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Reinforced Shotcrete Performance: Quantifying the Influence of Ground Support Installation Sequence

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ABSTRACT: Mining ground support systems typically include rockbolts, wire-mesh, and shotcrete or fibercrete. The selection and installation sequence of these products is determined by operational needs and ground support requirements. Without quantifiable performance data, finding the proper balance can be a challenge. In this study, mechanical testing is used to measure the relative performance of different installation sequences of mesh, bolts, and shotcrete. 6×6-ft, 4-inch thick shotcrete panels bolted on a 4×4-ft pattern were constructed to represent different installation sequence options, and tested in a specially constructed test machine to measure the force-displacement response during 10 inches of deflection between the bolts. Afterwards, post-bolted macro-synthetic fiber reinforced shotcrete was tested for comparison with the wire-mesh alternatives. Low (5-lb/yd^3) and high (11-lb/yd^3) fiber content mixes were tested. Lastly, the influence of external mesh was measured. The results demonstrate the importance of shotcrete in the overall support system, the benefit of post-bolting, and provide a direct comparison between mesh and macro-synthetic fiber reinforcement. The test results are coupled with empirical shotcrete design guidelines to provide recommendations for selecting appropriate surface support based on ground conditions. The overall goal of this work is to help match the right support for the ground conditions, thereby improving the safety of underground workers.

1. INTRODUCTION

Underground metal mines typically use a combination of rockbolts, wire-mesh and shotcrete or fibercrete (usually 5 to 15 lb/yd^3 of macro-synthetic fibers) to support excavations. These products and their installation sequencing are determined by both geotechnical and operational requirements, which must be balanced. However, while the costs of different products and installation practices can be readily determined, the effectiveness of the support alternatives is difficult to quantify.

In cooperation with Barrick Gold Corporation's Turquoise Ridge Joint Venture (TRJV), the Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) conducted systems-based ground support testing to aid in determining best practices for using reinforced shotcrete as weak rockmass surface support and to quantify the performance of support alternatives.

Shotcrete panels, 6×6-ft, 4-inch-thick, were constructed to represent support installation sequencing options of shotcrete, wire mesh, and bolts, including: (1) shotcrete over mesh and bolts, (2) flash coat of shotcrete, followed by mesh and bolts, then additional shotcrete, and (3) post-bolting the entire mesh-reinforced shotcrete layer. The panels were bolted on a 4×4-ft pattern and tested to measure the force-displacement response of the surface support during 10 inches of movement between the rockbolts. Next, post-bolted macro-synthetic fiber-reinforced shotcrete (FRS) was tested for comparison with the wire-mesh alternatives. Low (5-lb/yd^3) and high (11.7-lb/yd^3) dose FRS mixes were tested. Lastly, the influence of external wire-mesh was measured.

The test results from this study are considered within the context of existing empirical design guidelines to make general surface-support recommendations based on ground conditions. Lastly, practical insights are highlighted with special attention paid to the use of shotcrete in weak ground.

2. BACKGROUND

2.1. *Ground Conditions*

Mines in northeastern Nevada mining Carlin-type gold deposits must contend with highly variable ground conditions. Production zones within these ore bodies are typically composed of highly altered and intensely fractured rock with Rock Mass Ratings (RMR) (Bieniawski, 1976) of less than 45 (Sandbak and Rai, 2013; Sun and Chen, 2013). Access drifts and infrastructure often intersect faults and altered material of varying thickness and geotechnical quality ranging from blocky competent rock to saturated soil-like material [Warren et al., 2016] as shown in Figures 1 and 2.

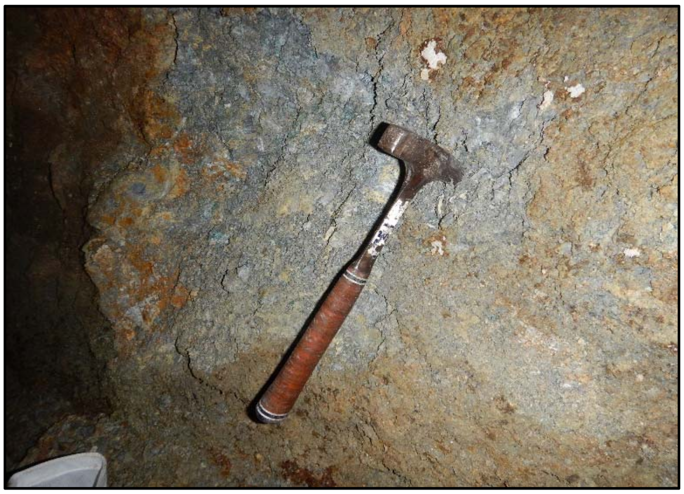


Figure 1. Weak ground conditions commonly encountered in/near ore-bodies in Nevada's underground gold mines.

Figure 2. Competent ground away from ore bodies can allow for very large excavations for permanent infrastructure.

2.2. *Ground Support: Practice*

Ground support typically consists of inflatable (Swellex™-type) rockbolts installed by mechanized bolters with welded-wire mesh for surface containment. Shotcrete is often sprayed over mesh and bolts to provide additional surface support.

Bolting requirements are determined based on the capacity required to support estimated dead weight loads (Pakalnis 2008, 2014), standard rules of thumb (Army Corps of Engineers 1980), and practical experience in similar ground and mining conditions. Most development headings are designed at roughly 16×16-ft using 8-ft bolts on a 4×4 pattern as a minimum, and miners often install additional support as needed. In squeezing ground, various methods have been attempted which include: (1) high-density bolting, (2) installation of bolts with greater length, (3) increased bolt capacity, (4) hollow bar grouted bolts, (5) fiber reinforced shotcrete, and (6) lattice girders.

2.3. *Ground Support: Operational Considerations*

Support designs must be effective, but also practical and economical. Therefore, in addition to capacity and support performance, designs must also consider factors such as material costs, installation time, corrosion resistance, rehabilitation requirements, workforce experience, safety, failure consequence and probability.

