SHORT-ENCAPSULATION PULL TESTS FOR ROOF BOLT EVALUATION AT AN OPERATING COAL MINE

James Pile, *Geotechnical Engineer*
Steve Bessinger, *Engineering Manager*
BHP Billiton San Juan Coal Company
Waterflow, New Mexico USA

Christopher Mark, *Section Chief, Rock Mechanics*
Stephen C. Tadolini, *Section Chief, Geotechnical Engineering*
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, Pennsylvania USA

ABSTRACT

The San Juan Coal Mine, located near Farmington, New Mexico, supplies the San Juan Generating Station with more than 6 million tons of coal annually. To replace dwindling surface mine production, San Juan installed a longwall in 2002. The roof rock in much of the underground reserve consists of interbedded coals, carbonaceous shales, and mudstones. Roof support consists of fully-grouted roof bolts, both tensioned and non-tensioned, supplemented by modified cable trusses.

Short-encapsulation pull tests conducted by San Juan's geotechnical engineering department showed that some of the immediate roof layers provided variable bolt anchorage. To ensure that the roof bolts were obtaining the necessary anchorage, additional tests were conducted in a variety of locations. The results have been used to determine the optimum support design for different areas of the mine. Another series of tests evaluated the performance of several bolt and hole diameter combinations. The experience at San Juan Mine shows that short-encapsulation pull tests can provide the information necessary to improve ground control in variable roof conditions. It also illustrates how a pro-active geotechnical engineering program can be an essential component of a state of the art underground coal mine.

INTRODUCTION

As part of a long-term effort to provide a cost-competitive fuel supply to the San Juan Generating Station, BHP Billiton's Mineral's San Juan Coal Company (SJCC) recently completed the installation of a state of the art longwall mine adjacent to its surface operations at Waterflow, near Farmington, New Mexico (figure 1). The underground mine was developed only after exhaustive geotechnical, geological, environmental, and economical evaluations were completed.

As part of the program, a small-scale pilot mine was developed within the No. 8 Seam on part of the surface mine lease in close proximity to the surface operation. The express purpose of the pilot mine was to assess the minability of the No. 8 Seam, including ground control concerns, subsidence, operational issues, and equipment selection. Room-and-pillar mining methods were employed for geological, geotechnical, and geomechanical evaluations. Variable roof and floor conditions, coupled with splits of the No. 8 Seam above the mining horizon, required experimentation with different mining horizons, opening and pillar geometries, and various roof and rib support systems to be evaluated.

Figure 1. Mine site location, Waterflow, New Mexico

A generalized geological column of the No. 8 Seam and the immediate roof is shown in figure 2. During the initial drilling program it became apparent to the Company technical staff that the roof and floor strata were relatively variable, and potentially susceptible to water degradation and air slaking. Typical UCS values for the immediate roof shales are between 1,000 and 2,000 psi. The relatively low uniaxial compressive strength, and the presence of closely-spaced bedding planes, slickensides and other discontinuities in these rocks results in an estimated Coal Mine Roof Rating (CMRR) in the 30-35 range. Work is currently being undertaken to determine a more systematically derived value.

In some areas of the property as many as four significant sandstone channels may be encountered, three residing above the No. 8 Seam and one immediately above the No. 9 Seam. Difficult mining conditions can be encountered when the channels migrate closer to the No. 8 Seam because of differential compaction near the channel margins, compactional features below the sandstone body, and the potential for more water occurrence.

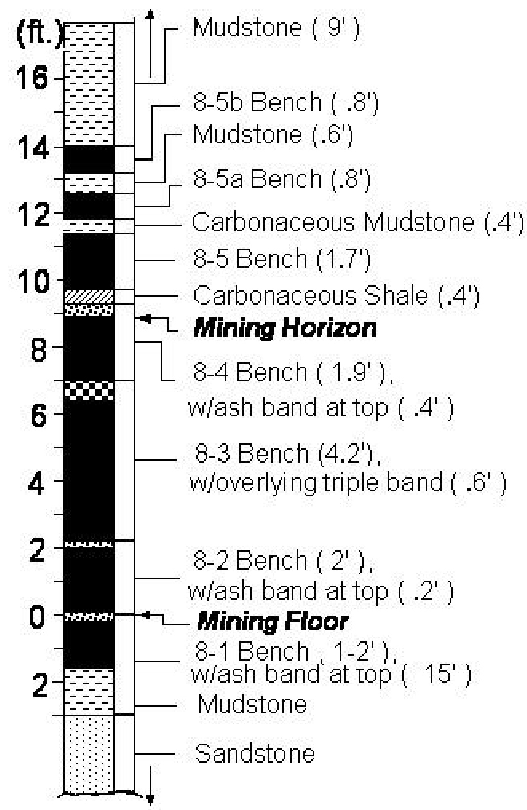

Figure 2. Generalized geological column of the mining horizon and immediate roof.

