In-Situ Tests and Numerical Simulation about the Effect of Annulus Thickness on the Resin Mixture for Fully Grouted Resin Bolt

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Abstract. The main purpose of this paper is to study the effect of annulus thickness on the quality of resin mixture for fully grouted resin bolt. Pullout and mixture tests were made in underground coal mines for the following arrangements: (a) 29 mm borehole diameter, and 19 mm roof bolt diameter with steel wire around the roof bolt; (b) 29 mm borehole diameter, and 19 mm roof bolt diameter with no wire around the roof bolt; and (c) 24 mm borehole diameter, and 19 mm roof bolt diameter with no wire around the roof bolt. The mixture test in steel pipe showed that the best resin mixture is for the 24 mm borehole diameter. The arrangement (b) produced big voids around the bolt. But for the 24 mm hole, arrangement (c), the mixture showed the best results. This was corroborated with the pullout tests results where there was a difference in grout stiffness: in the 24 mm borehole diameter is was about 10 times higher than in the 29 mm borehole diameter. On the other hand, as far as the cohesive strength is concerned, the difference is not significant. Numerical models were built to simulate the pullout tests, and also to simulate the roof support at an intersection. Convergence at two underground intersections, consisting of an immediate roof with laminated sandstone, was monitored to evaluate the performance of the roof supports, using the 29 and 24 mm diameter boreholes (*i.e.* arrangements 'a' and 'b'). The readings showed that the 24 mm borehole diameter resulted in a slightly smaller convergence.

Keywords: glove finger, roof support, numerical modeling, coal underground mining,

1. Introduction

Roof support designs require information about the thickness and quality of each roof rock layer, the entry dimensions, and the properties of the bolt and resin.

In terms of bolt anchor, there are two types of roof support in underground coal mining,: (i) point anchor bolt, and (ii) fully grouted bolt. The point anchor bolt works as a support for the weak strata, which is anchored on the immediate strong layer above, and a pre-tension might be applied to push the weak layers against the strong layer to close separations. On the other hand, the function of the fully grouted roof bolt is to reinforce the roof by building a strong beam within the bolted area. In the beam building concept, the immediate roof is reinforced by restraining the vertical displacements of roof layers using the fully grouted roof bolts (Peng, 2008).

In a fully grouted roof bolt, the void space between the bolt and the wall of the borehole must be completely filled by grout to obtain the maximum performance of the bolt/grout/rock reinforcement system.

The anchorage mechanism of a fully grouted roof bolt is the cohesive and shear resistance at the interface between the grout and host rock. When this contact is weak, the roof bolt can debond and result in premature failure.

One of the causes for the weakening of the contact shear resistance is called "the gloving or glove fingering" (Peng, 2007; Pastars & MacGregor, 2005; Zingano *et al.*, 2007). It primarily occurs due to operational problems, when the plastic film of the grout cartridge is not completely shred by the rotation of the bolt during installation. It can also occur if there is over drilling.

In addition, the gloving effect can be caused by mixture problems due to a large annulus thickness, between the rock bolt and borehole wall. If this space is too big, the grout mixture wouldnt be as effective because the bolt cannot provide a good mixture for such a large amount of resin.

The main result of the gloving effect is the reduced contact area between the grout and host rock, or between the grout and bolt. This reduces the strength of the contacts which reflects on the stiffness or cohesive strength of the grout/rock or grout/bolt interfaces.

Operational problems like over drilling can be solved by training the roof bolter crew and ensuring that the right equipment is used. However, one question remains: What is the maximum (or minimum) thickness of the space between the bolt and borehole wall to get the best grout mixture?

There are some alternative solutions to increase the efficiency of the grout mixture, which are: (i) to put a steel

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wire around the bolt; (ii) make some corrugations on the bolt; (iii) modify the bolt head so that the rotation of the bolt is not centered to enhance mixing, and (iv) to reduce the annulus thickness between the bolt and borehole wall.