From an operations perspective, single pass support is desirable, leading to the practice of shotcreting over mesh and bolts. However, shotcreting over mesh and bolts in weak ground often results in the shotcrete being pushed off the bolts and mesh as the ground deforms around the bolt heads. Post-bolting the shotcrete layer gives the bolt heads a solid platform to resist squeezing. Immediate flash shotcrete also reduces raveling, minimizing chimney risk. (Warren et al. 2018)

Synthetic-fiber is an alternative reinforcement and also facilitates post-bolting since it can be applied in a single pass. However, implementation of FRS may require workforce training and infrastructure investment. There are also additional QA/QC items such as early-age strength requirements for drilling and re-entry, which are important for mine cycle decisions. Without quantitative performance data for these support alternatives, it can be difficult to determine if such efforts are worthwhile. This paper is a step toward remedying that deficiency.

3. SHOTCRETE DESIGN FOR WEAK ROCK

Support provided by shotcrete is not well defined, particularly in weak rockmass conditions, and its use in combination with bolts and cables further complicates analysis of support contribution. As a result, design is primarily based on experience (Martin et al., 2015). Empirical design systems typically provide guidelines for shotcrete thickness and/or reinforcement based on rock mass classification (RMR, Q), excavation span, rockbolt spacing, etc.

Such empirical design systems include the Q-System (Grimstad and Barton, 1993), the Rock Mass Rating (RMR) system (Bieniawski, 1976), and the New Austrian Tunneling Method (NATM, 1962). The Morgan et al. (1995) "template method" for classifying fiber performance into toughness performance levels (TPL), combined with guidance on the appropriate TPLs for different ground conditions [Papworth 2002] also provides insight.

3.1. *Quantifying Reinforcement Performance*

Rather than specifying a particular fiber type and dosage, fiber reinforcement requirements are often specified in terms of beam (ASTM C1609; EFNARC, 2010) or panel (ASTM C1550; EFNARC, 2010) index tests. These tests quantify post-crack strength, and also provide insight into the mechanical behavior of reinforced shotcrete. Some researchers have performed these tests with mesh-reinforcement for relative comparison.

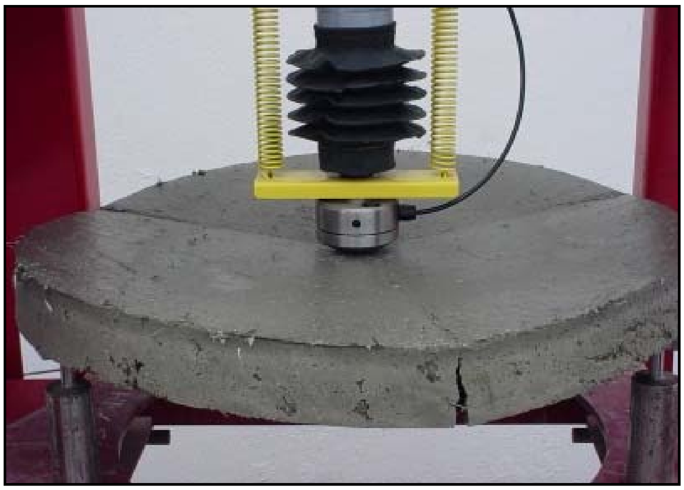


Figure 3. ASTM C1550 round determinate panel test being performed on a 75-mm thick FRS panel (Martin et al., 2015).

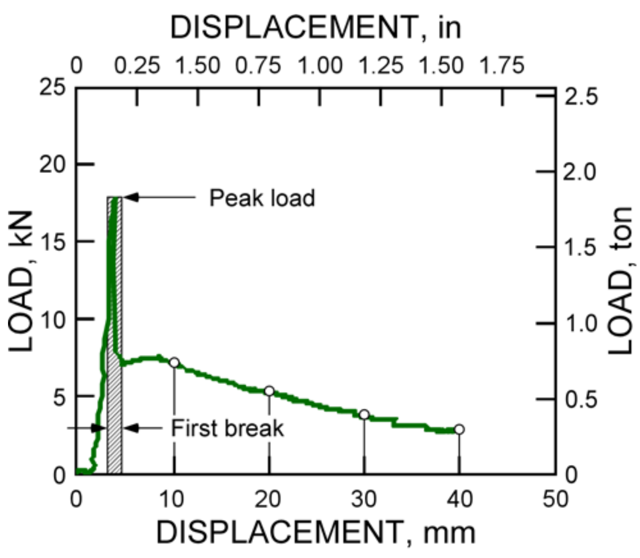


Figure 4. Load versus displacement curve from ASTM C1550 round determinate panel (RDP) test indicating peak load and first break (Martin et al., 2015).

The ASTM C 1550 round determinate panel (RDP) test (Bernard, 2000) has become the international standard for assessing FRS performance for ground support. In this test, a 75-mm-thick, 800-mm-diameter round panel is supported on three pivots symmetrically arranged around its circumference and subjected to direct loading at its center by a spherically shaped ram (Figure 3).

During the test, the load and controlled displacement at the center of the test panel is recorded (Figure 4). The post-crack performance is represented by panel *toughness* (measured in Joules), derived from the aggregate area under the load-displacement curve. Typically, the toughness is determined at 40-mm displacement. Toughness is a measure of the energy absorbed and represents the ability of fiber-reinforced or mesh-reinforced shotcrete to redistribute stress following cracking, and to continue to offer structural support.

3.2. *Specifying Reinforcement Requirements*

The Q-system is unique in that with updates developed by Papworth (2002)—based on Morgan's TPLs, correlations between beam and panel tests, and experience in the Australian mining industry—it incorporates recommendations for both shotcrete thickness and toughness in terms of RDP testing.

