REPORT ON EARLY STRENGTH PERFORMANCE OF MODERN DAY WEAK ROCK MASS SHOTCRETE MIXES

C. C. Clark, NIOSH, Spokane, WA
M. A. Stepan, NIOSH, Spokane, WA
J. B. Seymour, NIOSH, Spokane, WA
L. A. Martin, NIOSH, Spokane, WA

ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH), Ground Control Engineering Branch is investigating the use of shotcrete in weak rock mass mines with the objective of reducing fatalities and injuries resulting from rock fall accidents. When shotcrete is used as part of a multi-element ground support system there is a need to know when the material has developed a threshold early compressive strength of approximately 1 MPa (145 psi) for safe re-entry of miner and machine into shotcreted mine workings. This equates to the material having developed enough strength to be self-supporting and allow for emplacement of the remaining support elements that require drilling of the shotcrete layer without degradation. NIOSH researchers have developed methods and portable test equipment to measure shotcrete strength on-site in the first six hours after application using the ASTM C 116-90 (1990) standard. These advances were demonstrated in tests on five commercially available shotcrete mixes, sprayed as dry shotcrete using the field expedient methods and equipment. The strength values from these tests allowed for real-time identification of the early strength threshold and were consistent with strengths reported using laboratory-type equipment. The findings of this NIOSH research for determining shotcrete early strength can improve mine safety by providing a method for determining initial site specific material property values to be used for design and as a means to conduct on-site quality control and monitoring during production.

INTRODUCTION

Fall of rock is a major hazard in underground mining with thirty-six percent of all underground metal/nonmetal mines fatalities (1996-2004) being attributed to this cause. MSHA statistics show that of these unplanned falls of rock 95% weighed less than one ton with the majority 59% weighing 11 kgs (25 lbs) or less (Fig. 1. and Table 1). These small rocks can develop 106 N (23.8 lbf) of force over a 3-m (10-ft) fall (Lacerda, 2004). The falls often occur between traditional ground control support components (e.g., bolts, trusses, timber, etc.) and can only be prevented by skin control components such as shotcrete and wire mesh.

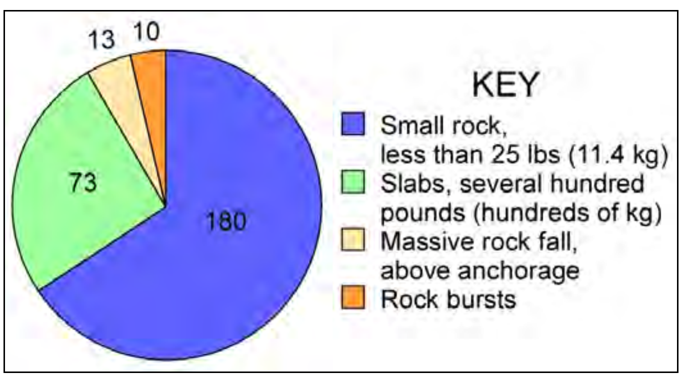

Figure 1. 1996 U.S. metal mine rockfalls (after Zipf 2002).

Table 1. MSHA rockfall review for Nevada Mines (after Lacerda, 2004).

Year	Small rock	Big rock	Cave
1990	3	9	
1991	12	4	
1992	8	2	
1993	5	6	1
1994	10	5	1
1995	17	8	2
1996	14	13	
1997	22	5	2
1998	13	12	
1999	10	5	4
2000	7	4	
Sum	121	73	10
Pct of total	59	36	5

When mining operations move into weak rock mass conditions (Rock Mass Rating of less than 45), such as those found in Nevada gold mines, rock falls are a constant threat. This is due in part to unraveling of the poor quality, broken rock.

The mining method commonly used in these mines is a modified form of mechanized cut and fill amenable to high ore recovery rates in irregular deposit geometries. Shotcrete is a key ground support element in this mining method. In addition, the time required for shotcrete to set sufficiently for safe re-entry is a key factor in the mining cycle. However, the early strength properties of shotcrete mixes used in these mining applications are not well defined and difficult to measure in situ.

Thus, there is a risk that miners will prematurely enter workings, before safety support is obtained. Because of this, the National Institute for Occupational Safety and Health (NIOSH) developed an in-mine test protocol and applied it to the study of early-age shotcrete strength for five dry shotcrete mixes currently in use in weak rock mass mines.

The ultimate goal of this work was to enable a mining engineer to characterize and define the strength properties of a particular shotcrete mix and thus determine when the mining cycle could safely restart with miners and machinery. This would be determined by knowing when the shotcrete applied as a surface ground support skin control has obtained or built the minimum strength required to resist the normal ground pressure (Iwaki et al., 2001) and upon development of sufficient bond strength or initial skin control interlock such that shotcrete-rock matrix does not fall off or apart within the first 20 minutes after application (Rispin, 2003).

