An analysis of flexural strength and crack width for fiber-reinforced shotcrete used in weak rock mines

L. Martin, B. Seymour, C. Clark and M. Stepan
Research mechanical engineer, mining engineer, mechanical engineer and engineering technician, respectively, National Institute for Occupational Safety and Health, Spokane, Washington

R. Pakalnis, M. Roworth and C. Caceres
Mining engineers, University of British Columbia, Vancouver, British Columbia

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 multielement ground support system, there is a need to know the support characteristics that the shotcrete contributes to the overall system. To quantify the support provided by the shotcrete, flexural strength tests were conducted with two common, commercially available fiber-reinforced shotcrete (FRS) mixes using the round determinant panel (RDP) test method, ASTM C 1550. A portable RDP test machine developed by NIOSH researchers was used to determine the peak flexural load and residual load capacity for a steel FRS and a synthetic poly FRS that were sprayed using dry mix procedures and equipment. Besides the flexural strength and loading behavior determined from these tests, a method was also developed for measuring the width of cracks exposed on the underside of a shotcrete panel during a RDP test and relating these measurements to residual load values. Quantifying the peak flexural load and residual loads of a shotcrete mix through on site testing at a mine and visually assessing the loading cycle and load-carrying capability of the shotcrete applied to underground workings will improve mine safety by providing a better assessment of the stability of shotcrete supported entries.

Key words: Shotcrete, Round panel tests, Ground control

Introduction

Underground mines in the western United States often have weak, raveling ground conditions (RMR_{76}<44), particularly the underground gold mines in Nevada. A typical drift in these mines usually has a span of less than 4 m (13 ft) and a service life of less than one month (Pakalnis, 2002). In these weak rock conditions, the surface or skin of the underground openings must be continually supported in order to adequately protect underground workers. The traditional support method for this type of ground is to install rock bolts for the primary ground support and then use wire mesh to support the loose broken material between the bolts. If the wire mesh does not provide sufficient support to maintain the integrity of the surface of the underground opening, shotcrete is applied, either instead of the mesh or in conjunction with the mesh to retain the loose, small material that would otherwise fall out. By providing a stiff flexural support that limits movement at the shotcrete/rock interface, the shotcrete securely holds the loose material in place, whereas the mesh exhibits a more flexible response to loading, stretching under load and allowing the broken material to move out of position. To provide additional support, fiber-reinforced shotcrete (FRS) is used instead of conventional shotcrete in the most extreme ground conditions (Pakalnis, 2010). The fibers hold the shotcrete together, preventing fragments of cracked shotcrete from falling out between the bolts and wire mesh.

In most underground mines, shotcrete is typically used to provide surface support in a multicomponent ground control system consisting of rock bolts, wire mesh, plates and shotcrete. A more complete explanation regarding the use of shotcrete in mechanized cut-and-fill stopes in Nevada is given by Clark et al. (2010). Figures 1-3 illustrate three general types of shotcrete loads and their resultant failure modes. Pertinent ground support design parameters for these idealized loading conditions include the thickness, flexural strength and residual strength (load capacity at deflection) of the shotcrete, the span between the rock bolts and the size, mass and distribution of the rock load at the mid-span distance between the bolts.

The failure shown in Fig. 1 occurs in blocky ground when a large rock mass loads the shotcrete lining to produce a moment that breaks the shotcrete at the mid span near the bolts. The weight of the block mass illustrated in Fig. 2 is held by the shear strength of the shotcrete lining around the block perimeter. This shear failure mode is more common in hard, jointed rock.

A different flexural loading model, representing a shotcrete lining that supports more highly fractured ground, is illustrated in Fig. 3. The highly fractured ground conditions and uniformly

Paper number TP-09-062. Original manuscript submitted December 2009. Revised manuscript accepted for publication October 2010. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to Sept. 30, 2011.

distributed flexural loading shown are encountered in many underground mines in the western United States, particularly in Nevada. This type of shotcrete loading is the main focus for this paper.

Furthermore, the use of fibers in the shotcrete enhances its support characteristics by giving it a post-break toughness. Toughness can be assessed in terms of either the residual load capacity or energy-absorption capacity, joules (kNmm or Nm). The former typically is used for measurements taken between the onset of loading and a specified deflection in a beam or panel test, while the latter is used for the area under the load deflection plot for the test specimen (AuSS, 2008).

To find peak and residual loads, along with the corresponding toughness or energy, FRS testing is conducted using the current testing practices of round determinate panel (RDP) after Bernard, 2002 and 2006. This peak load is directly related to the shotcrete's tensile strength and is primarily influenced by the water-to-cement ratio and the Portland cement content of the shotcrete mix.

A shotcrete testing standard, ASTM 1550-05 round determinate panel (RDP) test, was designed to replicate the typical shotcrete loading conditions in a mine or tunnel and gives the best representation and test repeatability. An explanation of the theory behind the round panel test can be reviewed in Johnansen (1972). For further explanation, Tran et al. (2005) give an eloquent review of multiple findings utilizing the yield line theory for post crack use and how the RDP test results compare back to the yield line theory. Additionally, a set of support guidelines has also been developed based on FRS strength properties (Papworth, 2002; Grant et al., 2001; Barton et al., 1974; Bernard, 2002; AuSS, 2008).