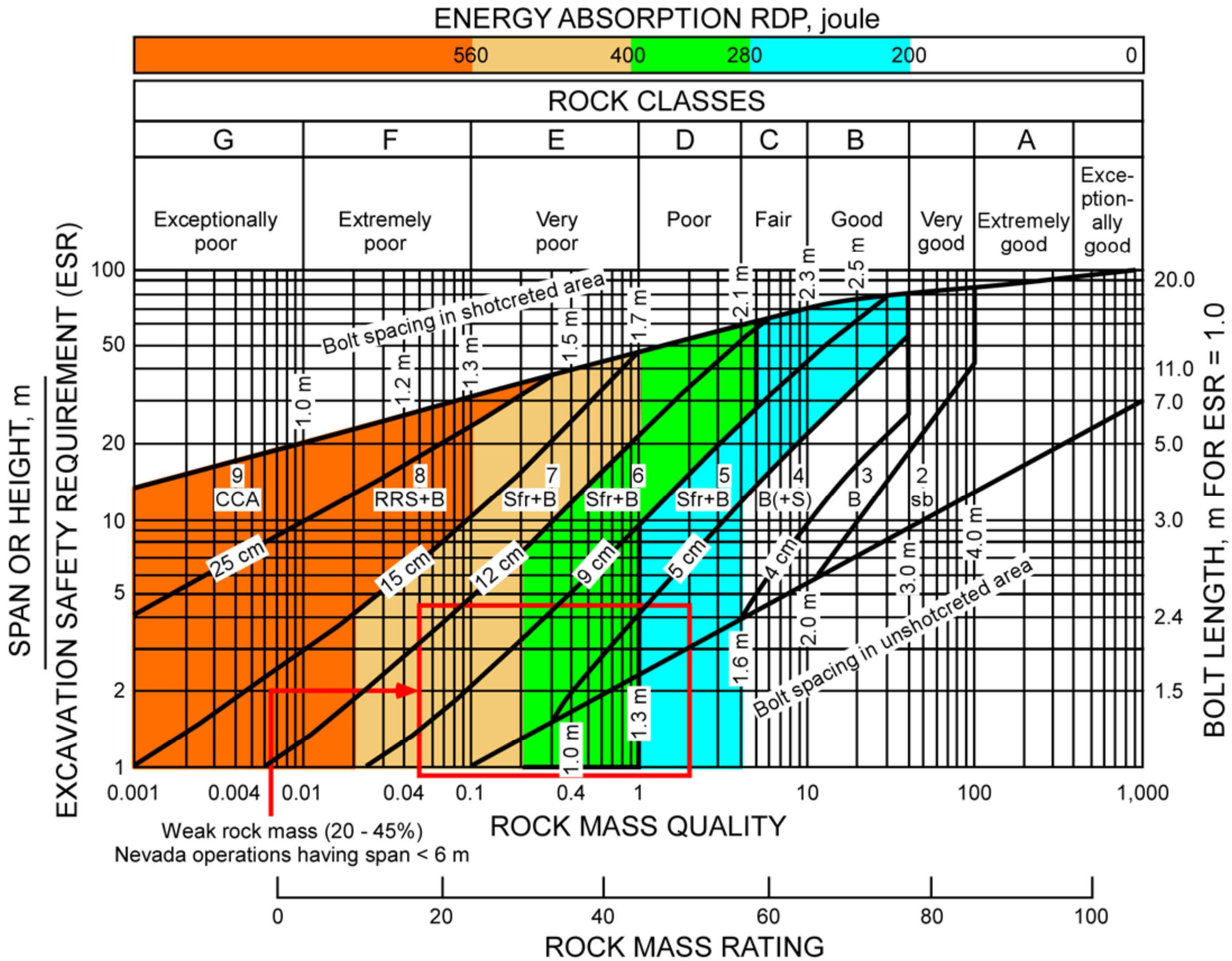
The design chart (Figure 5) indicates that shotcrete thickness and reinforcement should increase in poorer ground conditions and for wider excavation spans. Additionally, bolting through the FRS is also recommended beyond support category 4. Implicitly, the chart suggests that fiber dosage should be based on the anticipated rock deformation and potential shotcrete adhesion to the rock substrate (Papworth, 2002).

In good ground conditions, toughness (the post-crack load capacity) is of little importance, with the primary role of the shotcrete being to prevent gravity-driven failures of rock wedges between bolts with little to no fracturing of the shotcrete lining expected. In poor ground, where large displacements are expected or adhesion strength potential is low, toughness and post-bolting are a priority (Papworth, 2002).

3.3. *RDP Toughness for Macro-Synthetic Fiber*

Index tests are useful in that they account for the wide range of performance of different fibers and specify the requirements independent of fiber type, length, and dosage. As rule of thumb, 70 J per kg/m^3 (42 J per lb/yd^3) of macro-synthetic fiber dosing can be expected for 28-day shotcrete, but to ensure quality control requirements are met, 55 J per kg/m^3 (32 J per lb/yd^3) is a good assumption (Nitschke and Winterberg, 2016).

The authors collected published RDP toughness data for a range of different macro-synthetic fibers and shotcretes. The results are summarized in Table 1. This data is plotted with the recommendations of Nitschke and Winterberg (2016) in Figure 6. The chart shows that panels reinforced with typical modern macro-synthetic fibers 48 mm or longer tested at 28 days, will likely fall within Nitschke and Winterberg's rules of thumb.



Reinforcement categories

1. Unsupported
2. Spot bolting, **sb**
3. Systematic bolting, **B**
4. Systematic bolting and unreinforced shotcrete, 4-10 cm, **B(+S)**
5. Fiber reinforced shotcrete and bolting, 5-9 cm, **Sfr+B**
6. Welded wire mesh, fiber reinforced shotcrete and bolting, 9-12 cm, **Sfr+B**
7. Welded wire mesh, fiber reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8. Welded wire mesh, fiber reinforced shotcrete > 15 cm and reinforced ribs of shotcrete and bolting, **Sfr+RRS+B**
9. Cast concrete lining, **CCA**

Excavation categories		ESR
A	Temporary mine openings	3-5
B	Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large excavations	1.6
C	Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers, access tunnels	1.3
D	Power stations, major road and railway tunnels, civil defense chambers, portal intersections	1.0
E	Underground nuclear power stations, railway stations, sports and public facilities, factories	0.8

Figure 5. Estimated support categories based on Q-system rock mass quality, after Grimstad and Barton (1993), Papworth (2002), and modified by NIOSH

Table 1. Published round panel toughness values for different fibercrete mixes, 40-mm deflection

Reference	Fiber Type	Fiber Length (mm)	Fiber Content (lb/yd^3)	Age (day)	Toughness (J)	TPL*, Rock Class*
Martin et al., 2015	BarChip Shogun	48	3.2	28	160	I, B
	BarChip Shogun	48	5.0	28	276	II, C
	BarChip Shogun	48	7.0	28	302	III, D
	Fabpro Performax	48	3.2	28	175	I, B
Morgan et al., 1999	-	35	7.75	90	155	I, B
	-	50	15.5	90	295	III, D
	-	48	15.5	90	595	IV, F
	-	48	15.5	90	610	IV, F
	-	48	23.3	90	900	IV, F
Clements & Bernard, 2004	BarChip Xtreme	72	20.2	28	799	IV, F
	Synmix 55	55	20.2	28	580	IV, F
	Synmix 75	75	20.2	28	584	IV, F
Papworth, 2002	Scanfibre CXO50/40SS	40	11.0	28	>200	II, C
	Scanfibre CXO50/40SS	40	12.6	28	>280	III, D
	Scanfibre CXO50/40SS	40	15.2	28	>400	IV, E
	Scanfibre CXO50/40SS	40	19.4	28	>560	IV, F
Madsen et al., 2009	BarChip Shogun	48	8.42	7	310	III, D
	BarChip Shogun	48	11.8	7	388	III, D
Bernard, 2010	BarChip Shogun	48	15.2	28	546	IV, E

*Based on correlations between RDP toughness, Toughness Performance Level, and Q-System Rock Class [Papworth 2002].