BACKGROUND

Ground control systems used in mechanized cut-and-fill stopes in Nevada require extensive ground support. Typical support includes a shotcrete flash coat 19-to 25- mm (3/4- to 1-in) thick, followed by screen, plates, bolts, and a second layer of shotcrete bringing the combined thickness to 75- to 100-mm (3- to 4-in). In areas requiring rehabilitation, the second layer of shotcrete is plated and bolted as well.

Shotcrete is an integral and vital component of this ground support system. In the initial application, a remote controlled shotcrete machine sprays shotcrete to form a skin or shell. This thin skin prevents very small rock debris from falling and fouling the machinery used for remote application of the mesh and bolting. The second application of shotcrete ties together the plated and bolted mesh and prevents unraveling of the small-in-size rock which if left unchecked can propagate to allow for substantial slabbing and ultimately massive failure.

Most observed ground control failures involve broken rock within a half-meter of the excavation perimeter (Bauer and Donaldson, 1992). The failure mode is illustrated in figure 2.

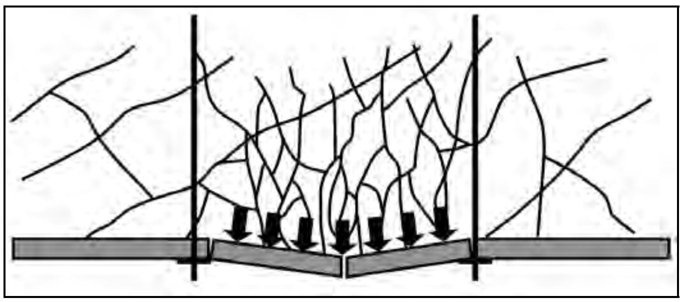

Figure 2. Flexural resistance model for a loosened block representing a distributed load (after Diamantidis and Bernard, 2004).

Setting of shotcrete in this support system is critical to the mining cycle. Re-entry time is the minimum curing time required for shotcrete to develop enough strength to protect miners. In other words (quoting Rispin, 2003), "the re-entry time is defined as when work can safely resume in an advancing underground heading." What this means in practical terms is that shotcrete can be drilled and support system components emplaced, without damaging long-term strength properties (O'Toole and Pope, 2006 and Clemets, 2009).

Development of early strength is a characteristic of shotcrete and occurs considerably faster than ordinary concrete, especially with lower water to cement ratios, Figs. 3 and 4. In addition, fiber additives have been developed that can greatly increase the toughness and tensile strength of shotcrete. This greatly benefits the structural properties of the shotcrete in terms of failure strength after onset of initial cracking.

Early strength is typically taken to mean the strength values the shotcrete material obtains in the time period from 0- to 6-hrs following being sprayed. Early strength values using unconfined compressive tests as low as 0.5A MPa (73 psi) have been used as a benchmark to identify conditions under which re-entry can safely and acceptably be permitted on International Mining Properties (Rispin, 2005). Typically however, for safe re-entry practices for North American mines, the shotcrete should develop a compressive strength of 1- to 1.6-MPa (145- to 233-psi) to be competent for drilling operations on it (O'Toole and Pope, 2006). The time reported for the safe re-entry has been as soon as 2 hrs (Knight et al., 2006) with 4 hrs and compressive strength equivalent to 1 MPa (145 psi) being the norm (Rispin, 2003 and 2005; O'Toole and Pope, 2006).

TEST PROTOCOL

Testing of the early strength of shotcrete introduces two issues not normally faced when testing of concretes. First, samples must be obtained "as shot" rather than poured into test cylinders. Moreover, it is not realistic to extract green samples, via a coring process, from a shotcrete panel for testing (Heere et al., 2002; Clemets, 2004). Second, samples must be tested very quickly after collection.

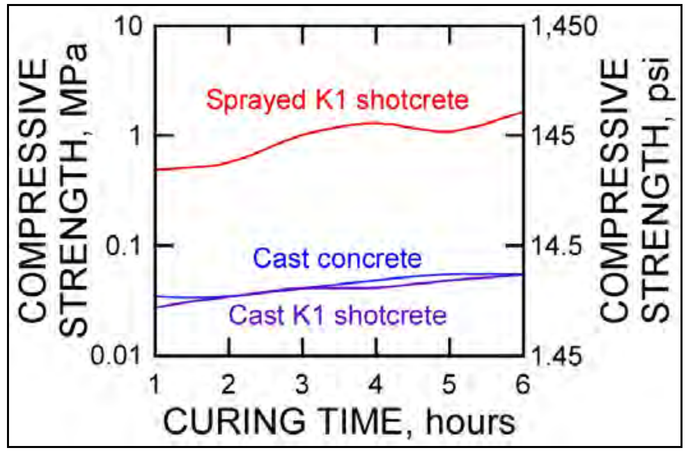

Figure 3. Typical early strength partial beam test values, for weak rock mass dry shotcrete and concrete, n=54 samples.

