Early strength performance of modern weak rock mass shotcrete mixes

by C.C. Clark, M.A. Stepan, J.B. Seymour and L.A. Martin

Abstract ■ The National Institute for Occupational Safety and Health (NIOSH), Office of Mine Safety and Health, 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, it is necessary to know when the material has developed a compressive strength of approximately 1 MPa (145 psi), the early threshold for safe re-entry of miner and machine into shotcreted mine workings. At this value, the material has developed enough strength to be self-supporting and to allow for installation of other ground support components 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 a partial beam test standard, ASTM C 116-90 (1990). These advances were demonstrated in tests with five commercially available shotcrete mixes, sprayed as dry shotcrete using 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. Measuring the early strength properties of shotcrete directly at the mine site can improve mine safety by identifying appropriate re-entry times and providing a convenient means of conducting on site quality control during shotcrete applications.

Introduction

Rock fall is a major hazard in underground mining, with 36% of all underground metal/nonmetal mine fatalities (1996-2004) being attributed to this cause. U.S. Mine Safety and Health Administration (MSHA) statistics show that of these unplanned falls of rock, 95% weighed less than 1 t (1.1 st), with the majority, 59%, weighing 11 kg (25 lbs) or less (Fig. 1). These small rocks can develop 106 N (23.8 lbf) of force over a 3-m (10-ft) fall (Lacerda, 2004). These falls often occur between traditional ground support elements (e.g., bolts, trusses, timber, etc.) and can only be prevented by surface or skin control such as shotcrete and wire mesh.

For mining operations in weak rock mass conditions (rock mass rating 20 to 45, very poor to poor), such as the Nevada underground gold mines, rock falls are a constant threat. This is due in part to the unraveling of the poor quality 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 and, as a result, the time required for the shotcrete to set sufficiently for safe re-entry is a key factor in the mining cycle. Because the early strength properties of shotcrete mixes used in these mining applications are not well defined and difficult to measure in situ, there is a risk that miners will prematurely enter workings before the shotcrete has gained sufficient strength to provide adequate ground support.

To address these concerns, 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 used in weak rock mass mines.

The ultimate goal of this work is 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 safe re-entry time is determined by knowing when the shotcrete applied to the surface of an underground opening has gained the minimum strength required to resist the normal ground pressure (Iwaki et al., 2001) and has developed sufficient bond strength or initial skin control in-

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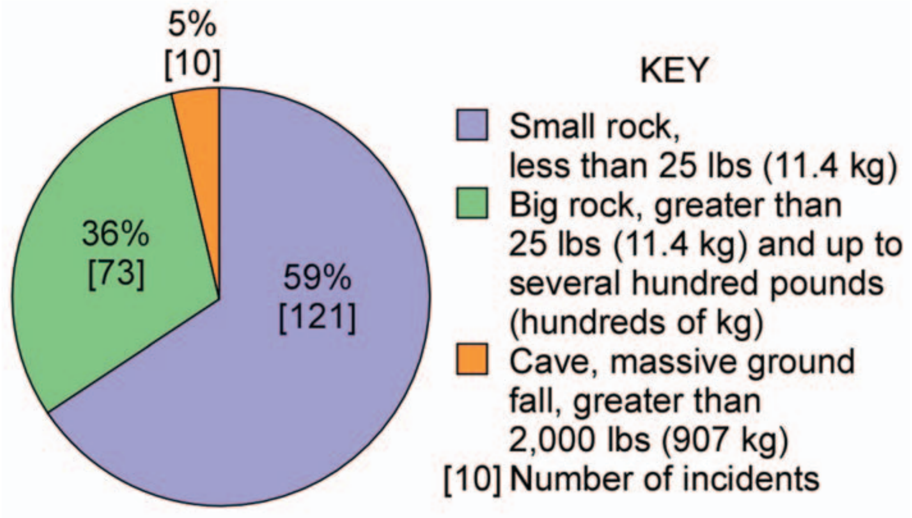
terlock such that the shotcrete-rock matrix does not fall apart within the first 20 minutes after application (Rispin et al., 2003).