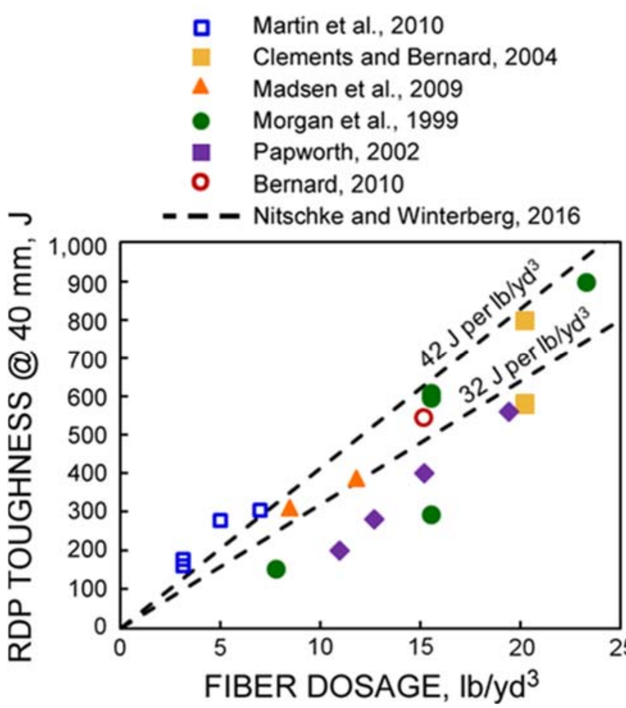


Figure 6. Typical performance of macro-synthetic fiber reinforcement based on test results (Martin et al., 2015a; Clements and Bernard, 2004; Madsen et al., 2009; Morgan et al., 1999; Papworth, 2002; Bernard, 2010) and industry experience (Nitschke and Winterberg, 2016).

3.4. *RDP toughness for wire-mesh*

Published RDP test results for panels reinforced at the mid-line with 6-gage, 4-in spacing, welded-wire-mesh indicate RDP energy absorption values in the range of 450 to 700 J (Martin et al., 2015). Thyni (2014) found that for 6-gage, 3-in spacing welded-wire mesh, 1000 J can be expected.

4. GROUND SUPPORT TESTING

While the RDP test is an effective tool for comparing relative performance of reinforcements, as an index test, it cannot quantify the effects of installation sequencing. To address this, NIOSH designed and built the high-energy high-displacement (HEHD) panel test machine [Martin et al., 2015b]. The main advantage of the HEHD tester is that the surface support can be evaluated as a system, taking into account the influence of the rockbolts, and providing strengths representative of in-mine support.

4.1. *HEHD Panel Test Machine*

The test frame is designed to accommodate a 6×6-ft shotcrete test panel and consists of four reinforced-concrete support columns with rebar bolts grouted into each column on a 4×4-ft pattern. The test panel is placed over the bolts, and nuts are torqued down over the bolt plates to 150 ft-lb. A 150-ton hydraulic jack with a 10-in stroke is used to drive a ram with a hemispherical loading head through the center of the panel (Figure 7).

The jack pressure and ram displacement are recorded continuously during that test to determine the force-displacement response. The test machine has been previously discussed in detail by Martin et al. [2015b], Raffaldi et al. [2016a, 2016b].

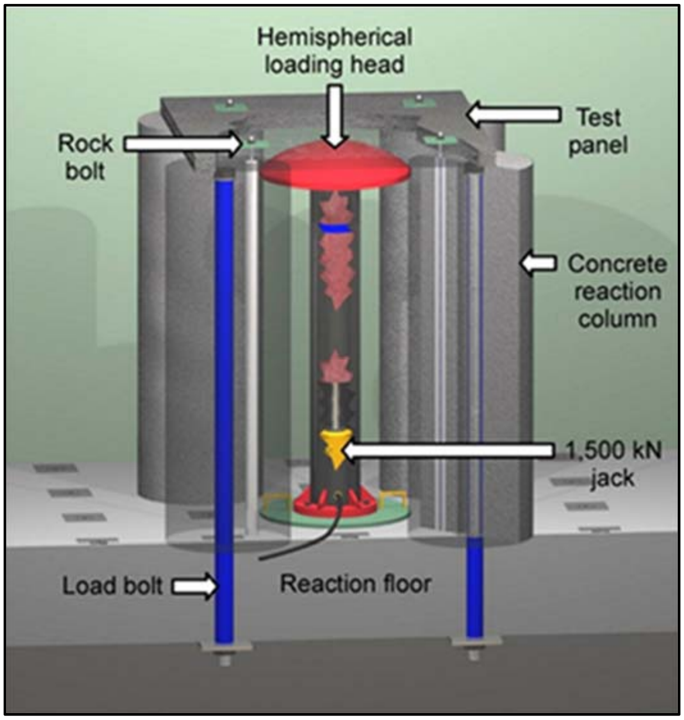


Figure 7. Technical schematic of the high-energy high-deformation (HEHD) panel test machine.

Figure 8 shows example force-displacement results for post-bolted, unreinforced shotcrete. The apparent resistance of the unreinforced shotcrete beyond first break is due to the dead weight of the panel acting on the ram (as much as 0.8 tons) and the clamping action of the bolt plates. A post-test photo of one of the panels is shown in Figure 9. The post-bolted, unreinforced panels provide a benchmark to compare reinforced panels.