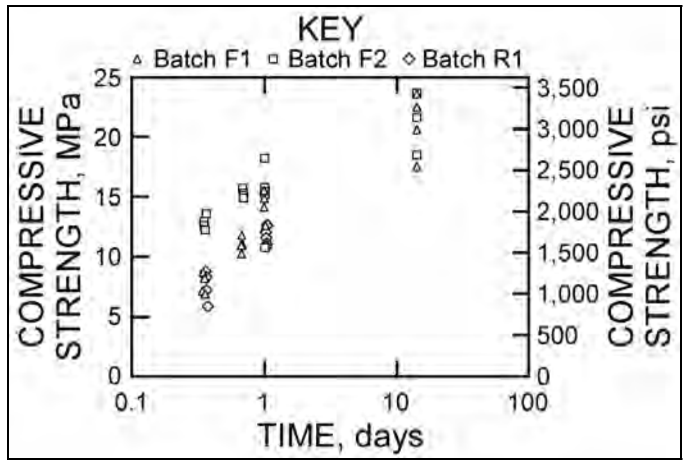

Figure 4. Strength gain of different blends of shotcrete (Brummer and Swan, 2001; after Tannant, 1994).

Researchers trying to determine the early age strength (0- to 6-hrs) of green shotcrete have had to resort to indirect test methods due to the difficulty in handling the material. Methods have been demonstrated using a Meyco penetrometer ASTM C 1117-89 (1989) (Jolin et al., 1999; Heere et al., 2002), and ASTM C 403-99 (1999) (Rispin, 2003, Clemets, 2004; Knight et al., 2006; O'Toole and Pope, 2006; Bernard, 2009), pneumatic pin (Iwaki et al., 2001), long partial beam, ASTM C 116-90 (1990) (Morgan, 1998; Heere et al., 2002) and partial beam ASTM C 116-90 (O'Toole and Pope, 2006; Bernard, 2009).

An example of early compressive strengths values obtained for five shotcrete mixes using penetrometer and partial beam methods as reported by O'Toole are shown in Fig. 5.

NIOSH researchers chose the partial beam ASTM C 116-90 (1990) standard in the 1- through 6-hr time frame because it allowed the early-age shotcrete specimen to be sprayed, de-molded, and emplaced in the test machine without degradation (due to its low strength state) prior to testing. The 0- to 1-hr time frame utilizing penetrometer technology was not used because of the non-linearity in data (Fig. 5) and the requirement for a second measuring protocol.

Beam molds have been used successfully for creating test specimens in the USA and Canada (Heere et al., 2002). The molds can be either hand, or manipulator arm, sprayed for both wet and dry shotcrete and provide suitable results. The partial beam ASTM C 116-90 strength determination test and apparatus used by researchers applies a compressive load that induces a diagonal tensile failure.

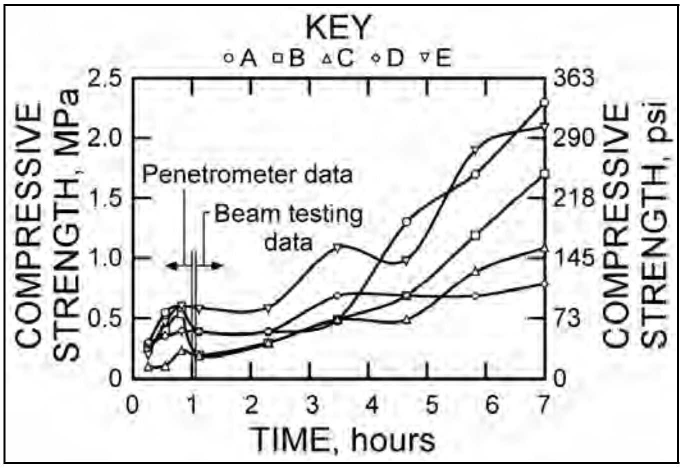

Figure 5. Penetrometer and sprayed beam compression test results for shotcrete mixes (O'Toole and Pope 2006).

