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ASSESSING THE MECHANICAL BEHAVIOR OF LARGE-SCALE SHOTCRETE PANELS

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ABSTRACT

The Office of Mine Safety and Health Research (OMSHR), Spokane Mining Research Division (SMRD), is continuing its High-Energy High-Displacement (HEHD) testing of field-scale shotcrete panels. A test program was developed to determine the relationship between applied force, displacement, and energy for both unreinforced and reinforced shotcrete panels. Reinforcement options consisted of synthetic macro-fibers, sprayed polyurea liners, chain-link fence, welded-wire mesh, and combinations of these products. During testing, photogrammetry was used to measure the geometric changes of the panels, including volume changes and panel cracking. These measurements were correlated with the load and displacement data, allowing visual observation to be related to the applied force and displacement. The test results provide a comparison of the mechanical performance of the various panel types and can be used by the practicing engineer to evaluate installed support based on visual observation of cracking and deformation. Visual assessment of the loading cycle and strength capacity of shotcrete in underground excavations will improve mine safety by providing a means to quantify the stability of installed shotcrete support.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH), Office of Mine Safety and Health Research (OMSHR), Spokane Mining Research Division (SMRD) is continuing research on the behavior of shotcrete when used as the surface support component in mining ground support systems.

Ground control safety often depends on supporting, or at least containing, the ground between the rockbolts. Shotcrete and mesh, in various combinations and with other components, are often used to accomplish this (see Figure 1). Maintaining support pressure during ground deformation is key to the performance of these systems, and to ensuring miner safety. However, the toughness of a ground support system–the ability to maintain strength over large deformations–is difficult to quantify.

Researchers at SMRD have responded to this deficiency by designing a full-scale test device, described previously by Martin et al. [2015a], and beginning a testing program to assess the behavior of shotcrete surface support reinforced with a variety of products including: fibers, chain-link mesh, welded-wire mesh, spray-on polyurea liners, and combinations of these products. This paper presents the findings of these tests.

BACKGROUND

When mining in weak or highly stressed rock (and in rockburst-prone ground), it is often not possible to prevent ground deformations caused by squeeze and rock mass bulking (or in the case of rockbursting, sudden rock bulking due to fracture and/or dynamic ejection of rock). Confining stresses generated by the ground support system are very small compared to the stresses associated with rock fracture, and the support pressure will have no direct effect on fracture initiation [Ortlepp 1969]. In squeezing ground, large deformations cannot be practically prevented, therefore the support must be able to undergo large deformations while maintaining integrity and support pressure. In the United States, such large deformations have been observed in the underground mines of Nevada despite heavy use of shotcrete and mesh.

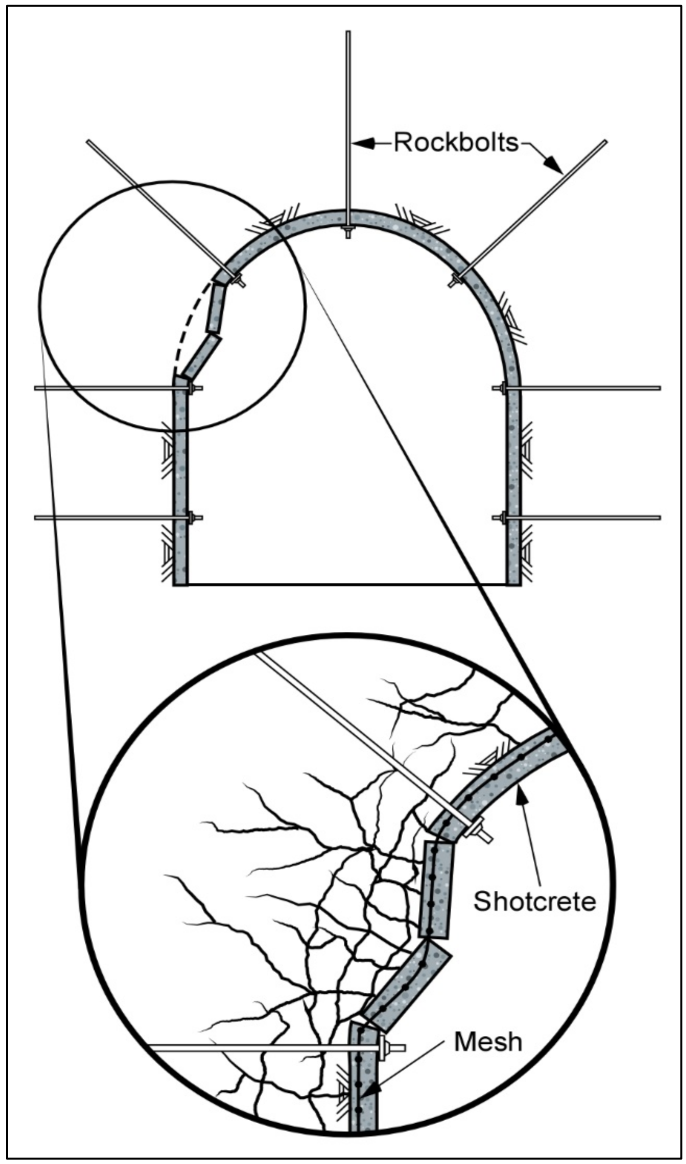

Figure 1. Ground support system consisting of rockbolts and mesh-reinforced shotcrete.

In Canada, rockburst damage usually occurs in the form of rock bulking due to fracturing [Kaiser et al. 1995]. In this case, rapid expansion of rock volume may result in sudden loading of the ground support system, which must be able to yield and absorb energy at high displacement rates. In South Africa, rockburst damage is commonly associated with violent ejection of up to a meter of rock (with velocities as high as 6 m/s or more) [Ortlepp and Stacey 1998, Stacey et al. 1995]. Such loading will overcome the initial strength of most ground support systems, therefore the support must maintain its strength over large, rapid displacements to absorb the kinetic energy of the ejecting rock, and bring it to rest [Wagner 1984, Roberts 1988]. This capacity for the ground support system to maintain strength over large deformations–the ability to absorb energy–is termed 'toughness' and is calculated for a given ground support system or component as the area under the force-displacement plot.

In these high-deformation, high-energy loading environments, the role of the ground support system is to maintain as much rock-mass strength as possible by inducing interlock of fragments to hold the rock-mass together as it deforms [Ortlepp 1969]. Under these conditions, rather than preventing deformation, a more appropriate goal is to prevent sudden catastrophic collapse, maintain safety and serviceability of the opening for its intended lifespan, and maintain an adequate escapeway for the miners in the event of an emergency. To meet these demands on the ground support system requires that the components have high 'toughness.' Additionally, it is desirable that the support strength is activated quickly after installation to arrest relative displacements between fragments in the rock mass surrounding the excavation.

A complete ground support system is composed of three main components [Ortlepp 1983, Potvin et al. 2010]: reinforcement (bolts and cables), containment (surface support), and connections. In the past, much attention has been given to design of reinforcement components. Although reinforcement is the critical component to stabilize the rock mass, any ground support system is only as effective as its weakest link [Potvin et al. 2010].