Fortunately, the in situ stress regime appears to be relatively benign. The depth of cover over the initial reserve ranges between approximately 300 and 800 ft, though ultimately the mine may be as deep as 1,400 ft. Hydraulic fracturing stress measurements indicate that the major principal stress is typically less than 1,000 psi. The ratio of the major principal horizontal stress σ_H to the minor horizontal stress σ_h averaged 1.6. No clear indications of roof damage caused by horizontal stress have been observed in the underground workings.

Concerns about the immediate roof strata, the potential for water degradation, and the potential effects of in situ horizontal stresses prompted a comprehensive roof support evaluation program. The goal of the program was to ensure that optimal performance would be obtained from the roof bolts. The program focused on the anchorage provided by the different roof strata, the potential bolt lengths, the required bolt capacities, and other parameters including the bolt diameter and the hole size.

ANCHORAGE CAPACITY OF FULLY GROUTED BOLTING SYSTEMS

Where the rock is weak, fully grouted roof bolts are prone to anchorage failure (*1*, *5*). Resin grouted bolt systems are typically used in such conditions, and consist of three components, the bolt, the resin, and the host rock. The components have very different material properties that can affect the final performance of the system. Steel materials are ductile and have high ultimate strengths and modulus of elasticity, meaning they can sustain large loads and deflections. Resin grouts and the host mine rocks can be brittle and are not capable of sustaining high tensile loads. The combinations of these two different materials usually result in shear failures at the rock and resin interface. However, if the length of the resin encapsulation along the bolt length is long enough to complete the required load transfer, the full capacity of the bolt can be achieved (*2*).

Grip Factor

The anchorage of a fully grouted bolt is measured by the Grip Factor, which is defined as *the bolt's resistance to pullout per inch of bolt length.* The Grip Factor is measured by loading the upper portion of the grouted bolt in a *short encapsulation pull test*, or SEPT. The maximum length of the resin column tested in an SEPT is 12-18 inches, depending on the strength of the host rock. This length provides enough material to ensure adequate mixing but more importantly minimizes the possibility of the bolt yielding prior to the bond failure occurring. The Grip Factor (tons per inch) is calculated as:

GF = (Load to Slippage)/(Resin Anchor Length)

The "Load to Slippage" is the load applied to the bolt, usually expressed in tons, and the "Resin Anchor Length" is the length, expressed in inches, of the bolt encased with resin.

A low Grip Factor (less than approximately 1 ton/inch) means that the bolt will have less available resistance to rock movement, as shown in Figure 3. Within the anchorage zone (the upper portion of the bolt), the bolts available resistance is less than its nominal yield strength. As a result, the bolt can be pulled out of the roof when rock movement occurs near the top of the bolt. Improving the Grip Factor can significantly improve the performance of a roof bolting system.

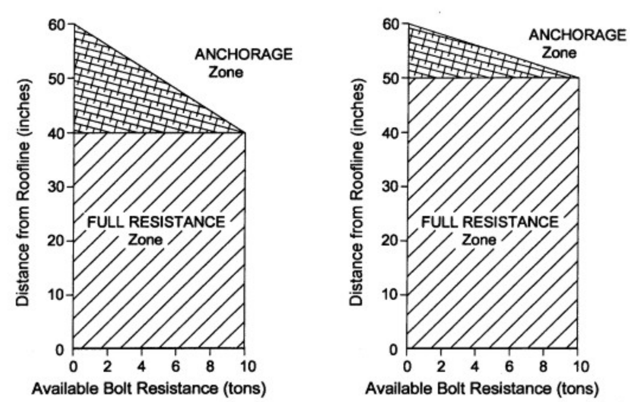

Figure 3. Effect of the Grip Factor on the resistance available from 10-ton roof bolts to react against roof loads. (left) Grip Factor = 0.5 ton/in; (right) Grip Factor = 1.0 ton/in.