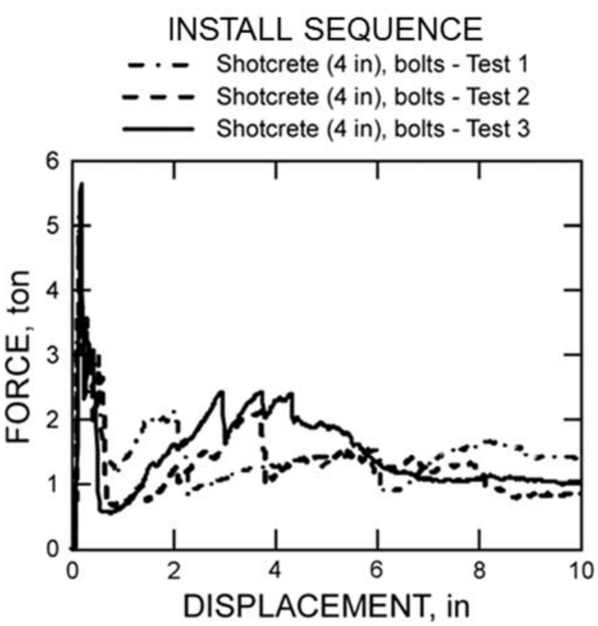


Figure 8. Example force-displacement curves for individual panel tests performed with the HEHD test machine.


Figure 9. Post-test photo of post-bolted, unreinforced shotcrete panels tested in the HEHD panel tester.

4.2. *Shotcrete Panel Construction*

Shotcrete test panels (6×6 ft, 4-in thick) were constructed to approximate surface support used in underground mines. Forms were sprayed by a certified nozzle operator (Figure 10). After filling each form, the top was screeded and floated to a uniform thickness of 4 inches (Figure 11).


Figure 10. Shotcrete being applied by a certified nozzle operator over mesh and bolts plates. Plastic spacers were used to maintain access for bolting to the test frame after curing.


Figure 11. After shotcreting, the panels were screeded and floated to a uniform thickness to provide consistent test results.

A total of 15 panels were constructed to represent different installation sequences of bolts, mesh (6-gage wire, 3-inch mesh size), and shotcrete. The mix design is provided in Table 2. The mesh-reinforced panels are summarized in Table 3.

Table 2. Shotcrete mix design used to construct test panels

Product	Quantity (lb)
Pea Gravel	500
Fine Aggregate	2,000
Cement	685
Fly Ash	165
Water	334

For panels in which plates were shotcreted over, plastic spacers were used during construction to maintain an access for bolting to the test frame. Panels used to simulate post-bolting were cored through on a 4×4 pattern before testing to attach to the test frame.

Table 3. Constructed mesh-reinforced shotcrete panels

Quantity	Panel Construction Type
6	Unreinforced shotcrete[1]
3	Shotcrete sprayed over mesh and bolt plates
3	Mesh and bolt plates embedded in shotcrete
3	Mesh embedded in shotcrete[2]

[1] tested with and without external wire mesh with plates on exterior of panel to represent post-bolting
[2] tested with plates on exterior of panel to represent post-bolting

Another 9 FRS panels, summarized in Table 4, were constructed to compare performance of FRS with that of mesh reinforced shotcrete, and to compare the performance of different fiber dosages (5 and 11.7 lb/yd^3). The panels were dosed with STRUX™ 85/50, 50-mm macro-synthetic fibers used at TRJV.

Table 4. Constructed fibercrete panels

Quantity	Panel Construction Type
6	Macro-synthetic FRS (5.0 lb/yd^3)[1]
3	Macro-synthetic FRS (11.7 lb/yd^3)[2]

[1] tested with and without external wire mesh with plates on exterior of panel to represent post-bolting
[2] tested with plates on exterior of panel to represent post-bolting

Table 5. Average unconfined compressive strength of cast cylinders and cores of shotcrete from blocks sprayed during panel construction.

Batch	Cast UCS (psi)	Cored UCS (psi)
Shotcrete	5,978	4,803[1]
FRS (11.7 lb/yd^3)	7,164	7,600
Shotcrete	5,689	6,847
FRS (5 lb/yd^3)	5,497	5,780

[1] Observed presence of voids accounted for low strength. However, the voids were not present in cores obtained from test panels.

Cast cylinders of concrete and shotcrete cores from blocks sprayed during panel construction were tested according to ASTM C39 standards for quality control purposes. A typical 28-day strength requirement of 5000 psi was met with the exception of the cored cylinders from the first shotcrete batch. However, voids present in these cylinders were not observed in the panels.

5. RESULTS: MESH-REINFORCED SHOTCRETE

Welded-wire-mesh-reinforced panels representing three different installation sequences of bolts, wire mesh, and shotcrete were tested. These included: (1) shotcrete over mesh and bolts; (2) flash coat of shotcrete, mesh, bolts, shotcrete; and (3) post-bolted mesh-reinforced shotcrete. In practice, to install this last sequence, two rounds of bolting is required: One to pin the mesh before applying the second layer of shotcrete, and a second round to post-bolt.

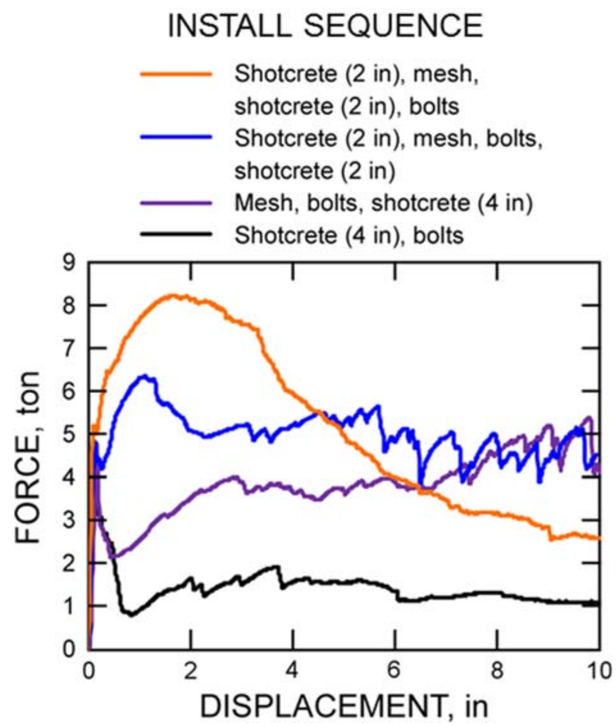


Figure 12. Average force-displacement responses of mesh-reinforced shotcrete using different installation sequences.