The shotcrete machine used to spray the fibered and non-fibered dry mixes was a hopper and pre-dampener design (Aliva 252.1 series) used on dry mine shotcrete mixes in Nevada and Alaska for production and rehabilitation. The use of a hopper and pre-dampener allows for a consistent mix of the shotcrete with an even distribution of material at the nozzle. The dry mix was sprayed at an average water to cement ratio of 35%. The water content of the mix as it left the pre-dampener was 5% with the nozzleman adding an additional 2.5% for a final water content of 7.75% for the spray. The same task trained nozzleman was used throughout the testing program to insure application consistency.

A number of initial partial beam tests were conducted with a traditional Carver, dual-gage read-out, manually actuated, hydraulic press. The 0- to 5,000-psi and 0- to 25,000-psi analog scales on the unit proved to be too large to reflect the resolution necessary for the low strengths of the green mixes. In addition the manual operation of the machine introduced error with respect to uniformly loading the samples over the specified time interval and extended the time interval for conducting each test. In addition to the difficulty in obtaining meaningful strength numbers for the green shotcrete from the test machine, staff also encountered difficulty in shooting the material into the partial beam molds with respect to rebound and maintaining the position of the molds. It became apparent that developing a sound method for properly orienting the molds and restraining them would be necessary.

A mold containment system consisting of two frames was developed to restrain the partial beam boxes and orient them at a 45° angle to reduce the amount of rebound that would build up in the boxes. The smaller frame houses three box molds and can be hand carried to the testing location to coincide with the 1-hr tests (Fig. 6 upper-left). The larger frame was constructed with forklift pockets to allow the entire unit to be moved to the test location (Fig. 6). This system allows the 2- thru 6-hr samples, the cure time necessary for movement while still allowing for the 1-hr tests.

A partial beam testing machine was designed, that had the capability to automatically load the samples at a fixed rate and collect the load versus displacement data (Figs. 7 and 8).

Upon delivery the unit was commissioned and pre-tested using cast and sprayed samples (Fig. 9). The unit was found to be capable of accurately measuring load rate and the automated load cycle greatly reduced the chance of human error and reduced the time to conduct a proper test. The field worthy design incorporates a small-footprint, self-contained, servo-controlled, stiff-frame press configuration with advanced load-rate and load-collection capability. The operator is presented with a proper scale and resolution load output display. The machine resolution is 0.45 kg (1 lb) over a 2,268 kg (5,000 lb) operating range. A servo loop controlled machine head applies a load to keep the machine at the proper ASTM test cycle displacement rate of 1.278 mm/min (0.050 in/min) with an auto return after 6.35 mm (0.25 in) of displacement (ASTM C 116-90, 1990). Load versus displacement values are collected and stored using a Campbell Scientific 850 data logger.

Figure 6. Partial Beam Box Shooting Frame.

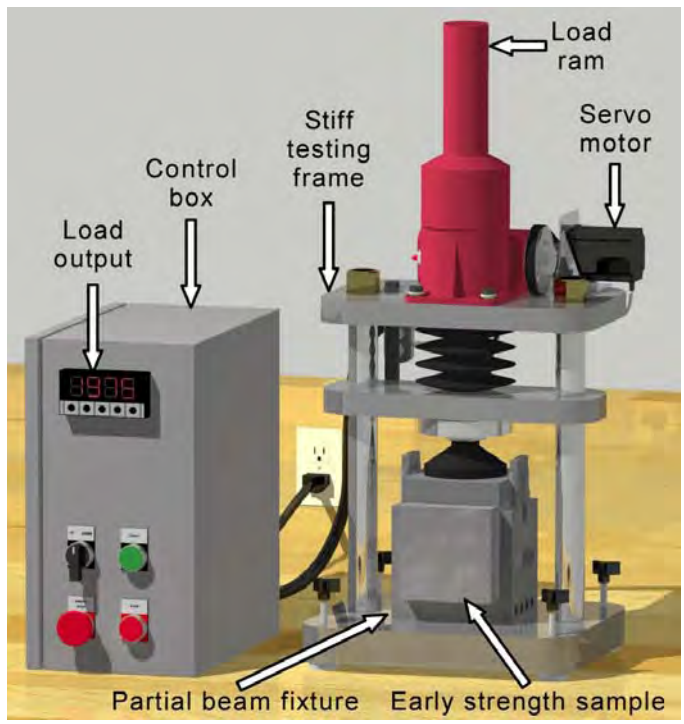

Figure 7. Early strength shotcrete test machine design.

The ASTM testing protocol used called for samples of the shotcrete mixes to be sprayed into 102- x 102- x 152-mm (4- x 4- x 6-in) mold boxes as seen in Figs. 6 and 10 to make the test specimens. Tests are conducted at one hour intervals on the de-molded specimens for the 1- through 6-hr testing. The shotcrete sample is carefully taken from the beam box mold and positioned with-in a specialized test fixture (Fig. 9).