Figure 1

U.S. metal mine rockfalls, 1996 - 2004 (after Zipf, 2002 and Lacerda, 2004).



Background

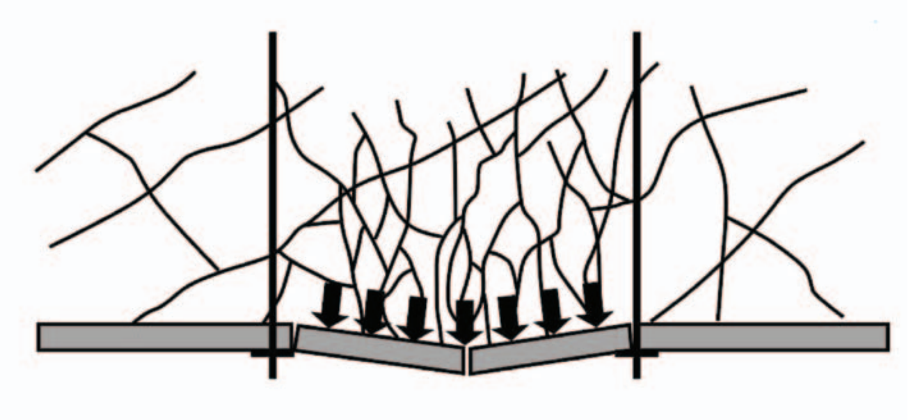
Mechanized cut-and-fill stopes in Nevada require extensive ground support. Typical support includes a shotcrete flash coat 19 to 25 mm (0.75 to 1 in) thick, followed by screen, plates, bolts and a second layer of shotcrete, bringing the combined thickness to 75 to 100 mm (3 to 4 in). In areas requiring 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 that is subsequently used to remotely install the mesh and bolts. The second application of shotcrete ties together the plated and bolted mesh and prevents unraveling of the small-sized rock. If this material is not confined, the small-sized rock can loosen and fall out, allowing additional material to fail and eventually causing substantial slabbing and ultimately massive failure.

Most observed ground control failures involve broken rock within 0.5 m (1 to 2 ft) of the excavation perimeter (Bauer and Donaldson, 1992). The loading and failure mode is illustrated in Fig. 2.

Figure 2

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



With this support method, the curing time or setting of the shotcrete 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, 2005), "the re-entry time really defines when work can resume in an advancing underground heading." What this means in practical terms is that the shotcrete can be drilled and other ground support components installed without damaging the long-term strength properties of the shotcrete (O'Toole and Pope, 2006; Clements, 2009).

Development of early strength is a characteristic of sprayed shotcrete and occurs considerably faster than cast shotcrete and ordinary concrete (Fig. 3). 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 typically refers to the strength values that the shotcrete material achieves shortly after being sprayed (zero to six hours). Early strength values from unconfined compression tests as low as 0.5 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). However, for safe re-entry practices in North American mines, the shotcrete should typically develop a compressive strength of 1 to 1.6 MPa (145 to 233 psi) to be competent enough for drilling operations required for the installation of other ground support (O'Toole and Pope, 2006). The time reported for the safe re-entry has been as soon as two hours (Knight et al., 2006), with four hours and compressive strength equivalent to 1 MPa (145 psi) being the norm (Rispin et al., 2003; Rispin, 2005; O'Toole and Pope, 2006).

Test protocol

The early strength testing of shotcrete introduces two issues not normally faced when conducting tests with concrete. First, samples of the shotcrete must be obtained as the material is applied or sprayed, rather than poured or cast into test cylinders. Moreover, it is not realistic to extract samples of

Figure 3

Typical early strength partial beam test values for dry-mix shotcrete and concrete, n=54 samples.