Another issue with a ground control system is ensuring that the level of ground support provided is safe. The installed support characteristics of FRS are difficult to determine in mine openings. There is a risk that miners will enter mine openings that no longer have sufficient strength to provide adequate ground support. To address these concerns, the researchers from the National Institute for Occupational Safety and Health (NIOSH) have developed at-mine-site testing and conducted studies on the development of test specimen cracks. These cracked shotcrete widths to applied loads have been selected for post crack analysis.

The ultimate goal of this work is to better enable a mining engineer to characterize the in situ load-carrying strength properties of mine-applied shotcrete based on a visual assessment of the condition of the shotcrete back as indicated by cracks and post-break crack width and, thus, determine when the mine support system is safe for re-entry of miners and machinery.

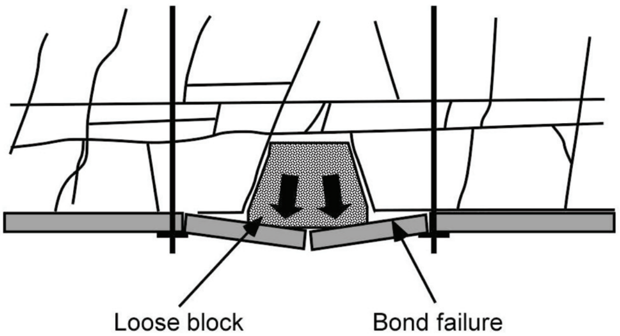

Figure 1 — Flexural resistance model for a loosened block representing a concentrated load (Diamantidis and Bernard, 2004).

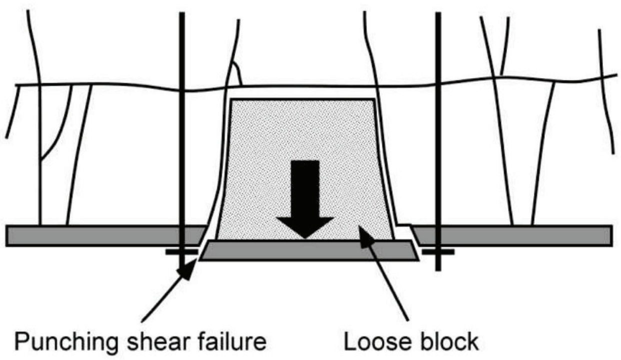

Figure 2 — Shear resistance model for a loosened block acting as a rigid body (after Diamantidis & Bernard, 2004).

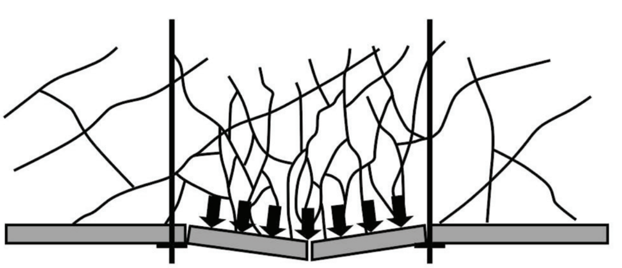

Figure 3 — Flexural resistance model for a loosened block representing a distributed load. (Diamantidis & Bernard, 2004).

Background

As currently used in the underground gold mines in Nevada, shotcrete acts as a thin shell or lining, providing surface support between the primary ground support elements, the rock bolts. As the ground starts to unravel, the shotcrete shell between the bolts is loaded by the dead weight of the loose rock in the mine roof. The shotcrete provides a resistive force, supporting this dead weight load until the weight of the loose rock exceeds the tensile strength of the shotcrete, causing the shotcrete shell to break in flexure. The flexural strength of the FRS is one of the key physical property parameters for ground support design calculations. The RDP test provides design engineers with a measurement of the shotcrete's peak flexural load at first break. As the shotcrete undergoes further displacement after this initial failure, the RDP test also provides important information about the shotcrete's residual load capacity and its toughness of the fiber-reinforced shotcrete.

Some of RDP's key factors that will be discussed in this paper include the peak flexural load, first break, crack-through, residual load carrying capacity and crack width. While observing a test on the machine, the load builds very quickly against the FRS panel, the panel starts to dish in the middle and then it pops. This is the first break with its corresponding peak flexural load, which usually occurs within the first 15 seconds of a ten-minute test (Fig. 4). From these two data, flexural strength is calculated. This is the maximum load applied to the panel before it breaks. It is evidenced as a hairline crack on the underside of the shotcrete. This test provides a conve-

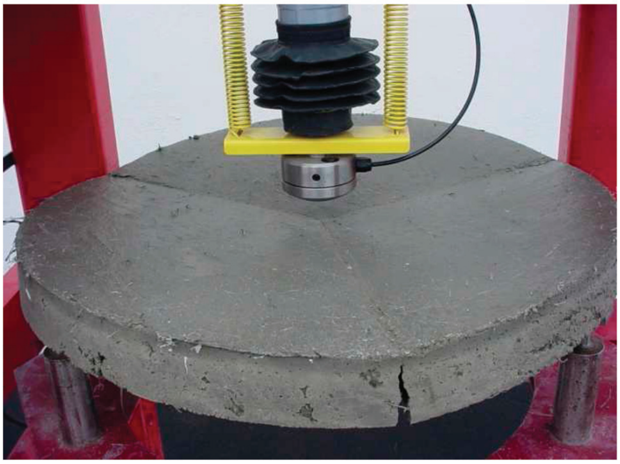

Figure 4 — Broken sample showing tension crack.

