrete: 2024

By Christoph Goss, Norbert Fuegenschuh, Lauro Lacerda, Kevin Robertson, and Shaun Radomski

Knowing the early strength of shotcrete has always been an important part of tunneling and underground mining. Unlike in other fields, personnel need to work under freshly placed overhead shotcrete to continue advancing the tunnel or drift. This typically requires the use of a rapid-set accelerator. A recent development in the industry is the use of ASTM C495 Type 1L cement to replace the well-proven ASTM C150 Type I/II cements which has led to more variability in accelerator dosing and thereby time to achieve a given strength. This requires us, as an industry, to take a fresh look at early age strength testing methods.

RE-ENTRY

Re-entry criteria vary and consist of both time and strength requirements. To minimize downtime, the goal is as low as possible but as high as necessary. NIOSH 2015 provides a summary table:

Region	Early Strengh, MPa (psi)	Re-entry time, hr
United States*	0.5–3.0 (75–435)	2–6
Canada	1.6–2.0 (232–300)	2
Austria	0.8–1.6 (116–232)	2–6
Australia	0.5–3.0 (75–435)	1-6

**1 MPa (145 psi [1 MPa]) has become more common*

Initial set begins in 5 to 60 minutes, depending on the accelerator; but no matter what the set time is, crews should wait at least 30 minutes before re-entry. This reduces the chance of shotcrete debonding from the ground and falling under its own weight — i.e. pancaking (Rispin 2005).

Since they concern both safety and construction means and methods, re-entry protocols should be determined by the tunnel or mining contractor based on the underground span, ground conditions, temperature, shotcrete thickness, and accelerator use. In support of this, the contractor should have on staff or hire a qualified shotcrete consultant and inspector to develop the concrete mixture design, work methodology, and calibration of the delivery system, including pumping stroke rate and accelerator dosage to shoot overhead without fallout or over-dosage.

Trials and testing should be conducted to validate the work methodology. The testing should be done before the start of construction for each proposed shotcrete mixture and range of accelerator dosing. Where Type 1L cement is used, the testing should include various mixtures with an expected range of powdered limestone and the proportional accelerator dosages. If the mixtures change during construction, a new set of tests should be conducted. Confirmatory tests should be conducted at various times throughout the project, especially if issues are encountered.

EARLY AGE SHOTCRETE

Early age typically refers to shotcrete that is less than 24 hours old and where standard compressive strength panels cannot be effectively cored, typically before 10 MPa (1450 psi). Once cores can be obtained, standard UCS testing on shot panels is the preferred approach. The early strength testing methods have been discussed in previous papers including Bernard 2005, Rispin 2005, Bernard & Geltinger 2007, Morgan, McAskill & Heere 1999, and Clements 2009. These papers provide more background and include lab and field testing that compare the methods more rigorously. The methods include:

- Soil Penetrometer
- Needle Penetrometer
- Hilti Gun (new & old)
- Schmidt Hammer (not recommended)
- Beam End Tester

ACI 506.5-22 Guide for Specifying Underground Shotcrete lists the needle penetrometer, stud driving, and beam end testing, but makes no recommendation for which method(s) to use. One of the goals for this paper is to review these methods, see if and how much they are currently being used in North America, and identify new technologies. Based on meetings with the American Shotcrete Association (ASA) Underground Committee, Underground Construction Association (UCA) Working Group 12, and other informal

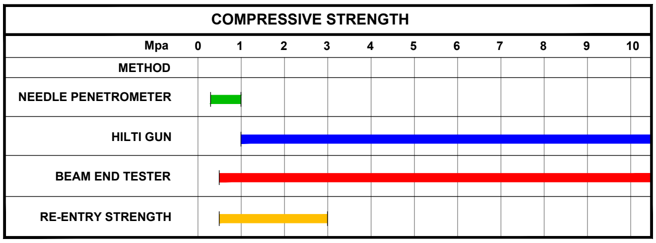

Chart 1

discussions that the authors have had at job sites and conferences, the same methods are still being used but no new methods have been employed on a large scale. Chart 1 provides a graphic summary of the most applicable methods with their effective ranges up to the point where standard cores can be taken.

Note that for all the early strength testing, panels and beams must be kept in the same environment as actual placement for the results to be valid. Note also that this paper only addresses standard cementitious shotcrete.