The force-displacement results for the mesh-reinforced panels are shown in Figure 12. Each line represents an average of 2 or 3 tests. Unreinforced post-bolted shotcrete is provided as a benchmark. All panels have an initial first-break at about 5 tons, a function of the shotcrete UCS. The post-crack resistance depends on the location of the mesh and bolt plates demonstrating the importance of mesh encapsulation and post-bolting to optimize performance.

5.1. *Shotcrete over Mesh and Bolts*

Shotcrete sprayed over mesh and bolts, shown by the purple line in Figure 12, had an initial post-crack residual strength of about 2 tons and slowly loaded to about 5 tons at 10 inches of displacement. During the tests, shotcrete was pushed off the bolt plates, and large areas of shallowly embedded mesh were pulled out of the shotcrete around the bolts (Figure 13). As a result, no wires were observed to rupture during these tests.

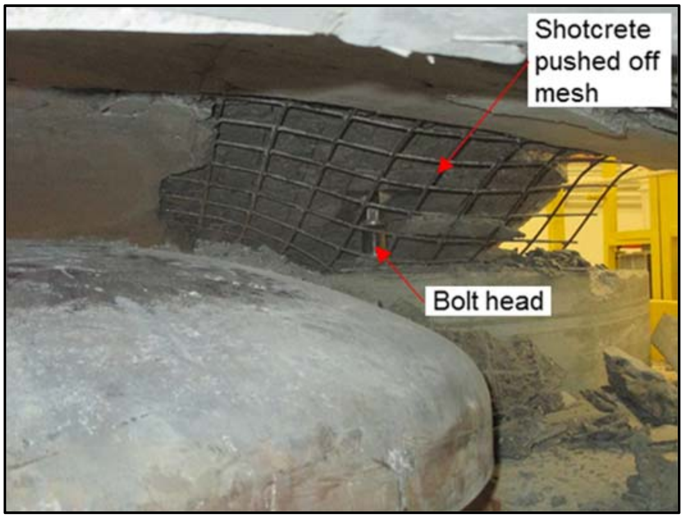


Figure 13. Post-test view underneath panel constructed to represent spraying shotcrete over mesh and bolts showing shotcrete being pushed off bolts and large areas of shallowly embedded mesh pulling out of the shotcrete around the bolts.

Figure 14. Post-test photo of a panel constructed to represent spraying a flash coat of shotcrete, installing mesh and bolts, and additional shotcrete showing separation of shotcrete at mesh interface.

5.2. *Flash Shotcrete, Mesh, Bolts, Shotcrete*

Panels with the mesh and bolt plates embedded in the center of the shotcrete, shown by the blue line in Figure 12, maintained significant resistance over the full 10-inches of displacement. Peak strength was just over 6 tons at 1 inch of displacement and 4 to 5 tons resistance remained after 10 inches. However, the shotcrete tended to separate at the mesh, and the outer 2 inches of shotcrete were pushed off the bolts (Figure 14, above). No significant rupturing of wires was observed.

5.3. *Post-Bolted Mesh-Reinforced Shotcrete*

Post-bolted mesh-reinforced shotcrete, shown by the orange line in Figure 12, had a max flexural resistance of more than 8 tons at roughly 2 inches of deflection between the bolts. The external bolt plates confined the shotcrete, minimizing slabbing. The mesh was also well encapsulated by shotcrete, and the mesh remained fully embedded during the test so that the main failure mode was wire rupture across cracks (Figure 15).

Figure 15. Post-test photo of a panel constructed to represent post-bolting of mesh-reinforced shotcrete showing complete tensile failure of wires spanning the shotcrete cracks.

6. RESULTS: MACRO-SYNTHETIC FRS

The post-bolted FRS average force-displacement results are shown in Figure 16. Post-bolted, unreinforced shotcrete is provided for comparison.

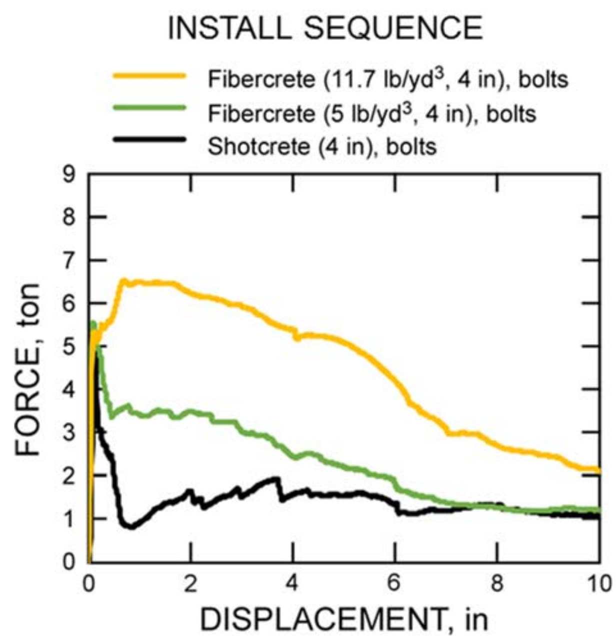


Figure 16. Average force-displacement responses of post-bolted macro-synthetic fiber reinforced shotcrete (FRS).

FRS performed well over the first 2 to 3 inches, but the resistance gradually diminished as cracks opened and the fibers pulled out of the matrix. First break occurred around 5 tons. Post-crack strength depends on the fiber content of the FRS. The post-bolted FRS also has the added benefit that the shotcrete forms a continuous layer with fibers tying together any loosened shotcrete, minimizing loosened slabs that may fall and strike personnel and providing a stable platform for the bolt heads to resist squeeze (Figure 18).

The low-dose (5-lb/yd^3) and high-dose (11.7-lb/yd^3) FRS panels differed in their fracture patterns. While the low-dose FRS panels exhibited a more random fracturing (Figure 17) similar to the unreinforced shotcrete, the high-dose FRS panels developed well-defined, predictable cracks between the bolts, nearly identical to the post-bolted, mesh reinforced panels (Figure 18).

Figure 17. Post-test photo of a post-bolted, fiber-reinforced (5-lb/yd^3) shotcrete panel, showing fracture pattern similar to unreinforced shotcrete.