To conduct a test, the ram is lowered to a position just above the specimen and the automated test cycle initiated by depressing the green start button along with the data acquisition start. The operator observes the specimen for development of single or dual side tension cracks (Fig. 11 and Fig. 12) along one of the platen-to-sample contact edges.

Figure 8. Early strength shotcrete test machine in operation.

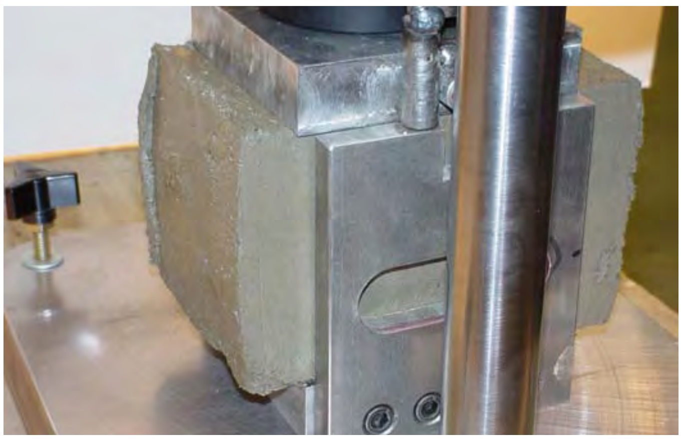

Figure 9. Shotcrete partial beam test specimen undergoing loading.

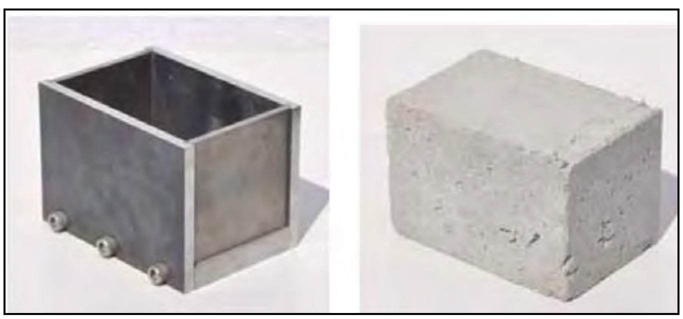

Figure 10. Partial beam box mold and test specimen.

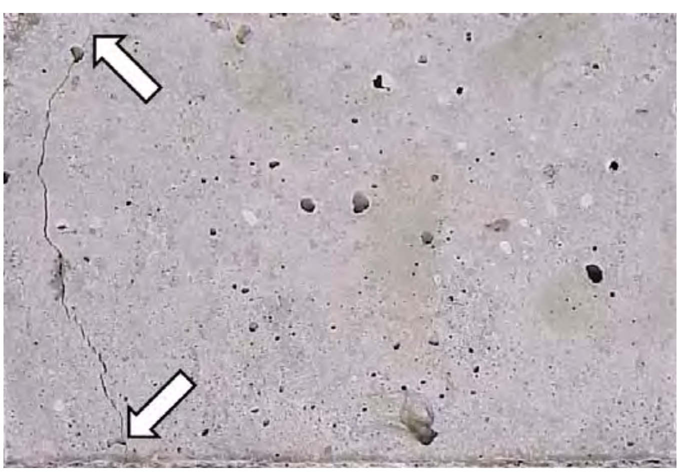

Figure 11. Shotcrete partial beam test specimen showing single side failure crack.

Upon on-set of a crack, the red button on the test machine control panel is depressed stopping the test. The shotcrete failure mode depicted in the diagonal tension failure illustration of Fig. 13 represents the failure cracks observed.

After testing only a few samples it is relatively easy to determine when a test has reached completion. This process is repeated for three specimens so that an average can be determined.

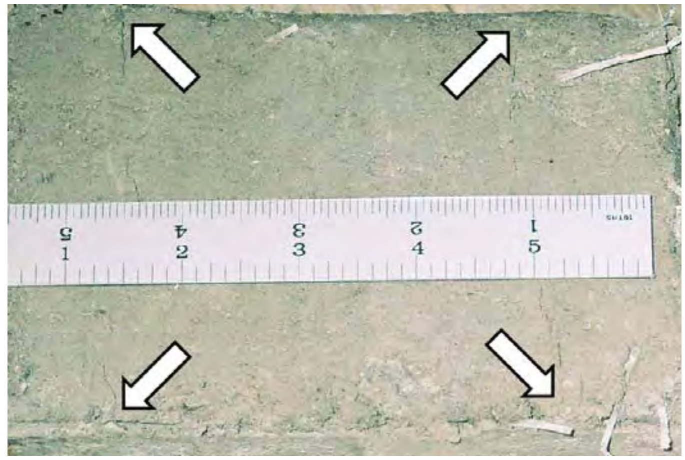

Figure 12. Shotcrete Partial Beam Test Specimen Showing Dual Sided Failure Cracks.