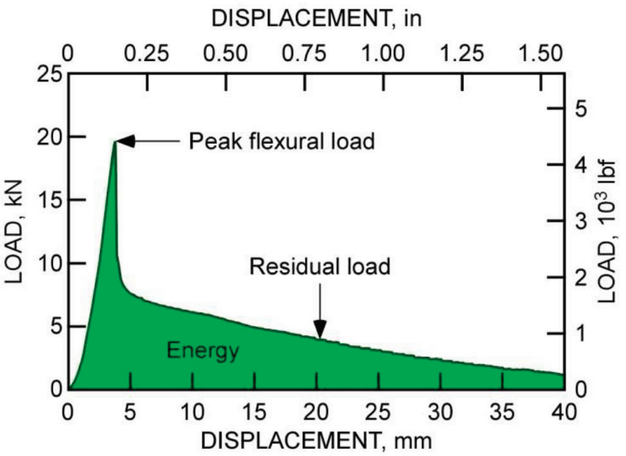

Figure 5 — RDPT Load vs. displacement graph indicating peak flexural load and residual load.

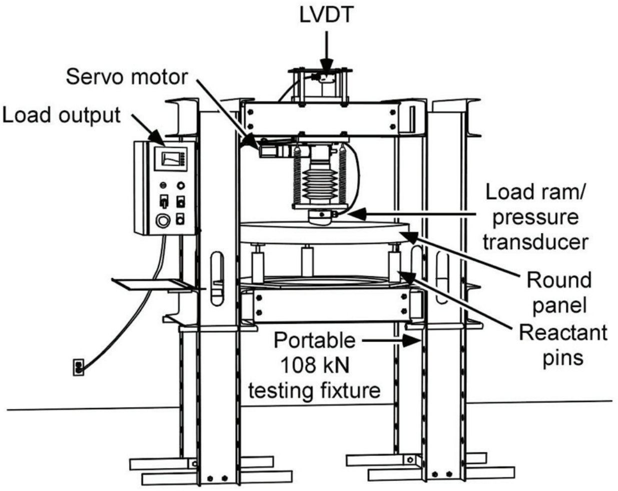

Figure 6 — Schematic of portable RDP test system.

Table 1 — Typical toughness values specified in recent Australian mining projects (after AuSS, 2008).

Type of support	Specified toughness
Nonstructural or low deformation	280 joules[1]
Moderate ground support	360 joules[1]
High-level ground support	450 joules[1]

[1]40 mm deflection in ASTM C-1550

nient standard for comparing shotcrete mixes having different mix constituents, including different types and densities of embedded fiber.

The next event to manifest visually is the crack-through of the panel. This is when one of the cracks reveals itself on the top of the panel crack-through. This is important, in that the load is now completely dependent on the shotcrete reinforcement. The reinforcement used could be either fibers, mesh or a combination of both of them. This now begins the load-carrying capacity of the shotcrete and the rock mass carrying capabilities between the bolts. Generally, the shotcrete residual load capacity at a given deflection is specified by the fiber type, gauge (diameter) and density used in the mix. Shotcrete residual load capacity is an important consideration when the material is expected to support rock mass in the mine roof. This is the most noticeable and observed trait for the major part of the test. The underside of the shotcrete panel opens up, increasing the crack width and exposing the fiber support matrix. The residual load capacity is provided by the fibers in the shotcrete mix, which break or are pulled out as the test progresses.

A typical load versus displacement profile obtained from the test results is shown in Fig. 5. The area under the load-displacement curve from 0 to 40 mm is the energy absorption or toughness of the shotcrete. The peak flexural load can be easily identified from the graph. The residual load capacity is denoted by the load values after the peak flexural load, and represents the load that the shotcrete can still support at specific displacement intervals beyond the displacement at peak flexural load.

Although RDP tests provide useful information, this type of testing has only been available in a few laboratories utilizing large stationary test machines. As a result, the shotcrete test panels usually have to be shipped after forming, causing logistical as well as testing problems, particularly for mines that are located in remote areas. Currently, very little information is available regarding either the flexural strength or the residual load capacity of FRS, especially for underground mines in the United States. Shotcrete toughness values have been related to different types of ground support requirements for recent Australian mining projects (Table 1). However, these guidelines have not yet been implemented in U.S. mines; these listed shotcrete toughness values may not be appropriate for the Nevada mines, because the type of support required would more than likely be classified as non-structural (i.e., surface support) but with high deformation.

By providing load versus displacement profiles for the shotcrete, RDP tests can supply specific strength and physical behavior attributes for the shotcrete that are not typically known. By determining the residual load at a specific displacement interval (residual strength), it may be possible to relate the width of the crack formed on the bottom of the round panel specimen during the test to the residual load that the cracked shotcrete specimen is still able to support.

Table 2 — Unconfined compression test results.