Surface support helps maintain stability of the rock mass between the bolts. Mesh, used as a stand-alone surface support, typically serves to prevent loose rock from falling into the excavation. Although mesh has high rupture strength and high deformability, it is not stiff until after significant displacement (10 cm or more) [Pakalnis and Ames 1983, Morton et al. 2007, Player et al. 2008]. Alternatively, unreinforced shotcrete is stiff and can provide high initial strength, and it also has the additional benefit of bonding directly with the rock, promoting stability through interface shear strength and filling of rock fractures [Stacey 2001]. However, unreinforced shotcrete loses virtually all of its load-bearing capacity after very small flexural displacements (a few millimeters or less), so it is has no toughness.

Encapsulation of wire mesh within a sprayed shotcrete lining, or the addition of fibers to the mix, results in surface support that has both high initial strength and toughness. This allows for support pressures to be maintained on the rock surface over large deformations, holding loose rock together and preventing sudden collapse of rock between the bolts.

For both reinforced shotcrete that has undergone large deformations and wire mesh, which does not bond to the rock surface, it is likely that significant de-bonding of the surface support from the rock mass will occur. In this case, adequate connections between the surface support and the rockbolt reinforcement (via bolt plate and nut) are crucial for transferring the loads acting on the surface support to the bolts. Additionally, the compression provided to shotcrete by the bolt and plate may somewhat enhance its mechanical behavior. For these reasons, the adequacy of the surface support as part of an overall ground support system can only be properly assessed by testing it in the presence of the restraint conditions provided by the reinforcement and connections.

In the last few decades, a significant amount of research has been undertaken in both the civil and mining industries to understand the behavior of wire mesh and shotcrete when used as surface support for underground excavations in rock. Much of this work has centered on laboratory testing of wire-mesh and shotcrete panels of varying width, thickness, and reinforcement type. Tests on shotcrete panels can be divided into two classes: (1) Round Determinate Panel Tests (RDPT) and (2) square or rectangular panel tests.

RDPT testing as performed by Martin et al. [2010, 2015b], Thyni [2014], and Ciancio et al. [2014] is usually performed in accordance with ASTM C1550 [2010]. This test provides a standardized means to study and compare the flexural behavior of shotcrete surface support, but simulates only an isolated section of shotcrete. The square or rectangular type tests are generally not standardized and often attempt to simulate some aspect of in-mine conditions such as surface adhesion, loading conditions, restraint from reinforcement, scale, or a combination of these conditions. The most applicable tests of this type to mining ground control have been performed by Kirsten and Labrum [1990], Kirsten [1992, 1993], Tannant and Kaiser [1997], Van Sint Jan and Cavieres [2004], Morton et al. [2009], and Martin et al. [2015a].

To date, the most comprehensive testing of total surface support toughness used a test frame described by Kirsten and Labrum [1990]. The test rig was designed for full-scale testing of 1.4-m square reinforced shotcrete panels anchored by bolts installed on a 1-m square pattern (Figure 2). This test design provided a valuable starting point for the testing machine developed at SMRD.

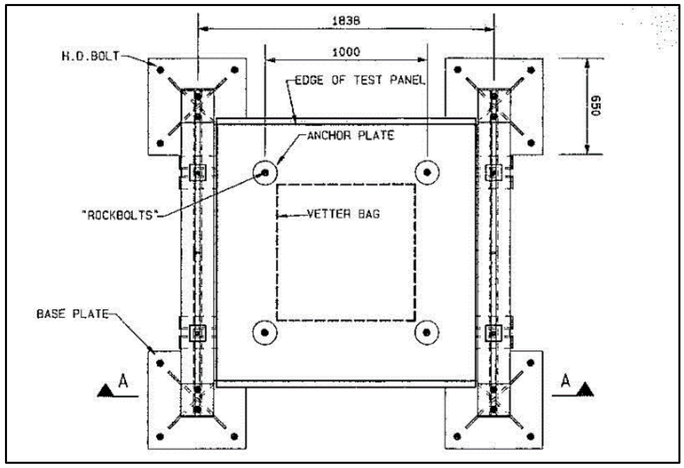

Figure 1. Plan view of panel testing frame, after Kirsten [1993].

The High-Energy and High-Deformation (HEHD) load frame, developed by SMRD, and described in the next section, improves upon this earlier work and is being used to advance industry understanding of the mechanical behavior of shotcrete when used as surface support in a complete ground support system. Large-scale shotcrete panels with various types of reinforcement have been tested.

One drawback to the use of shotcrete for surface support is that visual inspection of the rock behind the shotcrete is not possible. This can make it difficult to gauge and assess the current state of stability of the opening. Additionally, the visual presence of large deformations and cracking in the shotcrete, combined with a lack of understanding of reinforced shotcrete support mechanisms, can lead to unnecessary and costly rehabilitation of the support. In fact, cracking of reinforced shotcrete is a necessary condition for the strength-enhancing properties of the fibers or mesh to be utilized. It is not until cracking of the shotcrete occurs that the high tensile strength and yielding characteristics of the reinforcement act to increase the toughness of the support. Importantly, reinforced shotcrete panels may still have significant residual strength even if large displacements and wide cracks occur. When some combinations of shotcrete reinforcement are used the panel may actually be gaining strength as cracks develop and grow.

SMRD is using photogrammetry in conjunction with the HEHD testing to relate volumetric deformation and crack widths to shotcrete support capacity for different types of reinforcement so that more quantitative assessments of installed shotcrete support can be made. This expands upon the work of Martin et al. [2010, 2015b].

HEHD PANEL TEST

The HEHD test frame specifications for the current test program were developed by modifying Kirsten and Labrum's [1990] test design. The new test frame includes a ram stroke of 25.4 cm, roughly doubling the test stroke of Kirsten and Labrum's design. Additionally, the scale of testing was increased 0.2 m from Kirsten and Labrum's design to accommodate a 1.2-m bolt pattern while minimizing edge effects. Although the work of Kirsten and Labrum [1990] and Tannant and Kaiser [1997] found that geometry of the loading head has a minimal effect on test results, a spherical loading head is used that avoids edge effects inherent in a square loading plate, but is more durable than a pressurized bag. It was decided to ignore adhesion between shotcrete and ground, as was done by Kirsten and Labrum [1990] and Tannant and Kaiser [1997]. The loading was intended to represent bulging between the bolts. More detailed description of the testing apparatus is provided by Martin et al. [2015a].

When performing the test, the spherically shaped head is pushed through the shotcrete test panel which is restrained by bolts embedded in the four reinforced concrete columns of the test frame (Figure 3). This loading action simulates the field loading condition caused by the unsupported rock-mass contained between the bolts. For the tests described in this paper, the testing system uses four D-bolts [Li 2008, 2011] that have 222-kN capacity bolt plates, and are torqued to 203 N·m, providing a compressive load on the panel system at the bolts. If required, rockbolts, bolt plates, bolt resin, and other details can be adjusted to match typical in-mine use.