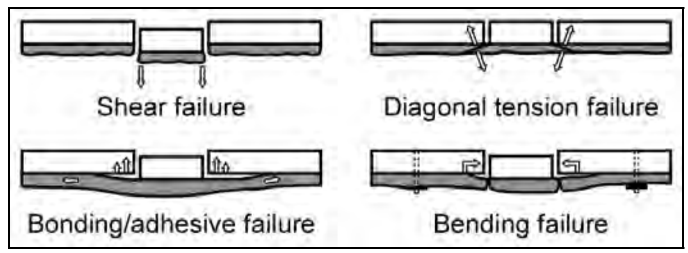

Figure 13. Shotcrete failure modes (Rose, 1985).

EXPERIMENTAL RESULTS

Figure 14 shows the rate of early strength development for the five commercially available weak rock mass dry shotcrete mixes tested by NIOSH researchers using a sprayed mold system subjected to ASTM C 116-90 partial beam methods.

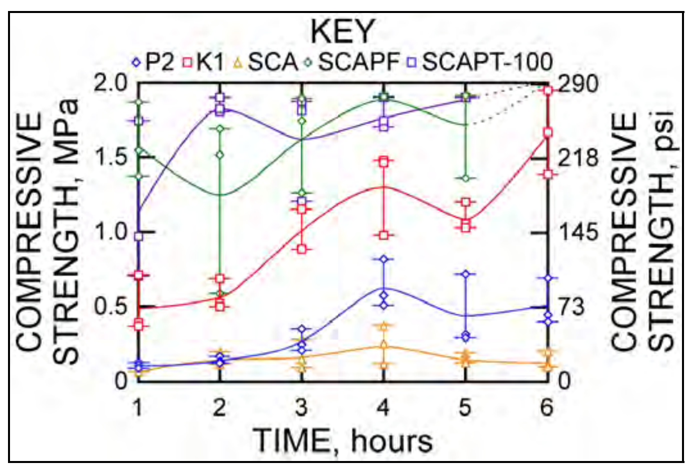

Figure 14. Summary graph of early age sprayed partial beam compression tests on five commercially available Nevada weak rock mass mine shotcrete mixes, n=72 samples.

Examination of the data indicates a consistent early strength rise followed by a plateau at the 3- to 4-hr curing time. This initial set and then phase transfer was observed in all shotcrete samples tested in the NIOSH study. This characteristic has been well referenced in the literature on shotcrete (Jolin et al., 1999; Heere et al., 2001; Knight et al., 2006; Rispin, 2005, O'Toole and Pope, 2006; Bernard, 2008) and is depicted as well in Figs. 15 and 16. This characteristic has been attributed to the initial added accelerants giving way to the cementitious hydration phase. For the mixes tested, three out of the five, reached the early re-entry strength threshold of 1 MPa (145 psi) within 3 hrs and were confirmed again at the 4 hr mark (Note: all of the mixes tested exceeded 1 MPa (145 psi) after 24 hrs of curing).

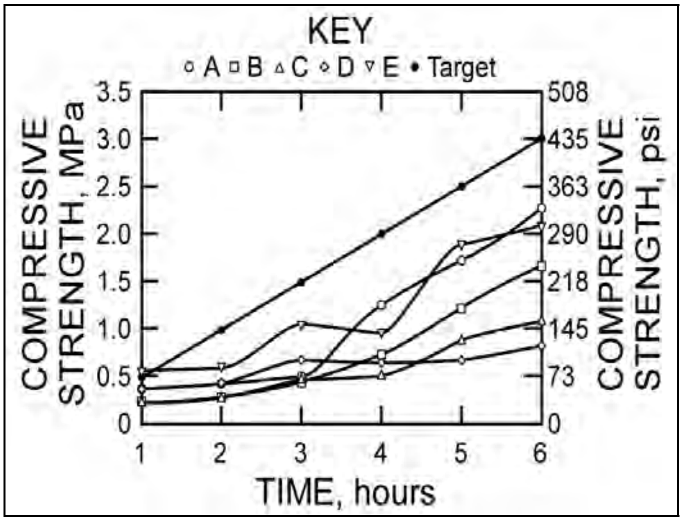

Figure 15. Summary graph of early age sprayed beam compression tests from surface trials of shotcrete mixes (After O'Toole and Pope, 2006).