Shear Strength and System Stiffness

Other useful properties that can be obtained from SEPT are the peak shear stress and system stiffness (***3***). The shear stress τ (psi) can be calculated by using the equation:

$$\tau = \frac{\Delta F}{\pi \phi L}$$

where: ΔF = change in force over the encapsulated length, lb
L = final resin length, inch
ϕ = bolt diameter or borehole diameter, inch.

The system stiffness, k (lb/inch) or the ability of the system to resist load, can be determined by applying this equation:

$$K = \frac{\Delta F}{\delta}$$

Where: δ = change in length, inch.

The key to using these relationships is that shear failure must take place between the resin-bolt, or resin-rock interfaces. In weak roof materials the resin-rock interface controls the failure mechanism. If the rock materials are strong, the failure surface may be the resin-bolt interface, which simply tests the resin strength and/or the bolt rib profile performance. If failure does not occur and the peak shear strength exceeds the applied force, the equation can be used to calculate the shear stress for the applied force and system stiffness can be calculated for the applied force and measured displacement (***4***).

Factors Affecting Bolt System Performance

A variable that often affects resin bolt performance is the size of the resin annulus, defined as the difference between the hole and bolt radii. As the annulus increases, the mixing of the resin paste and mastic becomes less efficient. Conversely, if the annulus mixing is too small, higher installation pressures can force some material into cracks or fissures, though this may be compensated for with additional cartridge length.

While a number of studies over the past 25 years have indicated that 0.125 inch is the optimum annulus for resin grouted bolts, the industry practice is actually different (5, 6). On the other hand, two recent US studies did find a significant annulus effect (2, 5).

The annulus can be reduced either by decreasing the hole diameter or by increasing the bolt diameter. However, reducing the bolt hole diameter also reduces the contact area between the resin and the rock. Figure 4, shows a nominal No. 7 rebar bolt, 0.804 inch diameter, installed in 1, 1-1/8, 1-3/8 & 1-1/2-inch diameter holes. As shown, the outside circumferential contact area between the resin and rock interface increases with the hole size. If the shear strength of the host material is 725 psi, the shear strength capacity of the bolt installed in the 1-inch hole (circumference 3.1416 inch) would be 725 psi x 3.1416 inch = 2,278 lb/inch. The 1-1/2-inch diameter hole has a circumference of 4.7 inches resulting in a shear strength of 3,416 lb/inch, an increase of 50 percent. This can make a major difference in the final hole and bolt selection in weaker roof materials, but often remains unexamined.

Bolt performance can also be affected by *bolt surface roughness*, the *hole roughness*, and the *resin characteristics* (3, 6, 7). Rougher bolt profiles generally result in improved anchorage, as do rifled holes. Resins with higher compressive strength are also generally expected to improve bolt anchorage performance.

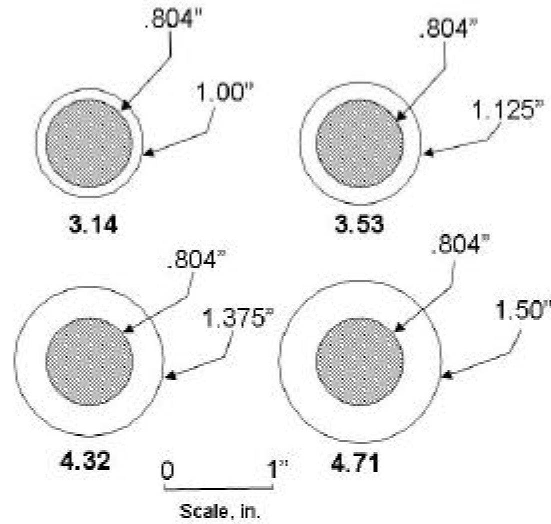

Figure 4. The available rock-resin contact surface for the respective borehole diameters with a 7/8-inch diameter bolt installed.

TESTING PROGRAM

The bolt testing program undertaken in the San Juan Mine had two goals:

- *Optimize the bolt length* by determining the best anchorage horizon in different parts of the mine, and;
- *Optimize the bolt system performance* by determining the best combination of hole diameter and bolt diameter.