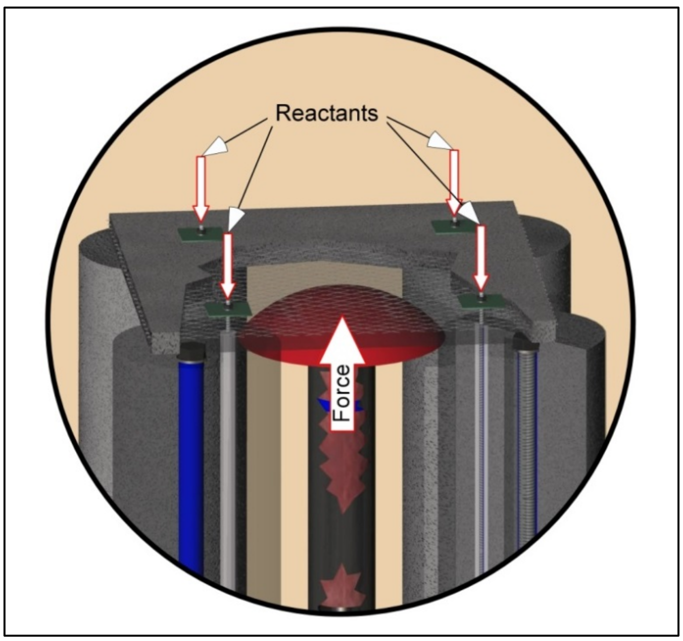

Figure 3. Diagram of the testing machine and reaction forces during the high-energy high-displacement panel test.

Load and ram displacement data are collected during the test using an advanced data acquisition system. Panel-geometry changes and crack opening widths are determined from images using photogrammetric methods.

PANEL CONSTRUCTION AND QUALITY CONTROL

The shotcrete test batches are mixed according to specified mix designs, typically matching the mix design of the mine of interest. The shotcrete test panels are constructed using methods that replicate field installation, as reasonably as possible. The panels are sprayed while in a 45-degree position by an experienced nozzle operator. After filling the form, the top is floated and struck flat. This ensures that the test panels are constructed to a uniform thickness. All panels in this report have a thickness of 10.2 cm.

For mesh reinforced shotcrete panels, the mesh is placed in the bottom of the form before spraying. This results in the mesh remaining in the bottom one-third of the panels after curing. Although this is not the ideal placement, it better corresponds to in mine conditions. Completed panels are then covered with a tarp and allowed to cure for at least 28 days.

For quality control and assurance measures, a slump test is performed on the shotcrete according to ASTM-C143 [2012] at the time of construction. Additionally, both formed and drilled cores are procured following ASTM-C1604 [2012] and C1140 [2011], and uniaxial compression (UCS) tests are performed according to ASTM-C39 [2015]. Splitting tensile tests are also performed on both types of test specimens according to ASTM-C496 [2011]. This testing is performed to verify and document the compressive and tensile strength of the cured shotcrete at the time of panel testing. All panels were tested immediately following 28 days of cure time.

For panels that included a polyurea liner, the liner was installed after the shotcrete had cured for 26 days. This product is applied by a professional contractor with experience in applying this product in an underground environment.

Lastly, when any set of reinforced panels is tested, at least one unreinforced panel test from the same batch of shotcrete using the same construction techniques is tested for control.

CHAIN-LINK AND WELDED-WIRE MESH

HEHD tests were performed on both cyclone chain-link fencing and welded-wire mesh to compare the force-displacement behavior, over the test range of 25.4 cm, with other containment options. The chain-link was stretched taught between the bolts by hand. Maximum ram force achieved over a 25.4-cm displacement for the chain-link (in green) and welded-wire mesh (in orange) was around 7.1 and 14.2 kN, respectively (see Figure 4). During the chain-link tests, the measured force did not increase until 5 to 10 cm of ram displacement. It was observed that the chain link is relatively loose during the initial 5 to 10 cm of loading and there is play in the system until the links interlock. Once the slack is overcome, the force increases nonlinearly with displacement. Permanent (ductile) deformation was observed in the test samples after the test. In the welded-wire tests, welded connections between wires broke during testing. Although the mesh could not be tested to failure with the available test stroke, the observed non-linear force-displacement behavior agrees with previous testing by others [Pakalnis and Ames 1983, Morton 2007, Player 2008]. However, the peak load increased much more slowly. This is likely due to the boundary conditions of the test, which have been shown to have a significant effect on the measured force-displacement behavior of chain-link and welded-wire mesh [Morton 2007].

UNREINFORCED SHOTCRETE

Tests on unreinforced shotcrete panels were characterized by their high stiffness, high first-break strength, and brittle failure mode. A typical example of an HEHD test performed on an unreinforced panel is shown by the brown line in Figure 4.

The apparent residual strength of the unreinforced panel is due partly to the self-weight of the panel (approximately 8 kN) acting on the ram, and partly to the clamping force provided by the bolt plates. This portion of the force-displacement plot for the unreinforced, standard-mix panel test is potentially misleading. The authors would like to point out that the practical load-bearing capacity of the unreinforced panel is lost after less than 2 cm of ram displacement. For this reason, the force-displacement plot is shown as a dashed line beyond this point.

Unreinforced panels typically develop first breaks diagonal to the panel corners, followed by a set of breaks near the supports and perpendicular to the first set of cracks following further deformation [Martin 2015a].

MESH REINFORCED SHOTCRETE

Figure 4 provides a comparison of the force-displacement behavior for the chain-link and welded-wire mesh products (green and yellow), a standard-mix shotcrete panel (brown), and standard-mix panels reinforced with the two mesh products (red and light red). Although application of shotcrete over mesh is generally not recommended, it is a standard practice in some underground, western United States, hard rock mines under certain high-deformation ground conditions [Martin et al. 2015a].

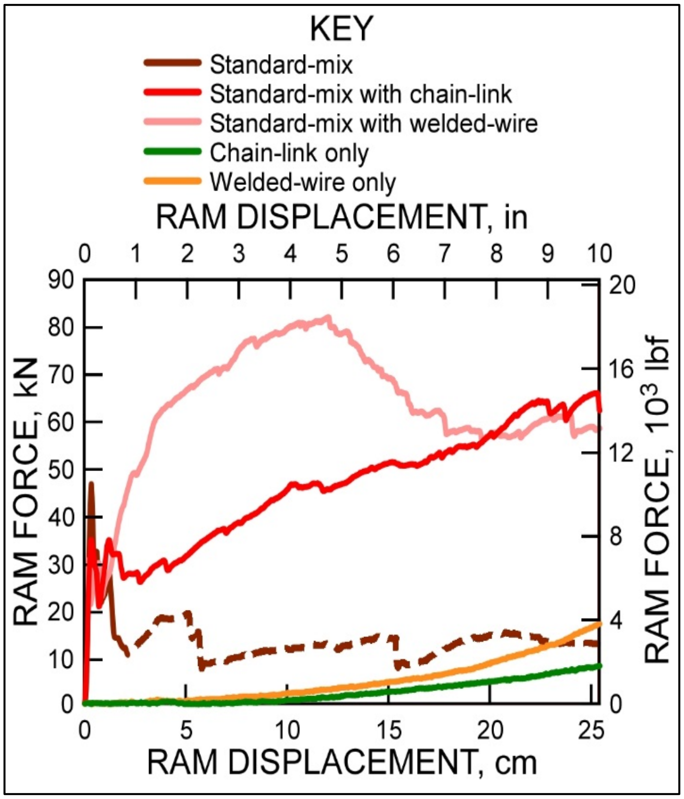

Figure 4. Comparison of ram force vs. displacement for mesh and shotcrete used as stand-alone products and combined to form composite systems.