Figure 18 Post-test photos of a post-bolted, fiber-reinforced (11.7-lb/yd^3) shotcrete panel showing (top) shotcrete providing stable platform for bolt head to resist movement, and (bottom) predictable fracturing between bolts, identical to post-bolted, mesh-reinforced panels.

7. RESULTS: SHOTCRETE & EXTERNAL MESH

When shotcrete is post-bolted with external wire-mesh, the shotcrete and mesh act independently. This is primarily due to the different stiffnesses of mesh and shotcrete. As a result, the force-displacement response is not influenced by the mesh until the mesh begins to bag enough to provide measurable resistance. This occurs between 2 to 4 inches of displacement (see Figure 19). With continued displacement, contribution of the FRS to total surface support resistance decreases while the mesh contribution increases. In several tests, rupture of wires near bolt plates was observed toward the end of the tests (Figure 20), indicating that 6 tons at 10 inches is roughly the maximum capacity of the mesh.

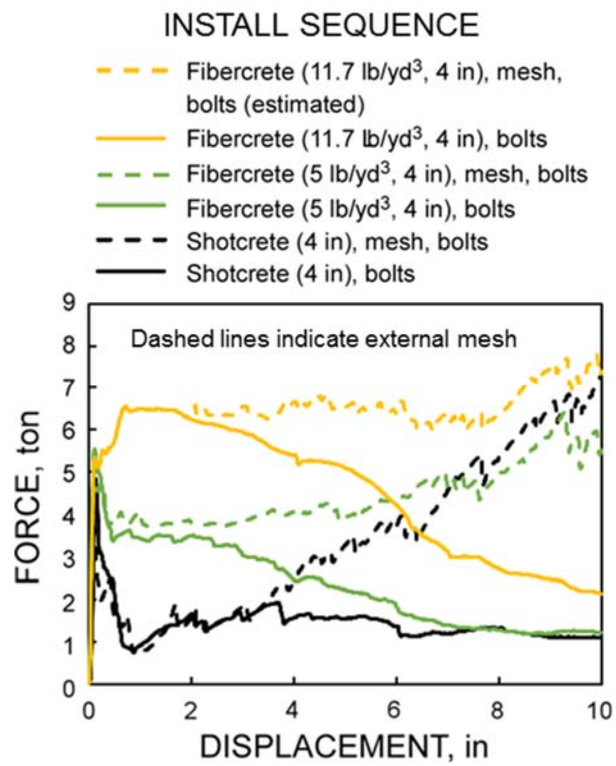


Figure 19. Average force-displacement responses of various shotcrete panels with and without external wire mesh.

Figure 20. Technical schematic of the high-energy high-deformation (HEHD) panel test machine.

To estimate the performance of the 11.7-lb/yd^3 FRS panels with external wire-mesh, the differences in resistance between panels tested with and without external mesh were calculated to estimate the contribution of the wire mesh. This result was added to the 11.7-lb/yd^3 FRS force-displacement results to estimate its response with external mesh (shown by the dashed yellow line in Figure 19). External wire-mesh greatly increases the displacement capacity of the surface support system by increasing the resistance of the surface support at displacements greater than 2.5 inches and containing loose shotcrete.

8. ANALYSIS OF HEHD PANEL TESTS

Although some panel types maintain resistance over many inches of displacement, owing to fiber pullout, mesh rupture, and/or shotcrete fracturing, a practical displacement limit for any reinforced shotcrete surface support, bolted on a 4×4-ft pattern, is roughly 2.5 inches of deflection between the bolts (or 5% of bolt spacing) unless external mesh is used. The force-displacement response to 2.5 inches is shown in Figure 21 for all tested reinforcement alternatives.

The toughness was computed over this displacement range by calculating the area under the force-displacement curves. The support alternatives are ranked by toughness in Table 6, allowing for comparison between fiber and mesh reinforcement. Unreinforced shotcrete had some post-peak force resistance due to it's dead weight after cracking and bending of the bolt plates. For practical purposes, its toughness should be considered zero. Because mesh and bolts alone does not provide significant resistance to movement in this displacement range, its equivalent energy is zero.

Table 6. Large-scale HEHD panel test toughness and correlation to estimated equivalent RDP toughness.

Surface Support Sequence	HEHD Energy, J	RDP Energy, J
Shotcrete (4 in), Bolts	850*	0
Mesh, Bolts	0**	n/a
Mesh, Bolts, Shotcrete (4 in)	1651	160
Fibercrete (5 lb/yd^3, 4 in), Bolts	2032	220
Shotcrete (2 in), Mesh, Bolts, Shotcrete (2 in)	3001	365
Fibercrete (11.7 lb/yd^3, 4 in), Bolts	3426	430
Shotcrete (2 in), Mesh, Shotcrete (2 in), bolts	4150	540

*the measured toughness at 2.5-in is an indication of load transfer between shotcrete and rock bolts, facilitated by post-bolting. For practical purposes, the toughness should be assumed to be zero.
**wire mesh does not develop significant force resistance at 2.5-in of displacement and therefore has zero toughness within this range.