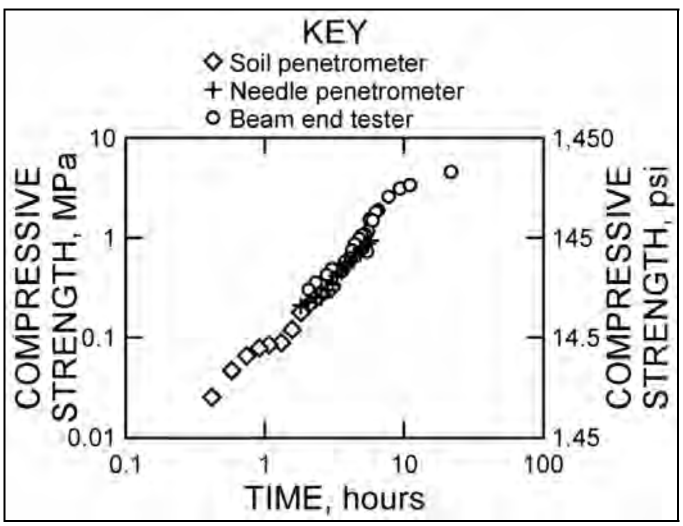

Figure 16. Compressive strength as a function of time after spraying for a typical trial (Bernard, 2008).

These early compressive strength values are in good agreement with O'Toole who reported trends between 0.25 and 2.25 MPa for tests on 1- through 6-hr partial beams (Fig. 15) and Bernard who reported trends between 0.2- and 3-MPa for tests on 1- through 10-hr partial beams (Fig. 16). The method of display used by NIOSH (Figs. 14 and 15) makes it easier to distinguish when the shotcrete goes into a holding state at 3- to 4-hrs of curing time.

The SCAPF and SCAPT-100 are fibered versions of the SCA mix. SCAPF is a poly-fibered mix and SCAPT-100 is a steel-fibered mix. After six hours of curing the fibered mixes exceeded the capacity of the test machine (shown as dotted lines in Fig. 14). The compressive strength exceeded 2 Mpa (290 psi). The addition of fibers seems to produce higher early strengths. Additional testing will be conducted at mine sites to examine and confirm this characteristic.

CONCLUSIONS

A field expedient test method and portable on-site test equipment have been developed. This test method allows for real-time early compressive strength testing of shotcrete "as-placed" underground.

This is important because there are a variety of conditions that can influence early development of shotcrete strength. These include the mine environment, application quality, application quantity, ambient temperature of the applied shotcrete and host rock, mix design of the commercial shotcrete used and its characteristics and the water to cement ratio at which the mix was actually sprayed. These factors are difficult to replicate in tests conducted elsewhere, and delays in obtaining results negate their usefulness in controlling quality and preserving safety.

The method was demonstrated in tests on five commercially available shotcrete mixes marketed for use in mining of weak rock. Three out of the five mixes developed the accepted minimum standard for shotcrete early compressive strength of 1 MPa (145 psi) within 4 hrs of set time Fig. 16 (Morgan, 1991; Clemets, 2004 and 2009).

The key consideration, though, is the actual shotcrete strength realized at the mining face as a function of time. Safe re-entry depends on assuring that adequate shotcrete strength has been obtained.

The findings and conclusions presented in this document have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy and mention of any company name or product does not constitute endorsement by NIOSH.

ACKNOWLEDGEMENTS

The authors would like to thank James Schumacher at Thiessen Team USA, Elko, Nevada, Vince Mendive at Thiessen Team USA, Big Timber, Montana and Mark Mudlin, BASF, Master Builders, Elko, Nevada for their technical support on commercially available mixes. Also Justin Deemer and Rocky Wegland at Westech Automation Spokane, WA for their technical and mechanical assistance in development of the early strength testing machine.

REFERENCES

ASTM C 116-90 (1990), Standard Test Method for Compressive Strength of Concrete Using Portions of Beam Broken in Flexure," in *American Society for Testing and Materials*, PA, (Withdrawn 1999).

ASTM C 1117-89 (1994), "Standard Test Method of Time of Setting of Shotcrete Mixtures by Penetration Resistance," in *American Society for Testing and Materials*, PA, (Withdrawn 2003).

ASTM C 403-99 (1999), "Standard Test Method of Time of Setting of Concrete Mixtures by Penetration Resistance," in *American Society for Testing and Materials*, PA.

Bauer, G. and D. Donaldson (1992), "Perimeter Control in Development and Breasting by use of a Blasting Program Readily Accepted by Miners", in Proceedings of the 18th Annual Conference on Explosives and Blasting Technique, Int. *Soc. of Explosives Engrs,* Cleveland, Ohio, 1992, pp. 133-140.