Curing time, days	Unified compressive strength			
	Shotcrete fiber type			
	Steel		Poly	
	MPa	psi	MPa	psi
7	11	1,616	10	1,450
14	13	1,858	12	1,740
28	16	2,294	17	2,465

Round determinant panel (RDP) test

To more easily determine flexural and residual strength values, NIOSH researchers developed a portable round determinant panel test machine that can be transported and set up directly at the mine site (Fig. 6). The usefulness of this field-ready test machine has been previously documented in a FRS fiber dosage comparison study conducted at the Chief Joseph Mine in Butte, MT by Martin et al. (2007) and also at the Devil's Slide Tunnel project near Pacifica, CA by Decker et al. (2010).

To prepare the round panel specimens for testing, FRS is sprayed into ring-shaped molds that are 800 mm in diameter and 75 mm thick. After the shotcrete is applied to the mold, the exposed top surface of the specimen is roughly leveled (screeded off) with a board and then finished flat with a trowel. The panels are stored and allowed to cure in an environmental chamber in a manner consistent with ASTM recommendations. The round panel specimens are tested after 7, 14 and 28 days of curing time, as prescribed in ASTM 1550.

The load applied to a round panel specimen during an RDP test (Figs. 4 and 6) roughly approximates the loading conditions shown in Fig. 3. Three reactant pins support the round panel specimen, as the test machine's loading ram exerts a downward load on the center of the panel at a rate of 4 mm per minute. This produces a determinate set of three cracks along hinge lines spaced about 120° apart, as shown in Fig. 4. As the RDP test continues and the deflection in the panel increases, the cracks open on the underside of the panel, exposing the fibers in the shotcrete that bridge the crack. At the conclusion of the test, the round panel specimen is broken apart and closely examined along these cracks to determine both the distribution and quantity of the fibers in the applied shotcrete.

The RDP test results can be used to determine the peak flexural strength and residual load capacity for the shotcrete. These values and crack width properties of FRS can be used to better understand the in-mine sprayed shotcrete to allow ground control engineers to determine when mine re-entry or applied shotcrete rehabilitation is needed.

Test results and observations

NIOSH researchers conducted RDP tests using two commercially available FRS mixes that are commonly used for ground support in weak rock conditions. In addition to the RDP tests, unconfined compression and splitting tensile tests were also conducted with cored samples of these shotcrete mixes after 7, 14 and 28 days of curing. An average of the unconfined compression test results are listed in Table 2. Splitting tensile strengths were generally about 12% of the measured compressive strength values. The compressive and tensile tests were primarily conducted to help evaluate the consistency and quality of the applied shotcrete.

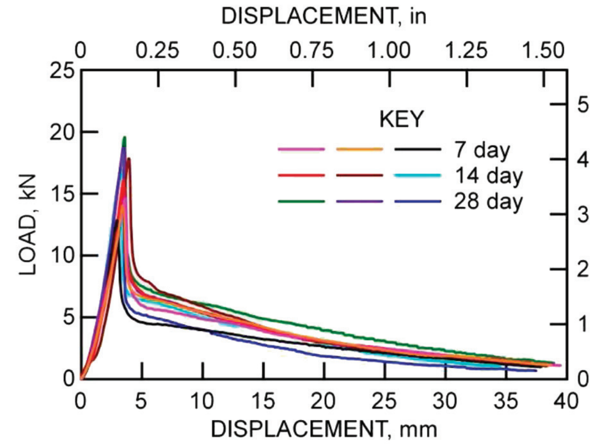

Figure 7 — Load versus displacement graphs for steel FRS.

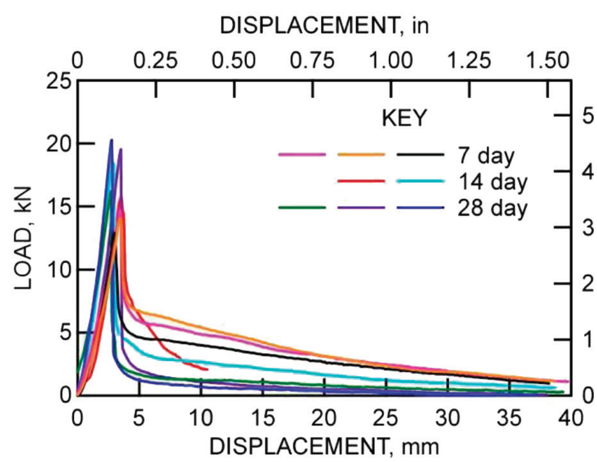

Figure 8 — Load versus displacement graphs for poly FRS.

Plots of the load versus displacement measurements from RDP tests with steel FRS and poly FRS are shown below in Figs. 7 and 8, respectively. A typical tested panel underside is shown in Fig. 9 with its distinctive 120 degree determinate sector cracks. RDP tests were conducted after 7, 14 and 28 days of curing time.

Both of the FRS mixes evaluated in this study are dry-mix shotcrete that are typically used in underground mines to rehabilitate previously installed shotcrete. The steel FRS, trade name Superstick Shotcrete SCA-PT100, has an open-staple design with smooth steel fibers that are 40 mm long. This product is applied at a steel fiber dosage of 44.5 kg/m^3. The poly FRS, trade name Superstick Shotcrete SCAPF, has twisted, smooth polyfibers that are 50 mm long. The fiber dosage for the synthetic polyfibers in this product is 4.15 kg/m^3.