During a mesh reinforced panel test, the panel acts as a composite system. First, breaks occur across the panel, bisecting the panel edges. Additional cracks develop in a repeatable pattern described by Martin et al. [2015a]. The shotcrete is brittle, strong in compression, and weak in tension. When the shotcrete fails in tension due to flexure (the modulus of rupture is exceeded), the tensile strength of the panel is effectively reduced to zero. However, as cracks form, the mesh, which is encapsulated in the shotcrete, spans the gap between the tensile cracks and loads in tension, maintaining the load-bearing capacity of the panel (surface support). For this to occur, the steel mesh must be encapsulated in the shotcrete. In short, tensile loads are redistributed to the steel strands between cracks in the shotcrete.

Without shotcrete, the mesh will not sustain significant loading until very large deformations occur and stretch the chain-link enough to activate the tensile resistance of the strands. However, without reinforcement, the shotcrete will exhibit a completely brittle failure mode. Combining the two materials results in a composite support with very different behavior than the individual components tested separately. When the shotcrete fails in tension, the loads are redistributed to the steel, which undergoes ductile deformation when loaded past the elastic limit. The results show that a combination of shotcrete with steel reinforcing mesh forms a very tough surface support.

SYNTHETIC MACRO-FIBER REINFORCED SHOTCRETE

Tests were also performed on fiber-mix shotcrete panels with and without mesh reinforcement. Elasto Plastic Concrete (EPC), Inc., BarChip^{54}© fibers were used for all fiber-mix panels. These fibers have a length of 54 mm. The fiber dosage was 6.5 kg/m^3. Application of fiber-mix shotcrete over mesh is in general not recommended. However, this testing was performed to evaluate the mechanical behavior of this type of support specifically for the western Unites States hard rock mining industry where the use of mesh in conjunction with shotcrete is more common.

Figure 5 shows the force-displacement behavior for representative samples from these test sets. The fiber-mix shotcrete (in blue) results in both higher peak strength and a less brittle failure mode than the standard-mix. Again, a dashed line indicates that the panel has effectively lost all load-bearing capacity. The apparent residual strength is due to the dead weight of panel and the bending of the bolt plates.

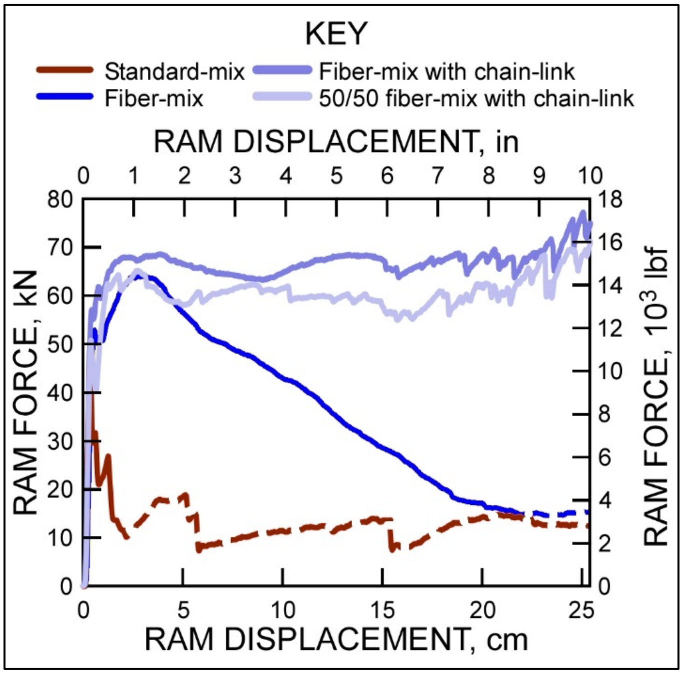

Figure 5. Comparison of ram force vs. displacement for panels constructed with and without fiber-mix shotcrete.

The fibers increase the tensile strength of the shotcrete, and when tensile fractures open in the shotcrete, the fibers span the cracks, maintaining continuity of the panel. As further deformation occurs, the fibers either break in tension or pull out, depending on the bond strength between the fibers and the shotcrete. In this set of tests, fiber pull-out was predominant.

A set of fiber-mix shotcrete panels with chain-link reinforcement were also tested (shown in light blue). These tests not only had a higher peak strength, but sustained peak strength over the entire 25.4 cm of displacement. It was observed that as the fibers pull out, the tensile load is gradually transferred to the chain-link. This panel type exhibits a nearly ideal force-displacement behavior for tough surface support, coupling the benefits of both fibers and chain-link mesh.

Lastly, a set of chain-link reinforced shotcrete panels was constructed using 5.1 cm of standard-mix shotcrete topped with 5.1 cm of fiber-mix shotcrete. This is shown in grey in Figure 5. It can be seen that this construction type resulted in nearly the same behavior as obtained for the all fiber-mix, chain-link reinforced panels. During panel flexure, the exposed side of the panel will load in tension, while the other half will load in compression. The fibers primarily improve only the tensile strength of the shotcrete and therefore are only needed where tensile forces develop.

POLYUREA-LINED SHOTCRETE

Three shotcrete panels lined with Turbo Liner® 5502 polyurea liner were tested. The target liner thickness was 3.2 mm. Following the completion of each test, panel liner thickness was measured at 10.2-cm intervals along the breaks. The average liner thickness for the three poly-lined panels (Tests A, B, and C) was 3.6, 4.3, and 3.5 mm, respectively. Tests A and C were performed successfully. However, during Test B, the data acquisition system malfunctioned and data was not obtained for this test. A fourth unlined panel (Test D) was tested for control.

The addition of the liner altered the mechanical response of the panel and resulted in increased energy absorption as compared to the unreinforced test. The force-displacement plots for the two successful poly-lined panel tests and the single control panel test are provided in Figure 6 and shown in green, pink, and brown, respectively. Again, the dashed lines indicate that the panel has completely lost any practical load bearing capacity.

The two force-displacement curves indicate similar overall behavior of the two polyurea lined panels. The difference in first break strength between the two lined panels is within the range observed for typical tests on unreinforced standard-mix panels. The polyurea does not add initial strength to the panel, but only helps hold it together as it fails.

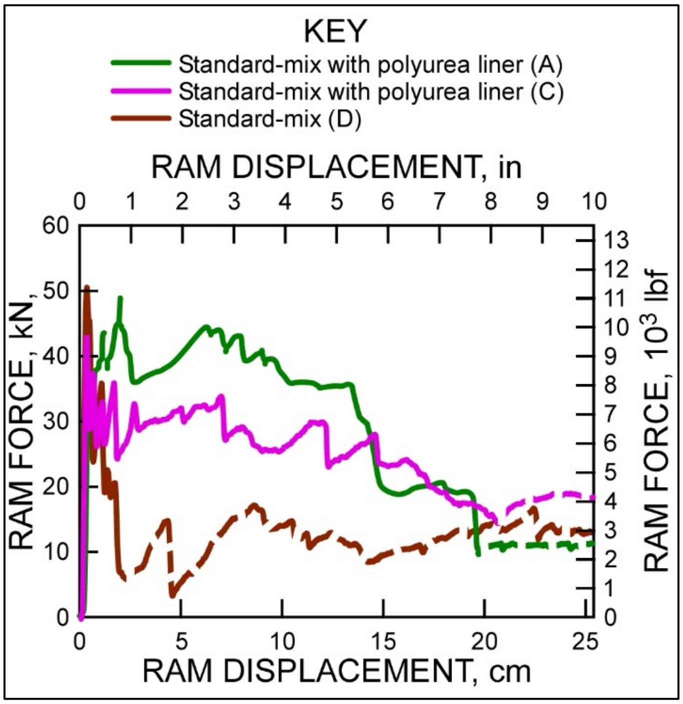

Figure 6. Ram force vs. displacement for the two polyurea-lined panels and the un-lined control panel.