SOIL PENETROMETER

There are many types of soil penetration needles and, as the name implies, they are generally used to evaluate soil compressive strength. They are made with one smaller sliding cylinder and a spring inside another larger cylinder. A 6 mm (0.25 in.) diameter solid steel plunger is attached to the end of the small cylinder which also has a reading gauge and sliding red ring. The operator pushes the plunger into the fresh shotcrete 25 mm (1.0 in.) and a reading is taken. The process is repeated 12 times (at random surface locations). Then, the high and low readings are discarded, and the average of the remaining 10 readings calculated. Their range of application is around 0.7 MPa (100 psi) to 4.8 MPa (700 psi).

The main advantages of the soil penetrometers are that they are very compact, inexpensive, give direct strength readings, and are easy to use. The main disadvantage is they are not very accurate because the large needle diameter can encounter aggregate and fiber and give high results. Given this combination of the advantages and disadvantages, soil penetrometers should be used to evaluate if shotcrete is gaining strength and setting, but more accurate methods should be used to obtain more representative compressive strength values.

NEEDLE PENETROMETER

The Meynadier needle penetrometer or Meyco© Penetration Needle reads a resistance to a force that can be correlated to compressive strength (psi or kPa). It corresponds to ASTM C1117-94 (Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance) which was withdrawn in 2003 but is still considered valid. The device is an all-steel 700 mm (27 in.) device with a needle on one side and 200 mm (8 in.) long T-handle on the other end. The needle is very thin with a 2.5 mm (0.1 in.) diameter which is fixed to a cylinder by a screw. The cylinder houses the spring. The other end is a T-handle which is marked and contains a floating ring. The floating ring marks the force needed to push the needle about 15 mm (0.6 in.) into the shotcrete at a constant rate. As with the soil penetrometer, 12 readings are taken, the high and low readings are discarded, and the remaining 10 readings are averaged. If the needle goes into shotcrete without moving the floating ring, that reading is recorded as zero. From the average readings on the rod (12 to 67) there is a table that converts the applied force reading to pressure. In general, penetration needles are more accurate and require less applied force than soil penetrometers.

ABOVE: Soil penetrometer top (smaller) Needle penetrometer bottom (larger)

RIGHT: Close up of needle penetrometer (left) soil penetrometer (right)

Shooting Hilti Gun stud into a panel

Their range of application is from 0.3 MPa (45 psi) to about 1 MPa. Their main advantages are that they are compact, inexpensive, and easy to use. Their main disadvantages are that they require replacement of worn-out needles (that are currently only available in Europe) and the readings must be converted to compressive strength using a calibration chart. Given their relatively accurate readings at low strength, the needle penetrometer is a useful tool for evaluating strength for re-entry, if the re-entry standard is 1 MPa . If the re-entry requirement is a strength greater than that, the needle penetrometer method should be followed up or replaced by the Hilti Gun or Beam End Testing described below.

A related beneficial use of the Needle Penetrometer method is for routine checking of the initial and final set times to confirm that the accelerator dosing rate is correct. This can quickly alert the field team to problems with the accelerator pump, hose, or valve. Initial set is when a needle of 1/10 in^2 bearing surface achieves a resistance of 3.4 MPa (500 psi), or a reading of 22.7 kg (50 lb) shown by the floating ring. Final set is when a needle with 0.025 in^2 bearing surface achieves a resistance of 28 MPa (4000 psi), or a reading of 45.4 kg (100 lb) shown by the floating ring.

Shooting into an end beam form. Photo credit PCiRoads, LLC.

HILTI GUN

The Hilti Gun stud driving method (also called the bolt-setting method) is used for early strength ranging between 1 and 16 MPa (2300 psi) which positions the method in between compressive strength measurements using the needle penetrometer and testing of drilled cores.

This "classic" stud (nail) driving method, which has been used almost exclusively for approximately 30 years (and which is still widely used around the world) consists of a stud gun that shoots studs into freshly sprayed shotcrete. The depth of penetration of the stud is measured. Subsequently the studs are pulled out from the concrete while measuring the pull-out force. The ratio of pull-out force to penetration depth is the parameter used to determine the compressive strength. It is important to use the correct equipment since the powder-actuated tool needs to drive the studs with a defined energy for at least 20 mm (0.8 in.) into the shotcrete. The method was developed and calibrated by Hilti and contacting the manufacturer will result in the right combination of stud gun (DX 450-SCT), studs (there are 3 different lengths available – the younger the shotcrete, the longer the nail needs to be), powder-actuating cartridge, and pullout force tester.