Bolt Length (Roof Horizon) Tests

Tests were conducted at 4 locations to examine the bolt anchorage at various horizons. At the first three sites (sites B, C, and D), the tested bolts were 0.804 inch diameter rebar installed in 1.125 inch boreholes. The bolt lengths examined were 5, 6, 7, and 8 ft. The resin cartridges used in the tests provided a nominal 12-inch anchorage.

The roof in all of the locations consisted of interbedded coal and carbonaceous shale, with a thin rider coal seam overlying it known as the 8-5b. The unit above the 8-5b coal consisted of a thick, clay-rich shale, or mudstone, as described earlier.

Site B

Test site B consisted of 24 bolts installed and tested in the East Mains at cross-cut 37. The thickness of the carbonaceous shale band above the 8-5b coal in this area measured approximately 10 inches. The bolts were installed and the load required to initiate a shear failure at the resin/rock interface was recorded. The grip factors for each bolt length are shown in figure 5.

The results show that better anchorage was obtained by the 5 and 6 ft long bolts. They obtained average grip factors of 0.72 and 0.65 tons/inch respectively, versus 0.50 and 0.55 tons/inch for the 7 and 8 ft bolts.

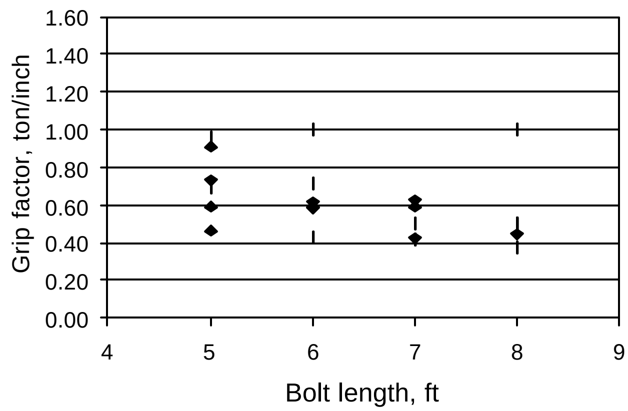

Figure 5. The grip factors for each bolt length in test site B

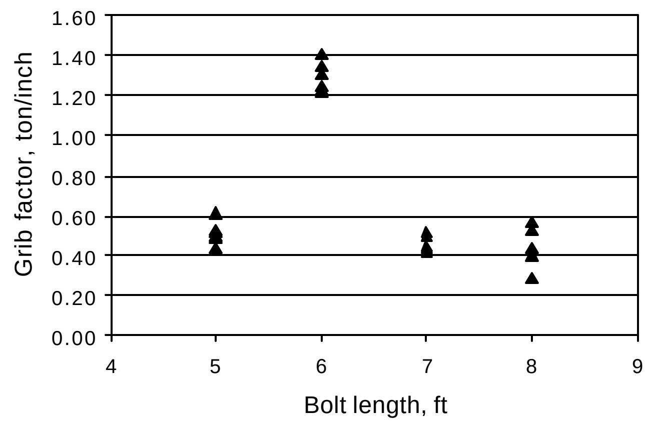

Figure 7. The grip factors for each bolt length in test site D.

Site C

The next series of tests was conducted in between cross-cuts 13 and 14 in the same East Mains, approximately 2,300 ft away from Site B. Test Site C consisted of 24 bolt installations. The thickness of the shale band above the 8-5b coal in this area measured approximately 14 inches. The bolts were installed in the same manner and the required force to initiate a shear failure at the resin/rock interface was recorded. The grip factors for each bolt length are shown in Figure 6. As can be clearly seen, the 7 ft long bolts had the highest average grip average of 0.73 tons/inch of grout. This value was nearly double the grip factors obtained with the 5, 6 and 8 ft bolts, which were 0.38, 0.35 and 0.34 tons/inch, respectively.

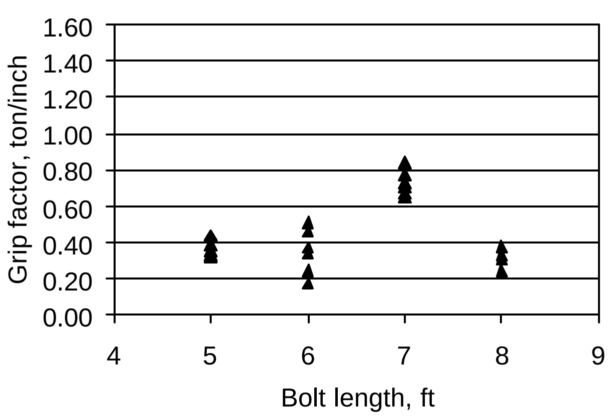

Figure 6. The grip factors for each bolt length in test site C.