Bernard, E. (2008), "Early-Age Load Resistance of Fibre Reinforced Shotcrete Linings," Tunneling and Underground Space Technology *23*:451-460.

Brummer, R. and G. Swan, (2001), "Support and Structural Use of Shotcrete in Mines," in *Underground Mining Method : engineering fundamentals and international case studies*, W. Hustrulid, and R. Bullock, eds., Soc. of Mining Engineers, pp. 593-600.

Clemets, M. (2004), "Comparison of Methods for Early Age Strength Testing of Shotcrete," *Shotcrete: More Engineering Developments*, Proceedings of the 2nd International Conf. on Engineering Developments in Shotcrete, Cairns, Queensland, Australia, Bernard ed., Taylor and Francis Group, London, pp. 81-87.

Clemets, M. (2009), "Exploring the Limits of Shotcrete Loading Capacity at Early Age," Website of Grenz Consulting Pty Ltd., www.grenz.com.au.

Diamantidis, D. and Bernard E. (2004) "Comparison of Methods for Early Age Strength Testing of Shotcrete," *Shotcrete: More Engineering Developments*, Proceedings of the 2nd International Conf. on Engineering Developments in Shotcrete, Cairns, Queensland, Australia, Bernard, ed., Taylor and Francis Group, London, pp. 109-126.

Heere, R., D. Morgan, and N. McAskill (2002), "Determination of Early-Age Compressive Strength of Shotcrete," *Shotcrete Magazine*, Spring 2002, pp. 28-31. Based on paper from *Shotcrete: A Compilation of Papers,* American Shotcrete Association 2008, pp. 23-32, originally published by Norwegian Concrete Association, in the 3rd Intl. Symposium on Sprayed Concrete, Gol, Norway.

Iwaki, K., A. Hirama, K. Mitani, S. Kaise and K. Nakagawa (2001), "A Quality Control Method for Shotcrete Strength by Pneumatic Pin Penetration Test," NDT&E International *34*(6):395-402.

Jolin, M., Beaupre, D., and Mindess, S. (1999), "Tests to Characterize Properties of Fresh Dry-Mix Shotcrete," Cement and Concrete Research *29*:753-760.

Knight, B., M. Rispin and I. Clegg (2006), "Wet-Mix Shotcreted as A Material, Process and Ground Control Component of a 21st Century Under ground Mining Operation," *Shotcrete for Underground Support X*, (SUS-X) proceedings of the 10th Int. Conf. Sept 1 2-16, 2006 Whistler, BC, Can., D. Morgan and H. Parker, eds., Amer. Soc. of Civil Engineers, pp. 298-306.

Lacerda, L. (2004), "Shotcrete and Other Surface Support Liners," *Preprint 04-36*, SME Annual Meeting, Denver CO.

Morgan, D. (1991), "Steel Fiber Reinforced Shotcrete for Support of Underground Openings in Canada," from *Shotcrete: A Compilation of Papers,* American Shotcrete Association 2008, pp. 203-211, originally published by American Concrete Institute, Concrete International *13*(11):56-64.

O'Toole, D. and S. Pope (2006), "Design, Testing and Implementation of 'In-Cycle' Shotcrete in *The Northern 3500* Orebody," *Shotcrete for Underground Support X,* (SUS-X) proceedings of the 10th Int. Conference, Whistler, BC, Can., D. Morgan and H. Parker, eds., Amer. Soc. of Civil Engineers, pp. 316-327.

Rispin, M., B. Knight and R. Dimmock (2003), "Early Re-Entry into Working Faces in Mines through Modern Shotcrete Technology—Part II," *Canadian Institute of Mining - Mines Operations Centre* (CIM-MOC), Saskatoon, SK, Can.

Rispin, M. (2005), "Reentry into a Shotcreted, Underground Heading," *Shotcrete Magazine*, Spring, pp. 26-30.

Rose, D. (1985), "The Role of Shotcrete in Hard-Rock Mines," in *Underground Mining Method: Engineering Fundamentals and International Case Studies*, W. Hustrulid, W.A., and R. Bullock, eds., Soc. of Mining Engineers, pp. 579-592.

Tannant, D. (1994), "Support and Structural Use of Shotcrete in Mines," in *Underground Mining Method : engineering fundamentals and international case studies*, W. Hustrulid and R. Bullock, eds., Soc. of Mining Engineers, pp. 593-600.

Zipf, R.K. (2002), Spokane Research Laboratory, Presentation at Colorado School of Mines, Golden CO, 2002. Also Biswas, K. and Zipf, K., "Root Causes of Groundfall Related Incidents in U.S. Mining Industry," In: Proceedings of the 22nd International Conference on Ground Control in Mining, Morgantown, WV, pp. 335-343.