Further development of this method by Hilti led to the Hilti BX 3-SCT system, which uses a battery actuated fastening tool. Therefore, no powder cartridges are required anymore. Another advantage of this upgraded method is that measuring of the pull-out force is no longer required. The method can be used from a concrete strength upwards of 1 MPa. A calibration curve was empirically evaluated based on experimental investigations performed by Professors Charlotte Thiel and Wolfgang Kusterle at the Regensburg University of Applied Sciences in Germany.

After release of the BX 3-SCT system, Hilti stopped selling the DX 450-SCT tools — however maintenance of existing tools is still provided, and studs and cartridges are still available. The simplicity of the methods described makes them widely used all over Europe and also in North

America. However, based on the author's own experience on several North American tunnel sites, many manufacturer representatives in North America are not really familiar with the system due to the fact that shotcrete projects where early strength measurements need to be performed are relatively rare. Initial difficulties in this regard are usually quickly overcome as soon as European counterparts are contacted.

The products are imported from Europe, leading to extended lead times, which must be taken into account when developing a test program at the beginning of a project. On top of that, local and site-specific safety precautions and regulations need to be considered. Some countries, and states in the US, require special safety classes (provided by the manufacturer) to be passed by the group of people operating the stud guns. The test measurements are usually performed either by one of the site engineers or the superintendent in charge.

A quick survey performed in May 2024 — including three construction sites in Austria, England and in the US (New York, NY) — confirmed that both stud driving methods are used. The site in Austria works with existing older DX 450-SCT equipment in combination with pull out force testing. The site in England opted for the new battery actuated system since black powder was not permitted on site. The site in New York bought new BX 3-SCT equipment at the start of the shotcrete placements.

Both stud driving methods are easy to use and provide quick results, which makes them front row candidates for use on all shotcrete sites where early strength development is of importance.

SCHMIDT HAMMER

A Schmidt Hammer, Type L is sometimes used to test shotcrete between 10 to 62 MPa (1450 and 9000 psi) but requires a minimum thickness of 100 mm (4 in.) or more to be used. Given that at this range actual cores can be taken which provide much more accurate results, the Schmidt Hammer should not be used for definite strength results; it is appropriate only for approximations or to identify problem areas.

BEAM END TESTER

Unlike the previous methods, the beam end tester directly measures compressive strength. It is a modified version of ASTM C116 (Test Method for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure) which was withdrawn in 1999 but is still considered valid. In this method, beams are made by shooting shotcrete into forms 75 x 75 x 400 mm (3 x 3 x 16 in.). After the shotcrete reaches at least 0.5 MPa (73 psi), the beams are removed from the mold and then placed into a testing frame with 25 to 50 mm (1 to 2 in.) of beam sticking out past the 75 x 75 mm platens. Compressive strength is determined by applying stress to the beam using a hydraulic pump on the ram until the shotcrete fails. A gage indicates the hydraulic pressure during the test and records the maximum value. Calibration of the apparatus allows for conversion of hydraulic pressure recorded, into stress applied to the shotcrete. Depending on the size of the ram, the effective testing range is 0.5 MPa (73 psi) to 5, 8, or 13.7 MPa (725, 1160, or 2000 psi).

The main advantage of this method is obtaining direct compressive strength which requires no calibration and results in less variability between tests. The main disadvantage is that beams can be difficult to remove from molds, particularly in cold environments though form oil can help.

The Sika/King Shotcrete End-Beam Tester is a commercially available product that uses a steel frame and hand pumped hydraulic jack. In addition, the Office of Mining Safety and Health Research at the National Institute for Occupational Safety and Health (NIOSH) developed a beam end tester that is portable and programmable-logic-controller (PLC) controlled. The PLC control loads the beam at the ASTM loading rate and stops when the required displacement is reached. The NIOSH

End beam sample removed from form ready for testing system also uses smaller 100 x 100 x 150 mm (4 x 4 x 6 in.) partial beam molds, in accordance with ASTM C116.