Site D

The next test site was inby test Site B between cross-cuts 42 and 43. The 24 bolts were installed and tested using the identical procedure. The thickness of the carbonaceous shale band above the 8-5b coal in this area measured approximately 10 inches, the same thickness determined in Site B. The bolts were installed and the load required to initiate a shear failure at the resin/rock interface was recorded. The grip factors for each bolt length are shown in Figure 7.

The average grip factor for the 6 ft long bolts was 1.29 tons/inch, the best value measured at any of the sites. It exceeded the averages for the 5, 7, and 8 ft long bolts by more than a factor of two.

Site E

The fourth bolt length test site was conducted approximately 450 ft to the northeast of site B, in cross-cut 40 of the East Mains. Only two b bolt lengths, 6 ft and 8 ft, were tested. The bolts had a diameter of 0.677 inches and were installed in both 1-1/32 and 1-1/8-inch diameter holes. The thickness of the carbonaceous shale band above the 8-5b coal in this area measured approximately 10 inches, the same as test area B and D. As shown in Figure 8, the grip factors obtained with the 6 ft long bolts averaged 0.75 tons/inch, compared to just 0.43 tons/inch for the 8 ft long bolts.

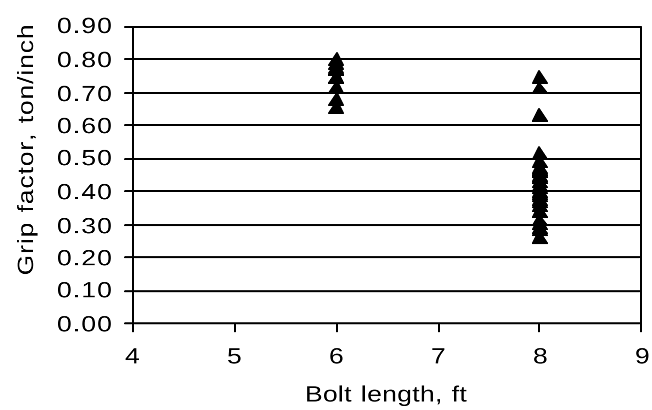

Figure 8. The grip factors for 6 and 8 ft long bolts in test site E.

Discussion of Bolt Length Tests

Geological columns were obtained near each test area as shown in Figure 9. The roof horizon is indicated and potential "anchorage" horizons are indicated for bolts lengths of 5 to 8 ft. The results show that in all four cases the best anchorage horizon was probably the shale just above the 8-5b coal. One hypothesis is that there is a hard band of stronger shale located there. Another is that the top of the coal may actually be "wallowing out" slightly during drilling to create a slightly larger hole and resin "keying" effect. This keying effect may be increasing the grip factors.

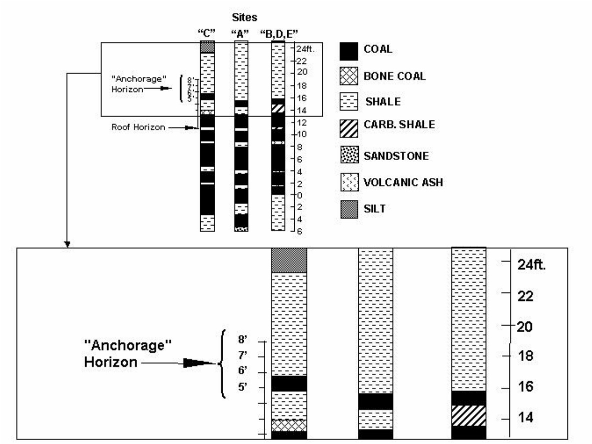

Figure 9. Geological columns for test sites A, B, C, D, and E.

As is the case with most sedimentary rock formations, the immediate roof can be highly variable and have a major impact on bolt performance and subsequent roof stability. Site geology from sites B, D and E are all specified from a single column that ranges in horizontal separation from 225 to 500 ft, indicating how quickly the immediate roof geology can change. When comparative testing is completed, it is extremely important to classify the roof horizon where the tests were performed.