Average peak flexural loads from the RDP tests are comparable to similar values shown in the AuSS guide (2008), below 25 kN. These test results also compare favorably with a shotcrete mix that was specifically designed for the Rodeo Mine near Carlin, NV by D. Thibodeau in 2005. As reported by Martin et al. (2007), this particular shotcrete mix had an average peak flexural load of 35 kN at a fiber dosage of 6.53 kg/m^3 using Kudo, bar-chip I fibers.

Figure 9 — Typical round panel with three cracks.

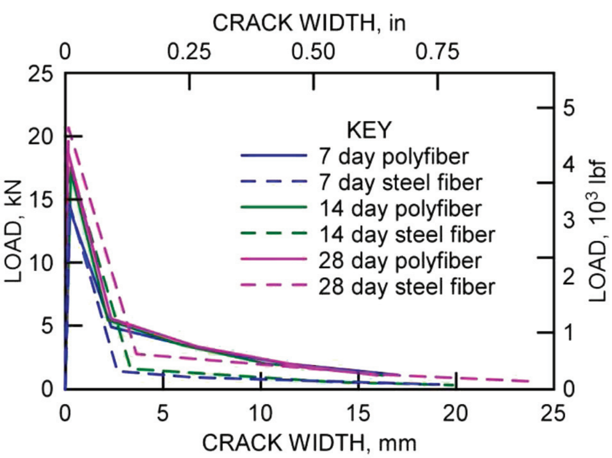

Figure 10 — Panel load versus crack width at center of panel.

Fiber comparison. As expected, the peak flexural load increased with shotcrete curing time (Figs. 7 and 8). However, the type of fiber (steel or poly) did not appear to significantly affect this peak load value, even though the polyfiber specimens did have a slightly larger average peak load compared to the steel fiber specimens, particularly after 28 days of curing. As the shotcrete cured, it increased in toughness compared to earlier curing times. This may indicate that the steel fibers become more interlocked in the shotcrete matrix as the shotcrete ages.

The steel FRS appeared to provide more uniform RDP test results. In contrast, the RDP test results for the poly fiber shotcrete were not as consistent with a couple of the tests, producing higher loads over the rest of the tests conducted. While the peak flexural load generally increased with curing time, the residual load capacity at given deflections of the shotcrete varied dramatically depending on the curing age of the shotcrete. As the polyfiber shotcrete cured, it appears to have become more brittle. Consequently, the post crack load that the shotcrete was able to support decreased markedly with an increase in curing time for a given displacement beyond the first break failure. These test results clearly indicate that the type of fiber governs to a large extent the residual load capacity (area under the load displacement curve) of FRS.

The difference in these two sets of curves also demonstrates quality control issues associated with different types of shotcrete mixes. Inconsistencies in the RDP test results for the poly FRS are at least in part caused by a higher percentage of rebound and a greater variability in fiber count for the applied poly fiber shotcrete versus the applied steel fiber shotcrete.

Crack width. The load and crack width values are shown in Fig. 10 and visually presented in Figs. 4 and 9. These graphs are the average results obtained from a series of the three round panel tests conducted for the times indicated.

Results from the round panel tests for loads versus crack width are presented in Fig. 10. These values were obtained by measuring the dilation or width of the crack at post peak flexural loads. Further measurements were taken after a crack had progressed through the entire thickness of the shotcrete panel and was visually apparent on the upper surface of the panel. This stage of crack development in the round panel specimen during the RDP test is referred to as crack-through. While the RDP test was being conducted, crack width values were measured on the underside of the shotcrete panel using a caliper at specific displacements of test machine's loading ram (e.g., 10, 20, 30 and 40 mm of displacement).

For the crack width measurements, the steel fiber shotcrete as a general rule supported higher loads with less crack width than the poly fiber shotcrete at a given measure of ram displacement (10-40 mm). As shown in Figs. 7, 8 and 10, the shotcrete still provides support after the first break. In contrast, a load versus displacement profile for a unfibered shotcrete would indicate that the cracked shotcrete is no longer providing support after the first break. The fact that the crack width expands and the sections still remain attached illustrates the type of in-place support characteristics that have been observed for applied shotcrete in underground mines, where the cracked FRS still retains the loose material and prevents the rock mass from unraveling between the bolts.

Crack-through. For the steel fiber shotcrete, the load at crack-through remained consistent with curing time, but the displacement at crack-through increased with shotcrete curing time, with 20 mm displacement after seven days of curing to 28 mm of displacement after 28 days of curing. In contrast, the displacement at crack through for the polyfiber specimens remained fairly consistent regardless of curing time, but the load at crack-through increased slightly with an increase in shotcrete curing time.

As shown in Figs. 7, 8 and 10, round panel tests can provide important information for determining the available ground support capacity of the in-place shotcrete and can also indicate whether or not rehabilitation of the shotcrete is needed. Because the movement of the shotcrete is difficult to detect, much less determine underground, the width of the exposed crack on the surface of the shotcrete may be a more appropriate indication of the deformation of the shotcrete after first break. Instruments for monitoring the geomechanical behavior (stress change, deformation, crack dilation, etc.) of the shotcrete are currently not available.

Methods for conducting visual assessment of FRS

The RDP test results and the crack widths that are measured and plotted with residual loads in Fig. 10 may provide a practical means for underground miners to assess the stability of shotcrete applied to the surfaces of underground openings. Assessment should include the following questions:

- What is the shotcrete on the mine back telling the mine personnel?
- What does a hairline crack represent in the shotcrete life cycle?
- What does a pencil-tip width represent in the shotcrete life cycle?
- What does a finger- or a thumb- width represent in the shotcrete life cycle?