The energy-displacement plots are provided in Figure 7. In these plots, the dashed lines indicate that the panel has completely failed and is no longer absorbing additional energy with increased displacement.

As stated above, the peak strength of the lined panels was similar to that of the unreinforced panel (Test D). However, the post-peak response of these samples is observed to be much less brittle. Additionally, the crack pattern that formed during failure of the lined panels was different from that of the unlined panel. In Tests A, B, and C, there was significant curvature in some of the fractures that developed. Figure 8 demonstrates this behavior for Test A. The curved crack pattern has not been observed in any previous unreinforced or reinforced panel tests. Further, the crack pattern was not completely predictable or consistent between the poly-lined panel tests. Some fractures oriented through the bolts, as is often observed in unreinforced tests, while others tended to run between bolts, normal to the panel edge, similar to the reinforced panel tests. This is also shown in Figure 8.

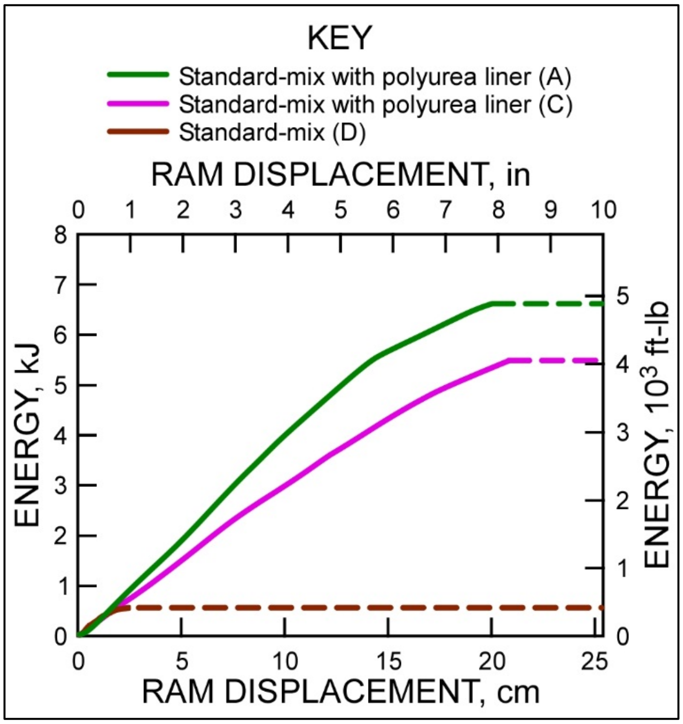

Figure 7. Energy vs. displacement for the two polyurea-lined panels and the un-lined control panel.

Figure 8. Post-test fracture and deformation for polyurea-lined panel (Sample A).

During the tests, cracks formed in the shotcrete but the polyurea liner stretched to bridge the gap, preventing catastrophic collapse. The maximum stretching of the polyurea liner across the cracks was about 5 cm. Additionally, the stretched liner failed from the interior of the panel outward. Once the initial tear started, the liner progressively tore with additional displacement of the ram.

The stretching of the liner between the cracks appears to have been primarily an elastic response. Once the liner ripped apart, virtually all of the stretching of the liner was recovered; no ductile deformation was observed in the liner. The peak and residual strengths for the polyurea-lined panel are similar to the unreinforced shotcrete panel. The gradual decrease from peak strength to residual strength in the force-displacement plot occurs as the liner progressively tears open.

The polyurea-lined panel tests likely overestimate the improvement in mechanical performance of the lined shotcrete panels. This is because the polyurea liner was applied to flat and clean, primer-etched shotcrete surfaces. In a field setting, the shotcreted surface would not likely be smooth or flat, and in the field it would be difficult and impractical to prime the surface and apply the liner. Without the ability to prepare the surface prior to application and allow the adhesion between the shotcrete and the liner to properly form, the added benefit of the liner is minimized, and it is known that liner adhesion is a critical aspect of the effectiveness of thin liners used as surface support [Tannant et al. 1999, Tannant 2001, Stacey 2001].

COMPARISON OF CONTAINMENT OPTIONS

Figure 9 provides a comparison of the force-displacement response for all panel types. Although the panels were constructed from different batches of shotcrete, all panels were constructed using the same shotcrete mix and construction techniques. The samples chosen for comparison are considered to exhibit a typical response for their respective reinforcement type. It can be seen that all previously tested reinforcement types (fibers, chain-link, and welded-wire) significantly outperform the polyurea-lined panel with respect to peak strength. Additionally, the ability of the welded-wire and chain-link panels to yield and maintain load with additional deformation is also far superior to that of any other reinforcement type. While the polyurea-lined and straight fiber-mix shotcrete panels provide an adequate peak strength, they are incapable of maintaining this strength over large deformations. The panels reinforced with chain-link and welded-wire either maintain or increase their load-bearing capacity over large deformations. This capability forms the basis for tough support. The fiber-mix shotcrete with chain-link reinforcement, exhibits almost ideal force-displacement behavior.

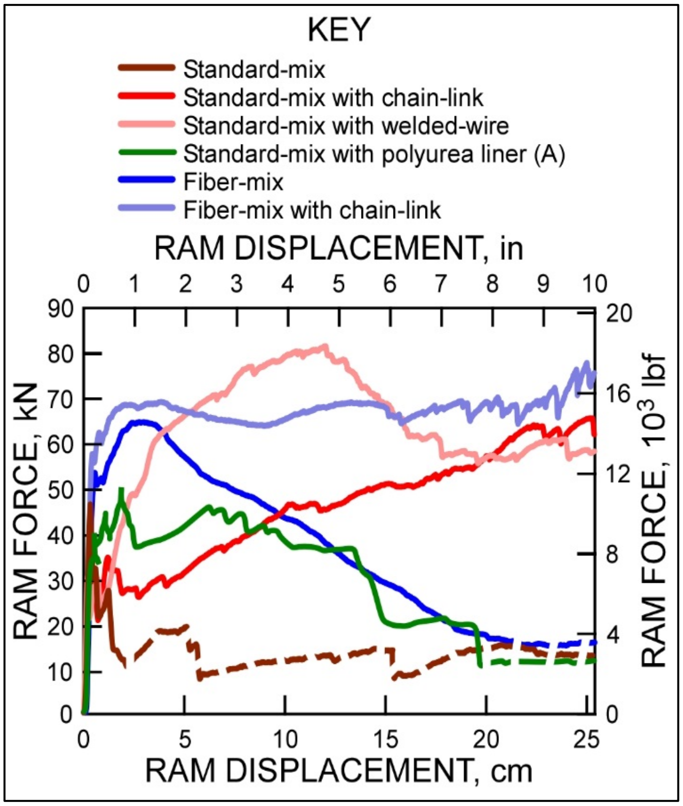

Figure 9. Ram force vs. displacement for representative samples of various shotcrete reinforcement types.