The complete results are contained in Table 1. Figure 10 shows the results using the measured encapsulation length to calculate the Grip Factor. Data from the 1.25 inch holes were excluded because difficulties with the bits resulted in anomalously low pullout loads. The results from 20 tests in which the bolt yielded are included in the data. In these cases, the peak load was not sufficient to cause the anchorage to fail, meaning that the true Grip Factor must have exceeded the calculated one.

Bolt System Performance

Ninety-two tests were performed at Site A, located between cross-cuts 31 and 32 of the East Mains, approximately 1,000 ft west of site E, to examine the effects of bolt diameter, hole diameter, and annulus. Two bolt diameters, 0.804 and 0.914 inch, were installed in 5 different diameter holes, resulting in 9 different annuli. The borehole diameters were 1.0, 1.125, 1.25, 1.375, and 1.5-inches. The final resin column lengths were actually measured and varied between 13 and 29-inches.

Figure 10 shows that the best results were achieved with 0.804 inch bolts installed in 1.125 holes, with an annulus of 0.16 inches. With this combination, mean Grip Factor was 0.87 tons/inch, with 7 of the ten bolts tested going to yield. However, the results for 0.914 inch bolts in 1.125 inch holes (annulus = 0.1055 inches) were nearly as good. The mean Grip Factor was 0.82 tons/inch, this time with four yielded bolts. On the other hand, the smallest annulus (0.804 inch bolts in 1 inch holes) resulted in some of the lowest grip factors.

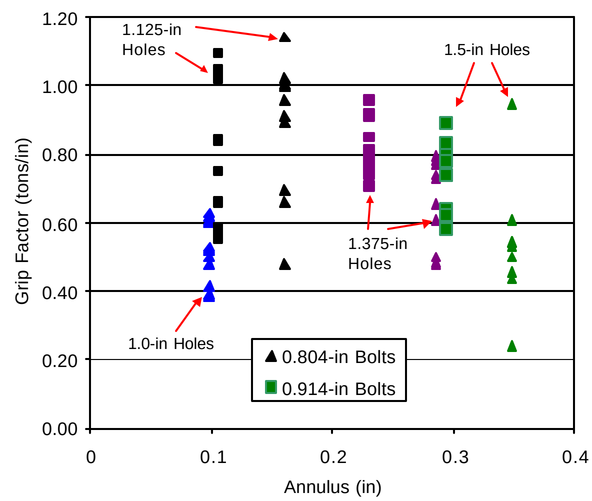

Figure 10. Grip Factor calculations for various bolt and hole combinations.

The data for the larger holes shows a generally declining trend in grip factor as the annulus increases. Higher grip factors were obtained in the 1.375 inch holes than in the 1.5 inch holes, and for a given hole size, the larger bar performed somewhat better.

Table 1. Site A Bolt System Performance Test Results

Annulus (in)	Bolt Dia (in)	Hole Dia (in)	Number Yielded Bolts	Shear Stress (psi)	Mean Grip Factor (tons/in)	Nominal Mean Grip Factor (tons/in)
0.161	0.804	1.125	7	498	0.88	0.73
0.231	0.914	1.375	4	380	0.82	0.73
0.293	0.914	1.500	3	306	0.72	0.67
0.106	0.914	1.125	4	464	0.82	0.57
0.168	0.914	1.250	0	321	0.63	0.60
0.286	0.804	1.375	0	301	0.65	0.60
0.348	0.804	1.500	0	229	0.54	0.50
0.223	0.804	1.250	0	255	0.50	0.45
0.098	0.804	1.000	0	331	0.52	0.42

Table 2. Site E Bolt System Performance Test Results

Annulus (in)	Bolt Dia (in)	Hole Dia (in)	Shear Stress (psi)	Nominal Mean Grip Factor (tons/in)
0.161	0.804	1.125	323	0.57
0.192	0.677	1.060	294	0.49
0.224	0.677	1.125	277	0.49
0.286	0.804	1.375	194	0.42
0.106	0.914	1.125	232	0.41
0.168	0.914	1.250	204	0.40
0.223	0.804	1.250	188	0.37
0.231	0.914	1.375	120	0.26

Measurements of the encapsulation length showed that the smaller the annulus, the smaller the actual encapsulation length when compared with the nominal. This is probably because resin losses during insertion have a much greater effect on the encapsulation length in smaller annuli. If the nominal encapsulation length is used to calculate the Grip Factor instead of the measured one, the relationships between annulus and grip factor are much less pronounced. As Table 1 shows, the Grip Factors obtained with the 0.914 inch bolts are fairly uniform, with the highest values occurring with 1.375 inch holes.