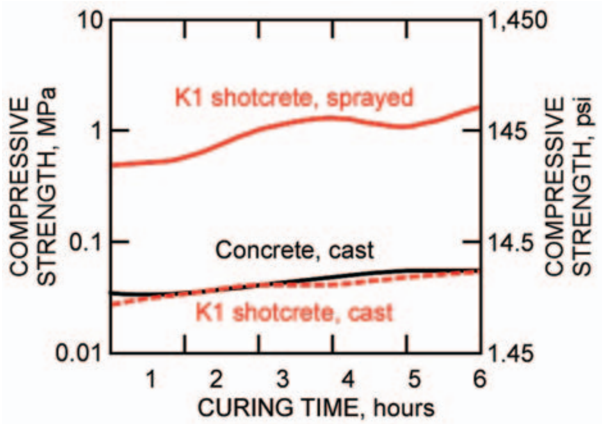
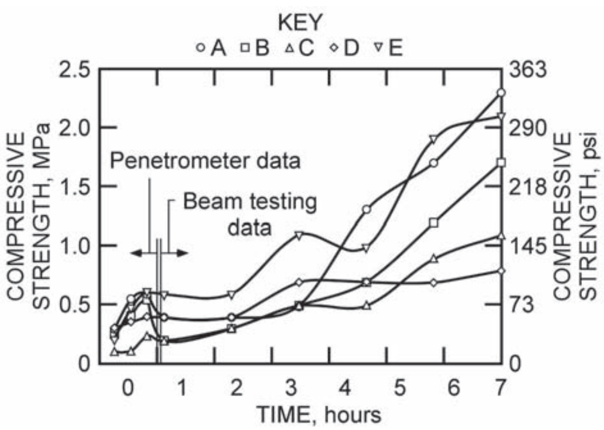


Figure 4

Summary of early-age penetrometer and sprayed beam compression tests from surface trials of shotcrete mixes (after O'Toole and Pope, 2006).



green or partially cured shotcrete, via a coring process, from a shotcrete test panel (Heere et al., 2002; Clements, 2004). Second, because the shotcrete gains strength at an accelerated rate, samples must be tested very quickly after collection.

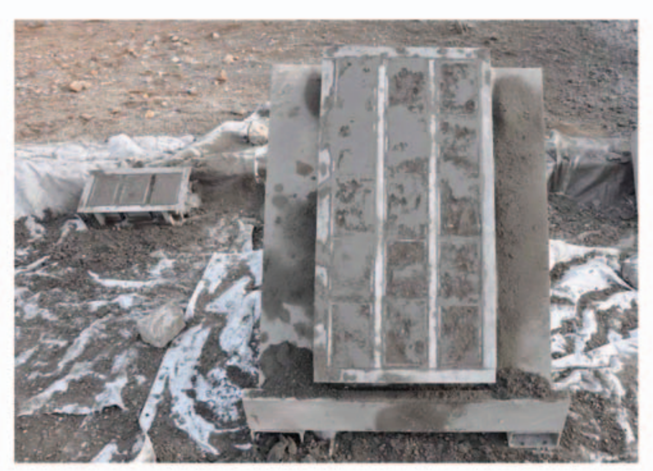
Researchers trying to determine the early age strength (zero to six hours) of green shotcrete have had to resort to indirect test methods due to the difficulty in handling the material. Methods have been demonstrated using a Meyco penetrometer, ASTM C 1117-89 (1989) (Jolin et al., 1999; Heere et al., 2002) and ASTM C 403-99 (1999) (Rispin et al., 2003; Clements, 2004; Knight et al., 2006; O'Toole and Pope, 2006; Bernard, 2008), pneumatic pin (Iwaki et al., 2001), long partial beam, ASTM C 116-90 (1990) (Morgan, 1991; Heere et al., 2002) and partial beam, ASTM C 116-90 (O'Toole and Pope, 2006; Bernard, 2008).

An example of early compressive strengths values obtained for five shotcrete mixes using penetrometer and partial beam methods as reported by O'Toole and Pope (2006) are shown in Fig. 4.

Problems have been reported with the penetrometer type devices, particularly a difficulty in obtaining consistent results. This is due to the penetrometer pin contacting materials of varying density within the matrix of the material being sampled. Penetrometers were not used in this study because of the difficulties reported in regard to their use, nonlinearity of penetrometer test results with those obtained from beam tests (Fig. 4) and the need for developing a second test protocol.

Figure 5

Partial beam box molds and spraying frame.