CONCLUSION

For improved safety in tunneling and mining projects that use shotcrete for ground support, early shotcrete strength should be evaluated by testing. Based on their range of effectiveness, two procedures stand out: The new Hilti BX 3-SCT stud driving method and the beam end tester. The Hilti system is indirect but fast and can be used on existing panels or directly on thick shotcrete. The beam end testing provides direct compressive strength results but requires special beam panels and more time and effort to produce the test samples and then test. The Hilti system appears to be more popular in Europe while the beam end tester seems to be more common in North America. Both systems should be considered by the shotcrete contractor, and should certainly replace any method of "winging it".

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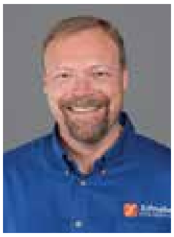

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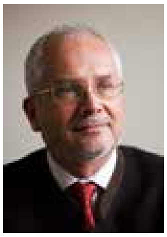
Lauro Lacerda *holds B.Sc. and M.Sc. degrees in mining engineering with specialization in rock mechanics. He is a Professional Engineer licensed in Nevada. He is Business Development & Key Account with SNF Holdings, a water science company involved in heavy Civil Engineering construction (tunneling and deep foundation). He started using dry-mix shotcrete in underground projects in 1986 and has vast experience in tunnel/mine project engineering including concrete/shotcrete infrastructure design and application. Mr. Lacerda has collaborated on several articles & position papers for ASA and was awarded the Carl Akeley Award in 2007 for the article "Watertight Permanent Shotcrete Lining in Tunneling and Underground Construction.*

Kevin Robertson *is the National Sales Manager, STM – Shotcrete, Tunneling & Mining for Sika Corporation. His area of expertise include shotcrete materials, application and equipment for all shotcrete applications. Robertson is a member of American Concrete Institute (ACI), Underground Construction Association (UCA of SME), and previously served on the Board of Directors for the International Concrete Repair Institute (ICRI) as the Region 4 Representative, and past member of the of ICRI Committee 320, Concrete Repair Materials and Methods. Kevin currently serves on the Executive Committee as treasurer for ASA and is a member of the Underground, Membership and Marketing Committees.*



Norbert Fuegenschuh *holds a masters degree in Civil Engineering, University of Technology in Graz, Austria (1989). He started working for BEMO Tunnelling in Innsbruck, Austria in February of 1990, is still employed by BEMO and gathered 34+ years of experience in SEM/ NATM tunneling. After work in the estimation department he started his on-site career filling different positions on construction sites in Germany, among others on the subway system in Munich, two SEM high speed railway tunnels between Frankfurt and Cologne and the Egge-Tunnel near Kassel in the North of Germany. In 2001 he became the Tunnel Manager on the Russia Wharf Tunnel in Boston, MA (MBTA Silverline subway between South Station and World Trade Center) and spent the time between 2004 and 2011 in Sweden as BeMo`s Area Manager for Scandinavia. Major projects there were Tunnel Troeingeberg, a 1,100 m long high speed railway tunnel in Falkenberg, Sweden and an 8,000 m long sewer tunnel from Lerum to Partille, Sweden – both are drill and blast tunnels with extensive hard rock pre-grouting. After his move back to the US in 2011 he started working as BEMO`s Area Manager North America and got involved in several high-ranking SEM projects, among others:*

- *MUNI China Town Station, Central Subway San Francisco Quikspray*
- *Cross over cavern on Regional Connector, Metro Los Angeles*
- *Quarters LRT Tunnel in Edmonton, Alberta*
- *John Hart Hydro Power Station in Campbell River, Vancouver Island, BC*
- *Plymouth Tunnel as part of the Purple Line in Silver Spring, Maryland (excavation and shotcrete final lining)*
- *Cross Passages on Purple Line extension Westside 1, Metro Los Angeles*
- *Frozen Ground Adits at 4th Street and Florida Avenue on the North East Boundary CSO Tunnel in Washington, D.C.*
- *McGill South Tunnel rehabilitation, REM in Montréal, Quebec (excavation and shotcrete final lining)*
- *Grand Central/ 42nd Street passageway circulation improvement Tunnel in New York City (excavation and shotcrete final lining)*

It is the goal of the ASA Underground Committee to issue this paper as it's fifth Position Statement, contributing to our growing library of best practice resources for shotcrete placement. Towards that end, the Underground Committee welcomes any feedback or comment on the content of this article, for consideration in the final Position Statement. Please send your comments, feedback, or questions to **Info@shotcrete.org** by January 31, 2025 for review prior to our Spring Committee Meetings in Savannah, GA, next March. Thank you!