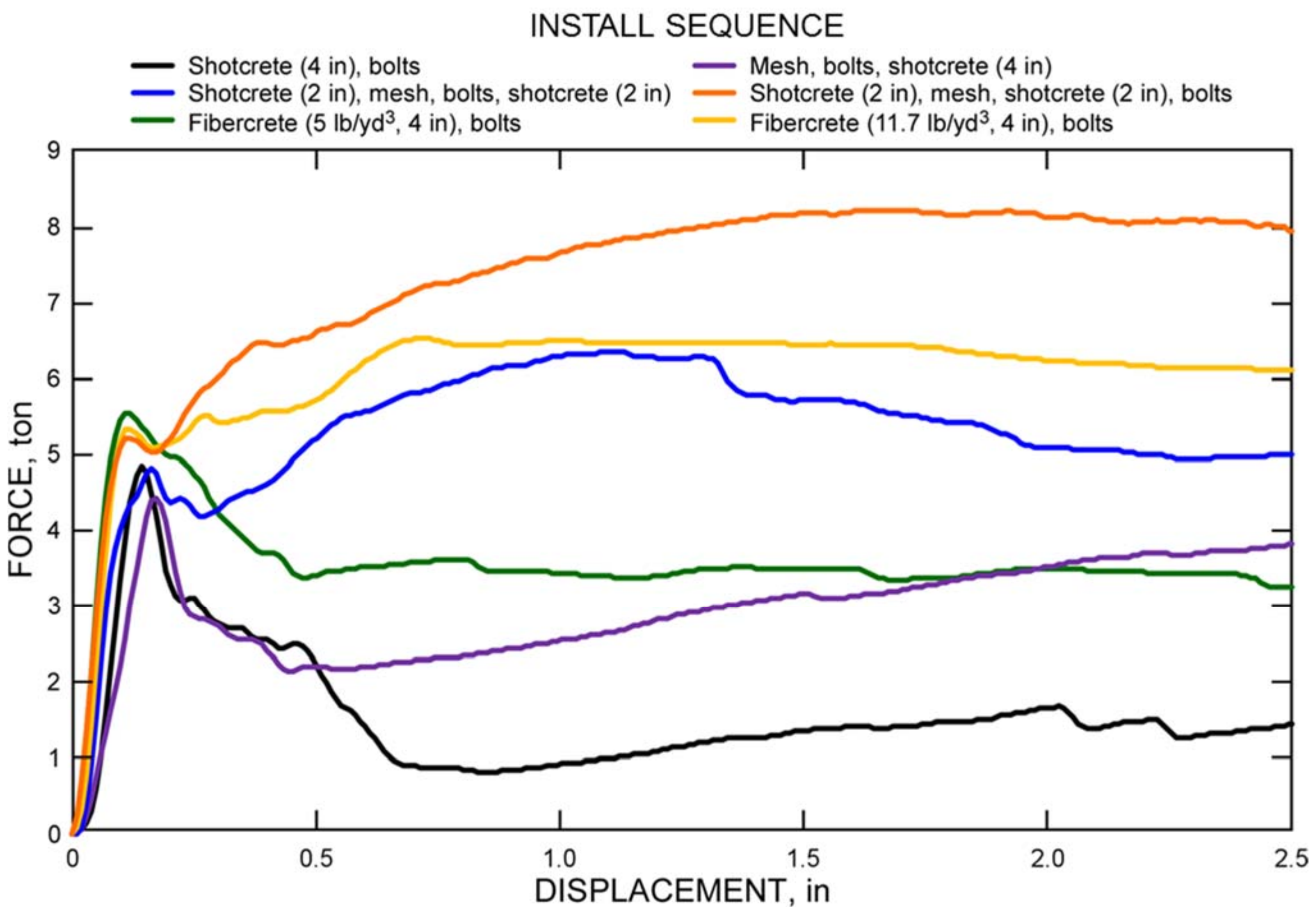


Figure 21. Comparison of post-crack performance of welded-wire mesh and macro-synthetic fiber reinforced shotcrete tested in HEHD machine to 2.5 inches of displacement between bolts.

9. SURFACE SUPPORT GUIDELINES

Using the modified Barton chart provided in Figure 5, RDP energy requirements for different rock classes were tabulated. The rock classes were then described in terms of rock mass rating (RMR). Using Figure 6, RDP energy was estimated for the large-scale fibercrete panels and used to linearly correlate RDP and HEHD energy (Table 6, above) . This allowed the wire-mesh panels to be expressed in terms of equivalent RDP requirements. Approximate Q-system ground support categories and toughness performance level (TPL) were also assigned. Table 7 was then constructed as a general guideline to serve as a starting place for selecting appropriate surface support. These guidelines can and should be adjusted based on site-specific experience and testing.

Table 7. Correlation of rock mass rating, Q-system rock classes, and RDP energy with surface support types for Span/ESR[1] < 10

RMR[2]	Rock Class	RDP Energy[3], J	Surface Support	Ground Support	TPL[4]
60-80	B/C	0	Mesh and bolts	4	0
55–65	C	200	Shotcrete over mesh and bolts Bolts over FRS (3.5–5 lb/yd^3)	4-5	I,II
45-55	D	200–280	Bolts over FRS (5–7.5 lb/yd^3)	5-6	II, III
25–45	E	280–440	Flash shotcrete, mesh and bolts, shotcrete Bolts over FRS (7.5–12 lb/yd^3)	6-7	III, IV
0–25	F	440–640	Bolts over mesh-reinforced shotcrete Bolts over fibercrete (12–18 lb/yd^3)	7-8	IV

[1]Q-system excavation support ratio
[2]rock mass rating
[3]suggested RDP test toughness determined at 40-mm of deflection using ASTM C1550
[4]toughness performance level

Wire-mesh primarily serves to contain rock falls between bolts. Due to its low relative stiffness, it does not truly provide surface *support.* Therefore, mesh alone may not be fully adequate to control squeezing ground which has a tendency to deform around the bolt heads, sometimes described as the bolts being "sucked into" the ground.

Shotcrete is an effective surface support component because it is stiff, providing early resistance to ground movement and preventing raveling of loose rock. Mesh or fiber reinforcement should usually be used because of the brittle nature of unreinforced shotcrete.

Post-bolting the entire reinforced shotcrete layer ties the surface support and bolts together into a system, greatly improving surface support performance. The shotcrete provides a stable bearing surface for the bolt heads, and bolts provide compression, minimizing unstable slabs.

Mesh-reinforced shotcrete performance depends strongly on support installation sequencing. The more thickness of the total shotcrete layer that can be post-bolted, the better the performance will be.

Fiber-reinforced shotcrete (FRS) is comparable with mesh-reinforcement if the FRS is post-bolted and sufficient thickness is applied. Performance will depend on the thickness of the layer and fiber dosage. Fibers also stitch the shotcrete together, decreasing spalling and detachment of loosened slabs.

External wire-mesh should be used anywhere the expected deflection between bolts exceeds roughly 5% of the bolt spacing (2.5 in for a 4×4-ft bolting pattern).

10. CONCLUSIONS

In mining operations, the importance of shotcrete in the overall ground support system is often overlooked, causing shotcrete to be applied as "stope paint" rather than considered an integral ground-support component. Although the complex interaction of shotcrete with rockbolts and surrounding rock is still not fully understood, experience suggests that properly installed and reinforced shotcrete can be effective in weak or squeezing ground conditions. The HEHD testing has quantified relative performance of different ground support installation practices and allowed comparison of mesh and fiber reinforcement. The guidelines provided in this paper provide an aid to specifying shotcrete reinforcement and determining installation sequencing.

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DISCLAIMER

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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