These questions are answered, at least in part, through the RDP test results and the additional insight gained by carefully observing the loading behavior of the round panel specimens during the test. For example, the peak flexural load is the maximum load applied to the panel before it breaks. At peak flexural load or first break, a small hairline crack can be observed on the underside of the shotcrete panel. This peak load value determines how much rock mass load the shotcrete can support under similar loading conditions.

The next event to observe is the crack-through of the panel. This is when the crack has progressed and broken through the entire thickness of the panel. The load is now primarily supported by the shotcrete reinforcement, which, depending on the application, may consist of fibers, mesh, or a combination of both fibers and mesh. At this stage of loading, the support provided by the shotcrete is dependent on the cross sectional area of the panel reinforcement, fibers and/or mesh. The typical crack width observed on the bottom or underside of the shotcrete panel at this phase would be about a pencil-tip width.

During the next phase of the RDP test, the crack width is measured in terms of the shotcrete's residual load-carrying capacity, after specific displacement ranges for the test machine's loading (10 mm through 40 mm). As the RDP test continues, the cracks on the underside of the shotcrete panel open up and significantly increase in width, exposing the shotcrete's fiber support matrix. This same phenomenon can be observed in underground mines, where the applied shotcrete is cracked and its fibers are exposed. An estimate of the post-crack load-carrying capacity of the applied shotcrete at a mine may be obtained by determining how much residual load the round panel specimen can support with the same corresponding crack width. Using common place measures for crack width, such as the width of a finger or thumb, may provide a convenient universal standard for visually representing the shotcrete crack width. As shown in Fig. 7, the residual load-carrying capacity of the shotcrete is relatively low at this stage of loading (2-4 kN at a 10-15 mm crack width).

Ground support load calculations

Determining the rock mass load that the applied shotcrete supports in an underground mine is difficult, because the load exerted on the shotcrete by loose material near the surface of the mine opening is hidden from observation. However, the maximum load anticipated from this loose material can be roughly estimated based on dead weight load calculations. Although these calculations are conservative, they provide an established method for estimating the maximum expected load on the shotcrete. In this multicomponent ground support system, the rock bolts provide the primary ground support and are therefore assumed to hold the active mining loads. The shotcrete, whether intact or cracked, is assumed to provide surface support for loose material in the immediate mine roof between the bolts.

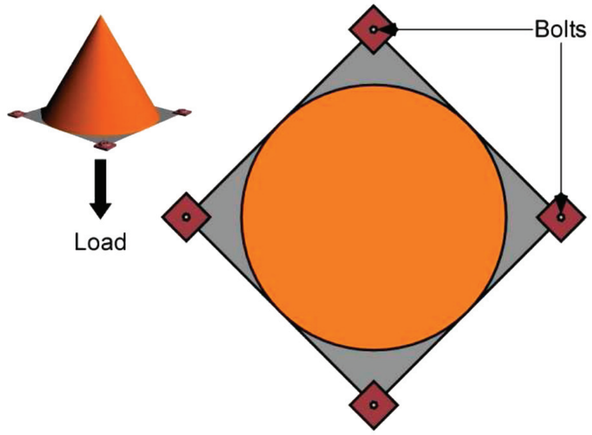

Figure 11 — Estimated cone volume for determining dead weight loading between the bolts, bolt spacing = 1.2 m.

Because the shotcrete primarily provides surface support between the bolts, the geometry of the bolt spacing can be used to determine the maximum volume of loose material that would be expected to load the shotcrete. Two methods are commonly used to predict the maximum volume of loose material that would be reasonably expected to load the shotcrete. These methods are based on the three-dimensional shape of the assumed volume of loose material. Using the block method, the volume of loose material is assumed to form a large block of ground that would separate from the mine roof within the existing bolting pattern or spacing. Using this method with a bolt spacing of 1.2 by 1.2 m, the volume of the largest block of ground that would be expected to fall out of the mine roof between the bolts would be 1.2 x 1.2 x 1 m high. For convenience, the rock block is assumed to have a 1-m height; therefore, the weight of the block (W_{tb}) is estimated to equal 1.2 t.

In weak, raveling ground conditions, a cone method provides a more accurate estimate of the expected volume of loose material that would load the shotcrete. As shown in Fig. 11, the base of the cone is a 1.2-m^2 circle circumscribed inside of the assumed bolting pattern. The height of the cone is assumed to equal to half of the 1.2-m span or 0.6 m, based on the volume of loose material that would reasonably be expected to separate from the mine roof at this span dimension (Pakalnis, 2002). As a result, the weight of the cone (W_{tc}) is estimated to equal 0.6 t.

Ground support load to panel load calculations

However, these calculations and comparisons do not account for the quality of the applied shotcrete or its adhesion strength, both of which significantly affect the ground support capability of the in-place shotcrete. Shotcrete adhesion strength can be measured at desired locations in an underground mine using a portable direct tensile test system, as explained by Seymour et al. (2010). In addition, the RDP test does not exactly replicate the loading and failure conditions of in-place shotcrete and a maximum expected load is estimated from the ground support load calculations, rather than the actual load applied to the shotcrete. Correcting for discrepancies in the geometrical length of the shotcrete panel and the assumed bolt spacing, the RDP test currently provides the best available method for ap-

Table 3 — Wire bag strength, 1.2 x 1.2-m (4 x 4-ft) pattern.