Beam molds have been used successfully for creating shotcrete test specimens in the U.S. and Canada (Heere et al., 2002). NIOSH researchers selected the partial beam standard, ASTM C 116-90 (1990) to measure the early strength of shotcrete, one to six hours after the material was sprayed. The molds can be sprayed by hand or manipulator arm, using either wet and dry shotcrete, and provide suitable results. The early-age shotcrete specimen can be sprayed, demolded, and placed in the test machine without degradation to the sample as a result of its low strength. During the partial beam strength test, a compressive load induces a complex shear failure in the shotcrete specimen. This type of loading and failure more closely replicates the shotcrete failures that are typically observed in the mines.

An Aliva 252.1 series shotcrete machine was used to spray the fibered and nonfibered dry-mix shotcrete. The Aliva's design employs a hopper and predampener and is commonly used to apply dry-mix shotcrete in underground mines in Nevada and Alaska. The use of a hopper and predampener 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 2.75% 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 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 is trapped within the boxes as they are sprayed. A smaller frame contains three box molds that can be hand-carried separately to a testing location to conduct the one-hour tests (Fig. 5 upper left). A larger frame was constructed with forklift pockets to allow the entire unit to be moved to the test location (Fig. 5). This two-frame system allows the two-hour

Figure 6

Early strength shotcrete test machine.

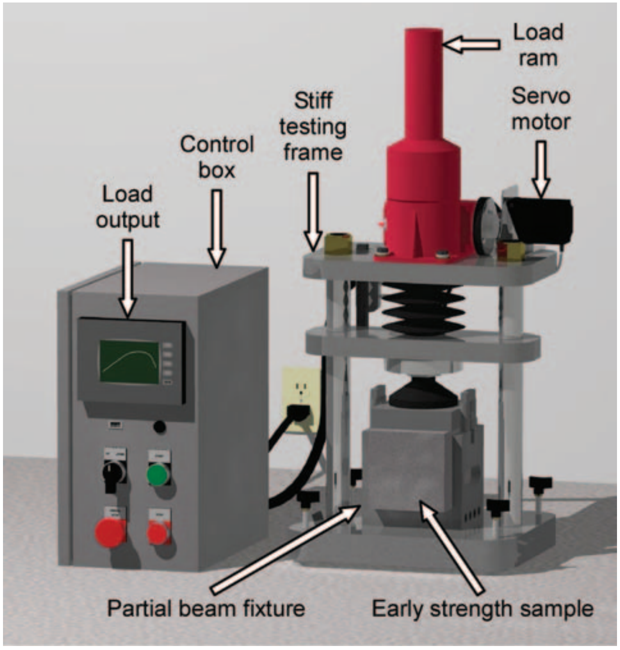


Figure 8

Vertical crack in a shotcrete test specimen.

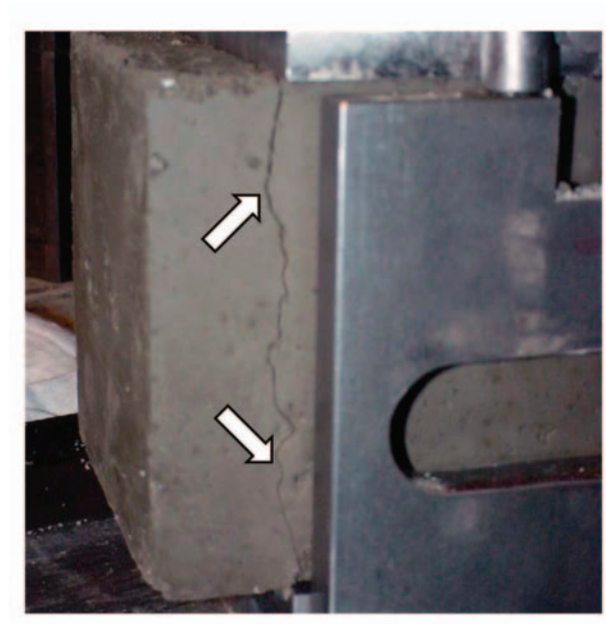
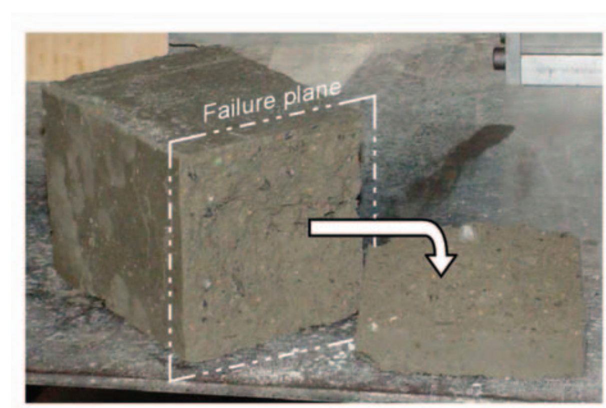