Figure 10 provides a comparison between energy for the same set of tests. It can be seen that over the 25.4-cm range of ram motion applied in the panel tests, the welded-wire and chain-link mesh panels are capable of absorbing significantly more energy than other types of panels.

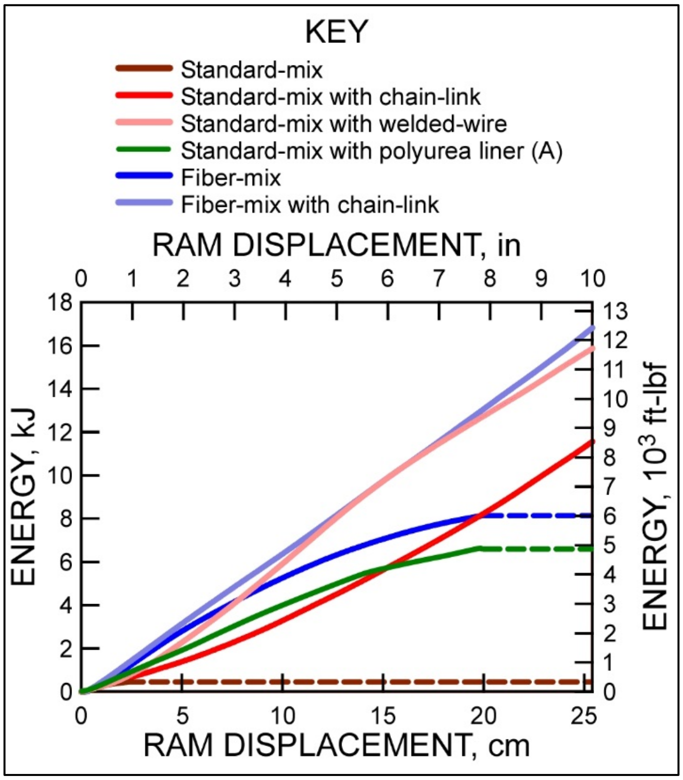

Figure 10. Energy vs. displacement for representative samples of various shotcrete reinforcement types.

Additionally, from the force-deformation plots for the tested panels, it is observed that while other panel types have completely failed, the welded-wire and chain-link reinforced panels continue to maintain support pressure after 25.4 in. of displacement. This means that if further displacement beyond the test range (25.4 cm) were allowed to occur, these panels could absorb even more energy. The panels without chain-link or welded-wire mesh, have lost their load-bearing capacity and cannot absorb more energy with further displacement.

Table 1 provides average values of maximum ram force, final ram force after 25.4 cm of displacement, and total energy absorbed for tests of varying reinforcement type. The number of tests for each type is also provided.

Table 1. Average Force and Energy at 25.4 cm of Ram-Displacement for Shotcrete Panel Reinforcement Types.

Type	No. of Tests	Max Force lbf*10^3 / kN	Final Force lbf*10^3 / kN	Absorbed Energy ft-lb*10^3 / kJ
Chain-Link and Fiber-mix	3	17.5/77.8	16.7/74.4	12.7/ 17.2
Welded-Wire	2	18.3/81.4	11.8/ 2.7	10.3/14.0
Chain-Link	3	16.6/73.9	15.2/67.6	9.8/13.2
Fiber-mix	2	14.9/66.2	3.0/ 13.1	6.9/9.4
Polyurea-Liner	2	10.3/46.0	3.3/14.9	4.4/6.0

Significant energy absorption capacity of ground support can only be accomplished with yielding components, because increasing the strength of a stiff, brittle component will not significantly increase its ability to absorb energy.

VOLUMETRIC ANALYSIS

Photogrammetric monitoring conducted during testing was used to calculate volumetric deformation. In this context, volumetric deformation refers to the increase in shotcrete volume between the bolts. These volumes were then correlated with ram-force and energy. Similar volume measurements in mines can be used to estimate the remaining capacity of surface support.

The laboratory photogrammetry system developed by SMRD has a linear measurement accuracy of 2.0 mm, and a volumetric accuracy of +/- 1.8% [Benton et al. 2015a]. The photogrammetric analysis techniques used to perform the volume calculations are described in detail by Benton et al. [2015a, 2015b].

The raw data from the shotcrete panel analyses are presented in Table 2. Ram displacement, maximum volumetric deformation, and energy are shown for each displacement interval.

Table 2. Deformation volumes and energy for each shotcrete panel type at 5-cm ram-displacement intervals.

Type	Ram Disp. cm	Max. Volume m^3	Absorbed Energy kJ
Standard-mix	5.08	0.03	~0.5
	10.16	0.08	~0.5
	15.24	0.13	~0.5
	20.32	0.18	~0.5
	25.40	0.27	~0.5
Fiber-Mix	5.08	0.03	2.84
	10.16	0.07	5.33
	15.24	0.12	7.13
	20.32	0.20	8.22
	25.40	0.26	8.53
Chain-Link in Fiber-Mix	5.08	0.04	3.20
	10.16	0.09	6.49
	15.24	0.15	9.91
	20.32	0.20	13.29
	25.40	0.25	16.82

Considering the data in Table 2, it is observed that panel volumes remained relatively constant for each interval, regardless of reinforcement type. This was expected because each volume measurement was based on the same ram displacement intervals. The slight variability in volume is caused by panel surface texture and differing geometries of panel failure.

Deformation profiles of each panel type at 25.4 cm of ram displacement are shown in Figure 11. While the unreinforced standard-mix panel broke into large sections that displaced along hinge lines, the fiber-mix and chain-link reinforced fiber-mix panels tended to conform to the shape of the loading head as the concrete fractured and the reinforcement was loaded in tension.

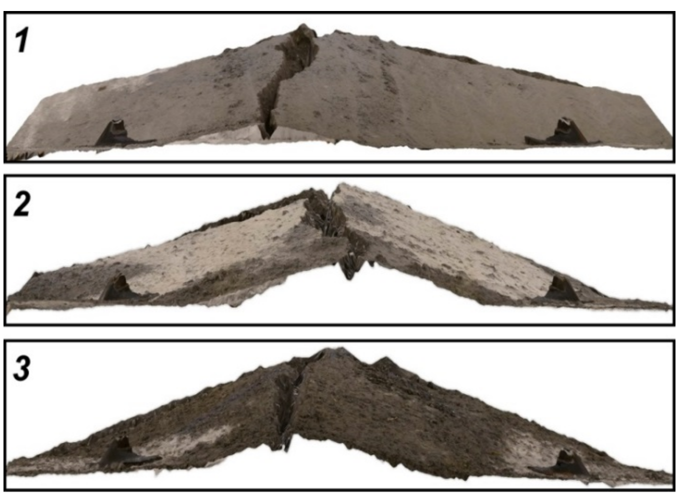

Figure 11. Side view of each panel and mesh type at 25.4 cm of ram displacement: (1) standard-mix, (2) fiber-mix, (3) chain-link in fiber-mix.