Item	Gauge	Bag strength, t
10 x 10 cm (4 x 4 in.) welded wire mesh	4	3.6
10 x 10 cm (4 x 4 in.) welded wire mesh	6	3.3
10 x 10 cm (4 x 4 in.) welded wire mesh	9	1.9
10 x 5 cm (4 x 2 in.) welded wire mesh	12	1.4
5-cm (2-in.) chain link	11 - bare metal	2.9
5-cm (2-in.) chain link	11 - galvanized	1.7
5-cm (2-in.) chain link	9 - bare metal	3.7
5-cm (2-in.) chain link	9 - galvanized	3.2

4 gauge = 0.58 cm (0.23-in.) diameter; 6 gauge = 0.5-cm (0.2-in.) diameter; 9 gauge = 0.4-cm (0.16-in.) diameter; 11 gauge = 0.3-cm (0.125-in.) diameter; 12 gauge = 0.28-cm (0.11-in.) diameter
Shotcrete shear strength = 2 MPa = 200 t/m^2

proximating the ground support loading of applied shotcrete. The geometrical size has been changed to the bolt geometry with plates at 1.2 m, but the only repeatable test for the mining industry is the round panel ASTM C-1550 test, to relate loads as seen by the shotcrete. Although the ratio of load-to-crack width will remain the same from test to field even with geometry, changes are expected when measurements are converted to units based on (kNmm or Nm) joules.

Given that 10 kN is equivalent to 1.0 t, the 0.6-t dead weight of loose material in the cone volume can be converted to an equivalent force of 6 kN. This rock mass load can then be used in conjunction with the RDP test results shown in Figs. 7- 9 to determine the residual load capacity at a given deflection of the shotcrete with the corresponding crack width. From the RDPT results, the peak flexural strength at first break was usually much greater than 6 kN, indicating that the shotcrete mix design is more than adequate. To further assess the stability of in-place shotcrete, the 6 kN rock mass load can be compared with the residual strength at given deflections of the shotcrete shown in Figs. 7, 8 and 10.

If the shotcrete has cracked, the load versus displacement curves for both the steel fiber and polyfiber shotcrete indicate that the shotcrete may not be stable after more than 10 mm of displacement or a corresponding crack width of 2 mm, about the width of a pencil tip.

Comparing the 6-kN rock mass load with the post-peak load values after first break that are shown in Fig. 7, it appears that none of shotcrete panels tested would be able to safely support this rock mass load for an extended period of time.

As a result, the shotcrete design methodology mentioned above is a good initial approach, but further testing is needed to quantitatively relate the crack width of the shotcrete to its residual strength. These residual load capacity values then need to be compared with some type of realistic assessment of shotcrete loading conditions in underground mines to more appropriately determine the loads that cracked shotcrete can safety support.

Strength characteristics of fiber-reinforced shotcrete and welded wire mesh as ground support system components in weak rock mass

Shotcrete is a brittle system with fibers to give it some yield ability; in other words, it is a soft mining system that is known to work by acting as a bag to keep loose rock from falling down. Both FRS and wire mesh systems are set for a 1.2 x 1.2-m bolt system with plates.

In calculating the applied shear on the shotcrete as mentioned in Fig. 2, a length of 4.8 m is used with a bolt spacing of 1.2 m^2. This value multiplied by the shotcrete thickness estimates the shear area. This value is then multiplied by 0.25% of the shotcrete compressive strength to give shear strength of about 2 MPa (Table 3). This value may or may not be used when conducting support design.

To relate the ground support capability of shotcrete to that of wire mesh, the peak flexural strength of the shotcrete at first break can be compared with the wire mesh bag strength values listed in Table 3. The bag strength of the screen listed in Table 3 is developed at over 254 mm deflection (Dolinar, 2006).

The energy of the panels and the energy of the wire mesh would be comparable in joules, but the use of the two systems is completely different. The shotcrete is used to contain the rock mass with small deflections and high loads while producing energy, whereas the wire mesh is used for large deflections of unraveling rock mass while building loads that produce energy. One is a stiff ground support system and the other is flexible. The reality is that the systems are used together in mines and therefore need to be analyzed as such. In work conducted by Stacey and Ortlepp (2001), an extensive test series was conducted that showed wire mesh gave 10 kJ at 100 mm of deformation, while welded wire mesh shotcrete gave 15 kJ at 150 mm of deformation. This data set shows that the ground support system is optimized when the support system components, the wire mesh and the shotcrete, are combined.

Conclusions

A series of round determinate panel tests were conducted with steel and synthetic ploy fibers, using two commercially available weak rock mass FRS mixes. Peak load and displacement was measured and both peak flexural strength and residual flexural strength were determined.

The FRS specimens enter “peak crack strength” with the appearance and propagation of a determinate crack. After this phase of the test, the specimens are in the residual load carrying capacity of the fiber matrix. This occurs at about 5 to 10 mm of vertical deflection. If the shotcrete has cracked, the load versus displacement curves for both the steel fiber and poly fiber shotcrete indicate that the shotcrete may not be stable after more than 10 mm of displacement or a corresponding crack width of 2 mm, about the width of a pencil tip.