Figure 7

Partial beam box mold and test specimen.

Figure 9

Shotcrete specimen showing post-test failure plane.



through six-hour samples to cure undisturbed while tests are conducted with the one-hour samples.

A partial beam testing machine was designed to automatically load the samples at a fixed rate while measuring load and displacement (Fig. 6). This automated load cycle greatly reduces the chance of human error and enhances the consistency of the test results. This field-worthy design incorporates a small footprint, is self-contained and has a stiff frame press configuration with advanced load rate and load-measurement capability. Test parameter measurements are presented to the operator in proper scale and resolution on a graphical and numeric output display. The machine's load resolution is 4.5 N (1 lbf) over a 22.2 kN (5,000 lbf) operating range. A servo loop-controlled head applies a load to the test specimen at a displacement rate of 1.278 mm/min (0.050 in./min) in accordance with ASTM C 116-90 and automatically returns to its starting position after 6.35 mm (0.25 in.) of displacement. Load and displacement values are collected and stored on a thumb drive.

As shown in Figs. 5 and 7, partial beam test samples are obtained by spraying shotcrete into 102 x 102 x 152 mm (4 x 4 x 6 in.) mold boxes. After the samples have been sprayed, tests are conducted at one-hour intervals over the next six hours (one-hour through six-hour tests). The shotcrete samples are carefully de-molded by disassembling the mold fixtures and removing the enclosed sample. Next, a shotcrete sample is placed in a specialized testing fixture and centered under the loading head of the test machine (Fig. 6). When the test sequence is initiated, a programmable logic controller (PLC)-driven press applies a fixed-rate load to the sample. The load profile is shown on a graphical output display and the measured test parameters (time, displacement and load) are stored on a thumb drive. Once the operator observes a well-defined peak in the load profile curve, the test is completed, and the test machine's loading platen can be returned to its initial starting position. Peak load is typically reflected

Figure 10

Shotcrete failure modes (after Rose, 1985).

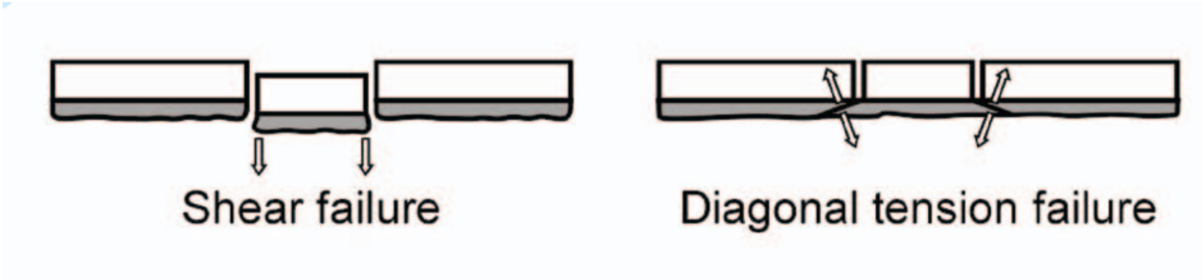
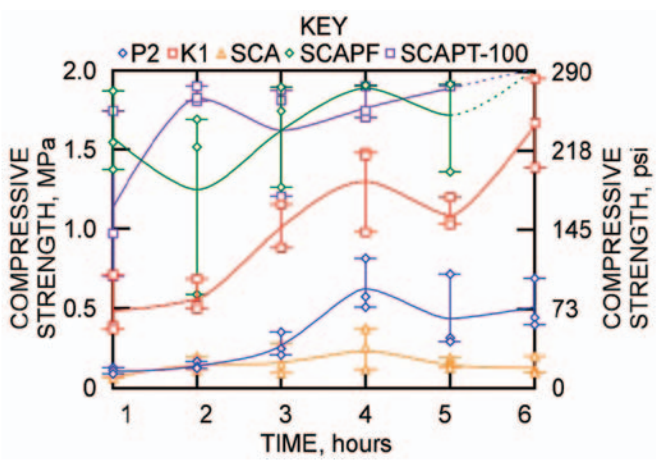