Figure 12 shows the volume-energy relationship for the three panels. Assuming a 1.2-m by 1.2-m bolt spacing pattern, the potential exists for a deformation volume to be assessed in field settings. While standard- and fiber-mix shotcretes appear to lose load-bearing capacity at deformation volumes of 0.10 m^3, chain-link reinforced fiber-mix shotcrete can still support additional loading at deformation volumes of 0.25 m^3. Photogrammetric analysis of the standard-mix shotcrete panels with chain-link reinforcement was not performed in this study.

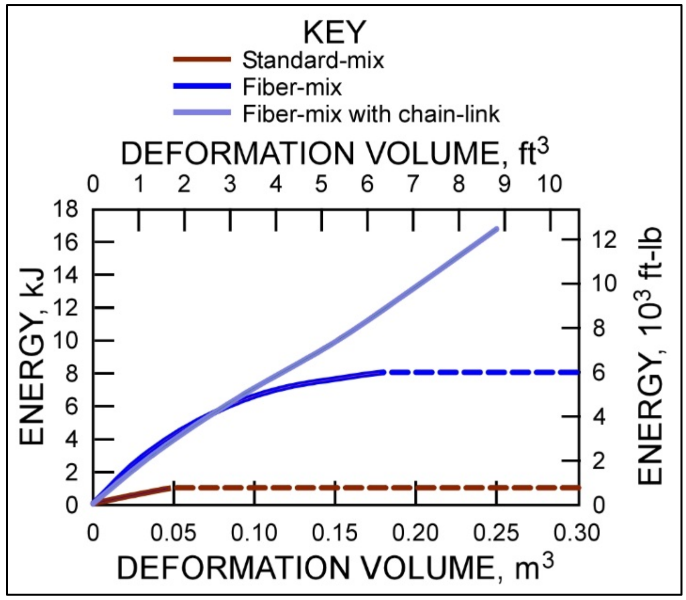

Figure 12. Relationship between energy and volume for shotcrete support systems, as determined through photogrammetric measurement.

CRACK WIDTH ANALYSIS

Relationships between crack width and load-displacement data from the HEHD tests can be used to infer remaining shotcrete support capacity from observed cracking. This work expands upon that of Martin et al. [2010] for round determinant panel tests (RDPT). To accomplish this, crack widths at several locations on the upper surface of the panels were photogrammetrically measured at 5.08-cm ram displacement intervals following each test. The same photogrammetric system used for the previous volumetric analyses was used in the crack width analyses.

The locations of these crack measurements can be seen in Figure 13. Ring 1 (1.2-m diameter) corresponds to crack locations between the installed rockbolts. These four measurements (denoted by the circle markers) were averaged for each ram displacement interval to determine an average crack width for this ring.

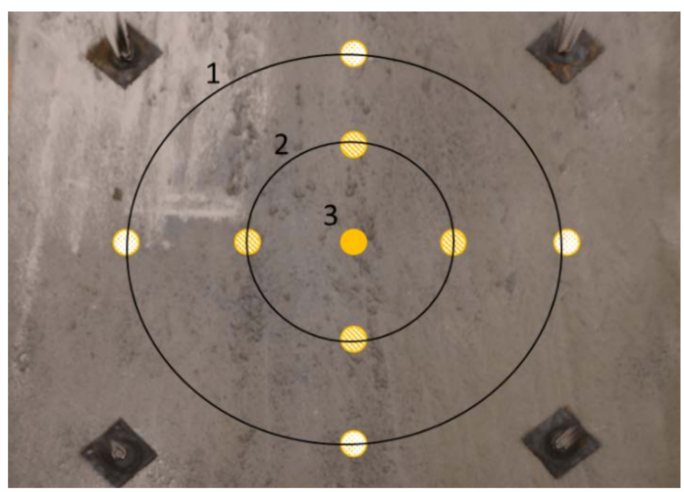

Figure 13. Locations where panel cracks were measured using photogrammetry.

The four measurements along ring 2 (0.6-m diameter) were also averaged for each ram displacement. A central crack measurement (point 3) was made at each displacement interval. Panel types included in these analyses were a standard-mix panel (no reinforcement), a fiber-mix panel, and a fiber-mix panel reinforced with chain-link. Figure 14 shows an example crack width measurement for the fiber-mix panel.

Figure 14. Photogrammetric crack width measurement on fiber-mix shotcrete panel (green line).

The ram-force and crack width at the three different locations for the three panel types are provided in Tables 3, 4, and 5. Graphical results of the crack width measurements are shown in Figures 15, 16, and 17, and relate width of the center crack to panel loading and ram displacement for standard-mix, fiber-mix, and chain-link in fiber-mix shotcrete, respectively. To assist the reader, the approximate thicknesses of the objects below help to visualize the width of the cracks.

- 1 mm, about the width of a lead pencil tip
- 5 mm, about the width of the lead-wood interface on a pencil's end
- 10 mm, about the width of a pencil's eraser
- 25 mm, about the width of a thumb
- 50 mm, about the width of three fingers
- 100 mm, about the width of a fist

The locations along the force-displacement curve at which these respective crack widths develop for the center crack are shown in Figures 15, 16, and 17.

Table 3. Ram force and crack widths for the standard-mix panel test at 5-cm intervals.

Ram Disp. cm	Ram Force kN	Outer Crack mm	Midspan Crack mm	Center Crack mm
5	13.8	6	6	9
10	20.2	17	16	24
15	11.6	29	32	49
20	9.4	49	62	116
25	8.8	67	80	158

Table 4. Ram force and crack widths for the synthetic macro-fiber-mix panel test at 5-cm intervals.

Ram Disp. cm	Ram Force kN	Outer Crack mm	Midspan Crack mm	Center Crack mm
5	56.3	3	3	6
10	42.8	10	11	21
15	28.3	22	26	45
20	16.4	36	44	83
25	15.5	52	77	128

Table 5. Ram force and crack widths for the chain-link reinforced synthetic macro-fiber-mix panel test at 5-cm intervals.

Ram Disp. cm	Ram Force kN	Outer Crack mm	Midspan Crack mm	Center Crack mm
5	66.4	4	5	8
10	65.1	12	16	24
15	65.6	21	29	27
20	67.7	36	51	86
25	75.2	66	84	161

The approximation of crack widths with common items may be used by personnel in the field for reference to estimate residual load capacity for installed shotcrete. For example, using Figure 15, a standard-mix shotcrete showing cracks the width of a pencil tip (1 mm) has effectively lost all support capacity, but a chain-link reinforced fiber-mix shotcrete panel (Figure 17) may still be performing effectively while having cracks the size of a fist (100 mm). It is the hope of SMRD researchers that increased knowledge of how to interpret shotcrete crack width in regards to remaining toughness will simultaneously increase worker safety and reduce operating costs.