A second series of bolt system performance tests were conducted at site E. The testing matrix for the 8 ft long bolts consisted of a sample size of 32 bolts, which evaluated three bar diameters, 0.677, 0.804, and 0.914 inches. The bolts were installed in holes that were drilled 1-1/32, 1-1/8, 1-1/4, and 1-3/8-inches in diameter. The bolts were anchored with resin, allowed to cure properly, and subsequently tested using the same procedures as before.

The data are contained in Table 2 and figure 11. The actual encapsulation length was not measured in these tests, so the nominal encapsulation length is used to calculate the Grip Factor. Statistical analysis indicates that there were no significant trends that could be attributed to hole diameter, bolt diameter, or annulus.

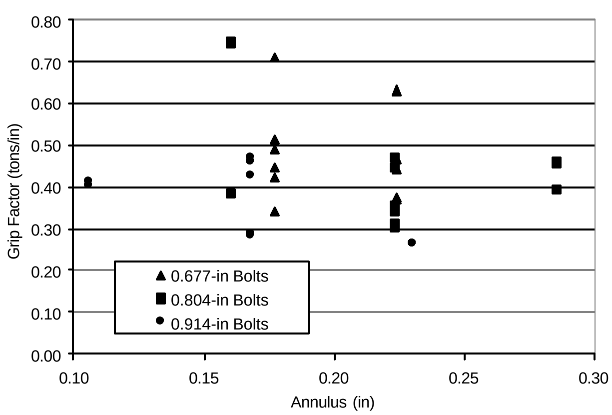

Figure 11. The Grip Factor for 8 ft long bolts with various annulus distances determined in test site E.

The data shows that the shear strength of the resin-rock interface decreased as the hole size increased. At site A, for example, the strength of the 1.125 inch holes averaged 481 psi, while the strength of the 1.5 inch holes was 268 psi. The reduction in shear strength more than compensated for the increased circumferential area.

Discussion of Bolt System Performance Tests

It is important to remember that the Grip Factor is simply an index property that provides insight into the anchorage capacity and the relationship between the host rock, resin, and bolting interfaces. Index property tests are most useful when the data is repeatable and confidence in the bolt system tested can be obtained. To minimize variables in the basic analysis here are some important considerations:

- Use a standard test procedure. The one suggested by Mark et al. (5) is a good starting point.
- An encapsulation length of 12-inches is recommended. This ensures there is enough resin material and also minimizes the possibility of achieving the bolts yield strength.
- Characterize the anchorage zone being tested with site specific core sampling or a color borehole camera.
- Combinations of various bolts and hole sizes usually necessitates the introduction of different bits, bolt surface profiles, and resin cartridge diameters and products. These additional variables can complicate interpretation of the results. Once the optimum annulus is determined, bolt length tests should all be completed with the same resin and bolt combinations.

CONCLUSIONS

The short encapsulation pull test results from the San Juan Mine indicate clearly that superior anchorage can be obtained in specific roof layers. The tests indicate that the optimum bolt length at this mine is probably one that penetrates the high-anchorage layers, but does not extend beyond them. Additional length would be largely wasted because the anchorage is low in the overlying mudstones. Based on these results, the tests are now being used routinely to select the best bolt length for different areas in the mine.

The most significant result from the bolt system test results has been that 0.677-in bolts can achieve the same anchorage as larger diameter bolts at the San Juan Mine. Therefore, it should be possible to use the smaller bolts without any discernable diminution in performance. The annulus results were less conclusive. While there has been some indication that the optimum annulus is approximately 0.125 inches, the evidence is inconsistent. It seems that at San Juan Mine, finding the proper anchorage horizon may be more important than optimizing the annulus.

The proactive research efforts continue at the San Juan mine to improve roof bolt performance. Current efforts are focused on evaluating the effects of borehole roughness on anchorage performance, through the use of rifled drill holes. In addition, equipment has recently been purchased to obtain geological cores from the test areas, and to over-core tested bolts for inspection. The goal of the program is to optimize the roof support systems, which will directly improve the safety of the work environment.

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