Figure 11

Summary of early-age compressive strength tests with sprayed partial beam samples of five commercially available dry shotcrete mixes, n=72 samples.



by the development of large, vertically oriented cracks (Fig. 8) along the platen-to-sample contact edges, which are indicative of the failure plane shown in Fig. 9.

The vertical crack is a complex failure that exhibits elements of shear, tensile and compressive failure modes. The test machine exerts a compressive load on the shotcrete sample through the test fixture that initiates primarily a shear failure in the sample. Figure 10 depicts examples of shotcrete failure modes. This early strength test process is repeated for three specimens so that an average test result can be determined.

Figure 11 shows the shotcrete early strength development as a function of time for the five commercially available weak rock mass, dry shotcrete mixes tested by NIOSH researchers. These mixes were applied using a sprayed mold system subjected to ASTM C 116-90 partial beam methods.

Examination of the strength gain with time for the mixes tested shows four of the five mixes plateau at the four-hour mark with one of the five plateauing at the two-hour mark. 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., 2002; Knight et al., 2006; Rispin, 2005; O'Toole and Pope, 2006; Bernard, 2008) and is depicted as well in Fig. 4. The initial strength gain provided by the accelerant additives appears to progress into a 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 three hours and were confirmed again at the four-hour mark. All of the shotcrete mixes exceeded 1 MPa (145 psi) after 24 hours of curing.

These early compressive strength values are in good agreement with O'Toole and Pope (2006), who reported trends between 0.25 and 2.25 MPa for tests on 1-to-6-hour partial beams (Fig. 4) and Bernard (2008), who reported trends between 0.2 and 3 MPa for tests on 1-to-10-hour partial beams.

The SCA mixes were supplied by a different shotcrete manufacturer than the K1 and P2 mixes. SCA is manufactured in Nevada and used in Nevada and Montana mines. K1 and P2 are manufactured in Washington and used in Alaska and Idaho mines. 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. K1 has a greater percentage of accelerants than P2, while P2 has a greater percentage than SCA. After six hours of curing, the fibered mixes exceeded the capacity of the test machine (shown as dotted lines in Fig. 11), with compressive strengths greater than 2 MPa (290 psi). For this test method, the addition of fibers generally produced higher early strengths.

Conclusions

A field-expedient test method and portable on site test equipment have been developed to measure shotcrete strength in the first six hours after application. Using this test method and equipment, underground mine personnel can measure the early compressive strength properties of "as-placed" shotcrete and clearly identify the shotcrete's early strength threshold in real time. This information allows more informed decisions to be made regarding safe re-entry times and can also improve mine safety by supplying pertinent site-specific shotcrete information for ground control plans and providing a viable means of conducting on site quality control during shotcrete applications.

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

The partial beam test method and portable early strength test machine were successfully demonstrated in tests with five commercial shotcrete mixes, which are currently used for ground support in weak rock conditions. Three out of the five shotcrete mixes shown in Fig. 11 developed the accepted minimum standard for early compressive strength of 1 MPa (145 psi) (Morgan, 1991; Clements, 2004 and 2009; Bernard, 2008) within four hours of curing.

Because safe re-entry depends on ensuring that the shotcrete has gained adequate strength, the key consideration is the actual strength of the shotcrete applied to the surface of the underground opening. Although these tests provide a valuable indication of the shotcrete's potential strength gain, they are not an actual measurement of the shotcrete's in-place strength.

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Disclosure

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. Mention of any company name or product does not constitute endorsement by NIOSH.

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