In addition, the progression of the post-peak cracks were mapped. These values were compared to calculated ground force loadings using two popular methods. The fact that the crack width expanded while the sections remain attached indicates the type of in-place support characteristics seen, where the FRS prevents the rock mass between the supports from unraveling. For the crack width measurements, the steel fiber shotcrete as a general rule supported higher loads with less crack width than the poly fiber shotcrete at a given measure of ram displacement (10-40 mm).

A visual assessment leading to better assessment of shotcrete support load capability and ground support stability in mine FRS support characteristics is offered, based on the similarity of the failure process observed in the RDP test.

Finally, a qualitative assessment of the crack width at which rehabilitation would be necessary at 5-10 mm or 2-4 kN is offered. The load-carrying capacity at the mine can be thought of as how much rock mass can be applied to the panel with the corresponding crack with. The visual representations of these crack widths are the finger and thumb.

Disclaimer

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.

Acknowledgements

The authors would like to thank James Schumacher with Thiessen Team USA in Elko, NV and Vince Mindive with Thiessen Team USA in Big Timber, MT for their technical support concerning commercially available shotcrete mixes. We also thank Justin Deemer and Rocky Wegland at Westech Automation in Spokane, WA for their technical and mechanical assistance developing the portable RDPT machine.

References

ASTM 1550-05, 2005, *Flexural Toughness of Fiber-Reinforced Concrete (Using Centrally-loaded Round Panel)*, ASTM, West Conshohocken, PA.

AuSS, 2008, *Shotcreting in Australia: Recommended Practice*, Concrete Institute of Australia & AuSS, Sydney.

Barton, N., Lien, R., and Lunde, J., 1974, "Engineering classification of rock masses for the design of tunnel support," *Rock Mechanics and Rock Engineering*, Springer Verlag, pp.189-236.

Bernard, E.S., 2002, "Correlations in the behaviour of fibre reinforced shotcrete beam and panel specimens," *Materials and Structures*, RILEM, Vol 35, April, pp 156-164.

Bernard, E.S., 2006, "The Influence of toughness on the apparent cracking load capacity of fiber reinforced concrete slabs," *Journal of Structural Engineering*, ACSE, Vol. 132, No. 12, December.

Clark, C.C., Stepan, M.A., Seymour, J.B., and Martin, L.A., 2010, "Report on early strength performance of modern day weak rock mass shotcrete mixes," SME Preprint 10-138, SME Annual Meeting, Phoenix, AZ.

Decker, J.B., Madsen, P.H., and Gall, V., 2010, ARMA 10-402, "Examination of shotcrete liner at Devil's Slide Tunnel utilizing ASTM 1550 field test results and back analysis," *Proceedings of the 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium*, Salt Lake City, UT, June 27-30.

Diamantidis, D., and Bernard, E., 2004, "Comparison of methods for early age strength testing of shotcrete," *Shotcrete: More Engineering Developments, Proceedings of the Second International Conference on Engineering Developments in Shotcrete*, 4 October 2004, Cairns, Queensland, Australia, ed. Bernard, E., Taylor and Francis Group, London, pp. 109-126.

Dolinar, D.R., 2006, "Load capacity and stiffness characteristics of screen materials used for surface control in underground coal mines," *Proceedings of the 25th International Conference on Ground Control in Mining*, Morgantown, WV, pp. 152-158.

Grant, N.B., Ratcliffe, R.C., and Papworth, F., 2001, "Design guidelines for use of SFRS in ground support," *Shotcrete: Engineering Developments*, ed. Bernard, E., Swets & Zeitlinger, Lisse, pp.111-118.

Johnansen, K.W., 1972, *Yield Line Theory*, Cement and Concrete Association, UK.

Martin, L., Dunford, J., MacLaughlin, M., and Cronoble, R., 2007, "Tests of fiber -reinforced shotcrete at the Chief Joseph Mine, Butte, Montana," SME Transactions, Vol. 322, pp. 61-64.

Pakalnis, R., 2002, "Site characterization design of underground mine openings," Notes taken during short course at Spokane Research Laboratory, May 28-29, 2002.

Pakalnis, R., 2010, "Design of underground mine openings utilizing shotcrete," Kencana Mine Presentation, Spokane Research Laboratory, April 8-9.

Papworth, F., 2002, "Design guidelines for use of fiber reinforced shotcrete in ground support," *Shotcrete Magazine*, Spring, pp.16-21.

Seymour, B., Martin, L., Clark, C., Stepan, M., Jacksha, R., Pakalnis, R., Roworth, M., and Caceres, C., 2010, "A practical method of measuring shotcrete adhesion strength," SME Preprint 10-137, SME Annual Meeting, Phoenix, AZ.

Stacey, T.R., and Ortlepp, W.D., 2001, "Tunnel surface support-capacities of various types of wire mesh and shotcrete under dynamic loading," *Journal of The South African Institute of Mining and Mineralogy*, Vol. 101, October, pp. 337-342.

Tran, V.N.G., Bernard, E.S., and Beasley, A.J., 2005, "Constitutive modeling of fiber reinforced shotcrete panels," *Journal of Engineering Mechanics*, Vol. 131, No. 5, May, pp.1-10.