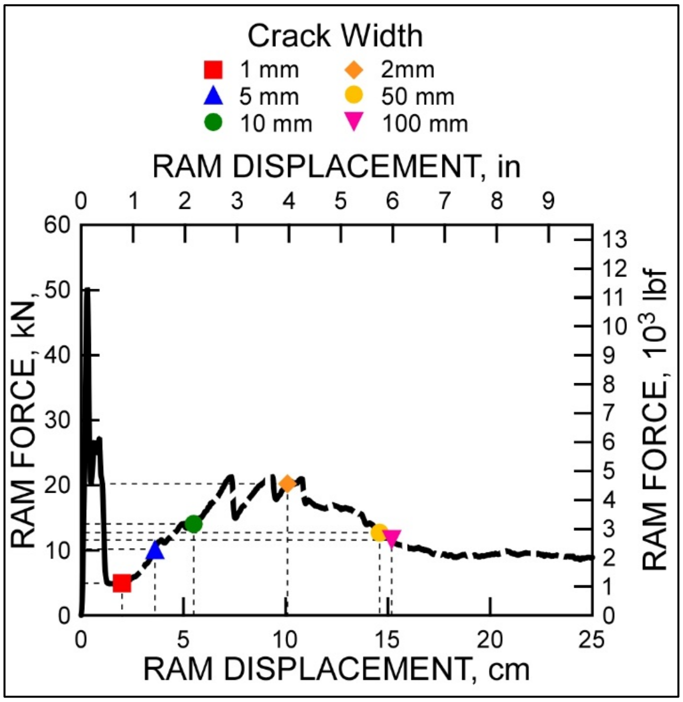

Figure 15. Force, displacement, and crack width for a standard-mix shotcrete panel.

CONCLUSIONS

The HEHD testing machine developed by SMRD has been used to perform quasi-static tests on shotcrete panels with different reinforcement types. The intent is to better understand the mechanics of yielding surface support for use in weak-rock or high-stress mining environments where either squeezing or rockburst-prone ground is present. This work provides further insight into the behavior of surface support and a number of conclusions can be drawn from these initial test series:

- It is important to consider surface support as a system. No single material has all desired attributes for use in high-deformation ground, but a well-designed composite system can provide the desired characteristics.
- The combination of steel mesh embedded in shotcrete results in a very tough surface support.
- Steel mesh embedded in synthetic macro-fiber-mix shotcrete results in a nearly ideal force-deformation response for a tough surface support.

- Photogrammetry can be used to perform more advanced analyses, including deformation-volume and crack width calculations.
- For shotcrete reinforced with steel mesh, panel strength will remain stable or increase even as crack quantity and width increase. This is commonly observed and a necessary condition for load transfer to the steel mesh.
- Photogrammetry has the potential to link laboratory results with field observation via volumetric-deformation and crack width measurements, allowing for estimation of the residual capacity of installed surface support. This could aid in determining whether or not rehab is required.

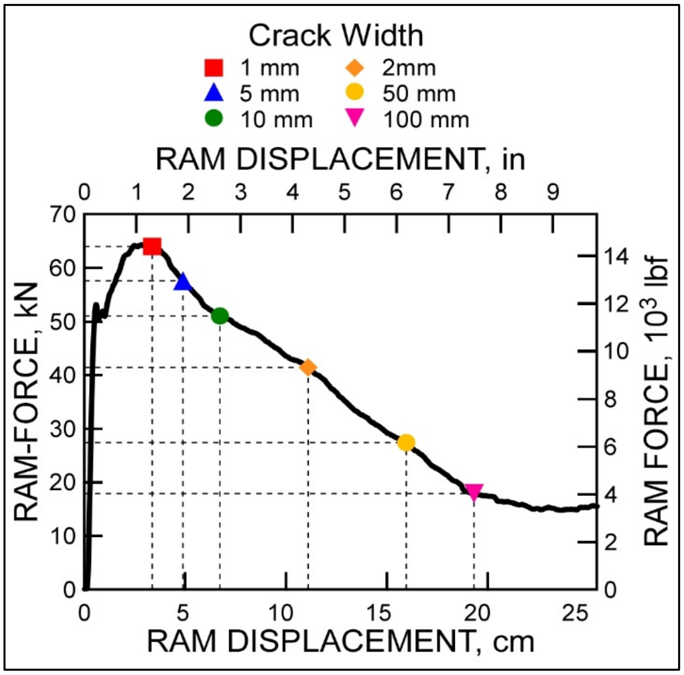

Figure 16. Force, displacement, and crack width for a synthetic macro-fiber-mix shotcrete panel.

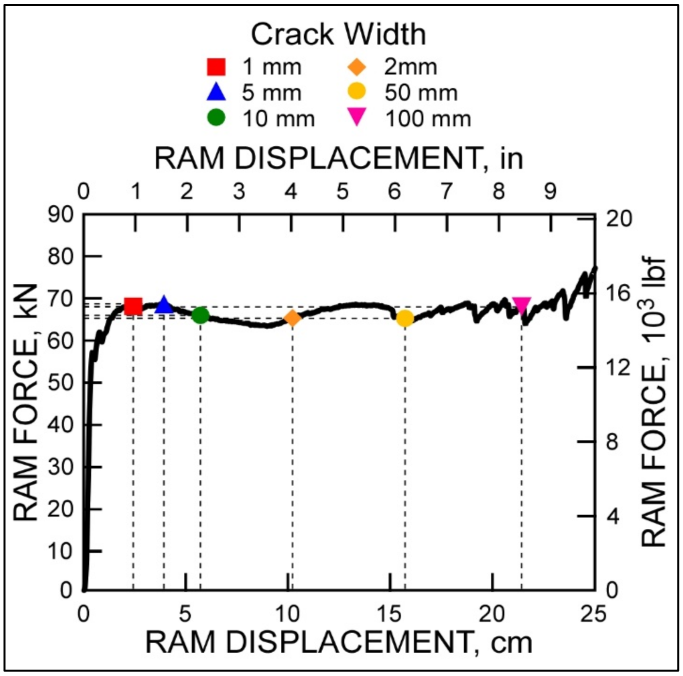

Figure 17. Force, displacement, and crack width for a synthetic macro-fiber-mix chain-link reinforced shotcrete panel.

The energy absorption for shotcrete panels over a flexural displacement of 25.4 cm has been quantified under controlled laboratory conditions for panels of different reinforcement type. For the dimensions and conditions described in this paper:

- An unreinforced standard-mix panel exhibits and elastic-brittle response and its energy absorption capacity is less than 0.5 kJ and can be assumed effectively to be zero.
- A standard-mix shotcrete panel lined with approximately 3.5 mm of Turbo Liner® 5502 polyurea can absorb approximately 6.0 kJ
- A fiber-mix shotcrete panel using BarChip[54]© synthetic 54-mm long macro-fibers at a dosage of 6.5 kg/m^3 can absorb approximately 9.4 kJ
- A standard-mix shotcrete panel with chain-link reinforcement can absorb approximately 13.2 kJ
- A standard-mix shotcrete panel with welded-wire can absorb approximately 14.0 kJ
- A fiber-mix shotcrete panel with chain-link reinforcement using BarChip[54]© synthetic 54-mm long macro-fibers at a dosage of 6.5 kg/m^3 can absorb approximately 17.2 kJ

Currently, shotcrete panels have been tested only under quasi-static loading conditions. This provides an adequate analysis of surface support for squeezing ground. However, to be effective in rockbursting ground, the surface support must also yield when subjected to very high displacement rates. In the near future, SMRD will be conducting tests under fully-dynamic loading conditions using a dynamic-drop panel testing machine. This will allow these various surface support types to be evaluated under true dynamic conditions.

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