The coal mine, which one is mining the Barro Branco (white mud) seam, the immediate roof is a laminated sandstone layer with a 3 m thickness in average, and above are found a siltstone and a massive sandstone layers more than 10 m thick. The floor is massive sandstone, too. The coal seam is 1.8 m thick on average (Fig. 1).

The usual roof support for intersections is built by 2.2 m long fully grouted roof bolt with 19 mm diameter, and the borehole diameter is 29 mm. The bolt spacing is 1 m at intersections. The roof bolt in the entries and crosscuts is 1.5 m long, and 1.2 m row spacing.

There are some installation problems for the long roof bolt in an entry (or intersection) 1.8 m height. The bolt has to be installed in two parts that are connected using a coupled connection. This connection has a diameter of 25 mm, and needs drilling at the larger borehole diameter. It causes slower bolt installation and lower advance rates of the mining face. A steel wire is put around the roof bolt to increase the grout mixture efficiency.

The problems described above were the motivation for this study, which goal is to increase the beam building efficiency by enhancing the resin mixture. The investigation also examined the possibility of reducing the bolt length so it could be installed without using coupled bolts

The purpose of this paper is to study the correlation of the grout properties (grout stiffness and strength) related to the annulus thickness between the bolt and the borehole wall.

The methodologies applied to reach this purpose are:

- Test the mixture efficiency of the grout for different borehole diameters and bolt specifications;

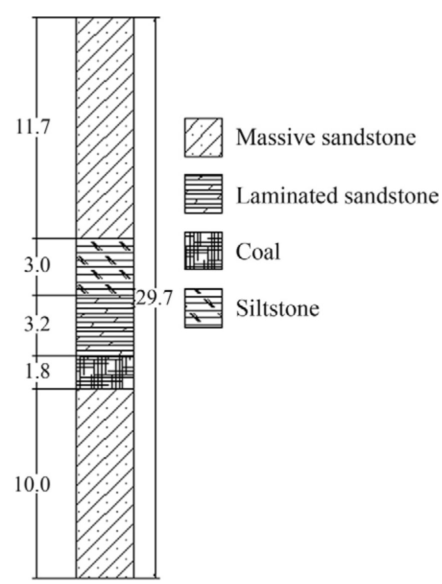

Figure 1 - Geology for Barro Branco Seam at MEL Mine.

- Conduct pullout tests with the same specifications from the mixture tests, and determine the grout properties (stiffness and cohesive strength);
- Construct numerical models to simulate the pullout tests using the grout properties;
- Design roof supports for intersections in a room-and-pillar underground coal mining, considering the new specifications for borehole and roof bolt;
- Monitor the convergence at the center of the intersection for the new roof support design, and compare it to the convergence of the actual roof support applied;
- Construct and calibrate numerical models for the new and actual roof supports.

2. Grout Mixture Test

The main goal of these tests is to check the mixture quality of the grout for different borehole diameter and bolt specifications. Table 1 shows the specifications for each mixture test.

The tests were conducted in steel pipes with the same internal diameters specified in Table 1, and the same diameters used in underground applications. Three tests were conducted, one for each specification below. The steel pipes were placed vertically to simulate actual bolt installations and the top end was closed to simulate the back of the borehole.

The roof bolt was a dowel GG50 from Gerdau Steel Co., with grooving around the bolt to facilitate the mixture of the resin in the hole (or steel pipe).

The grout is formulated by the company itself in a small grout cartridge manufacture facility. A cross-section of the resin cartridge is shown in Fig. 2a. The amount of required resin was calculated and placed in the pipe to guarantee that voids were caused only by mixture problems. It was observed that a small amount of resin return from the pipe occurred during mixture operation in the 29 mm diameter pipe, which is normal.

After three hours curing time, the pipes were cut and opened to examine the quality of the grout mixture. Figure 2b shows the results of the grout mixture tests for the three specifications (Table 1).

It can be clearly observed that the best grout mixture was in the 24 mm (0.94 in.) diameter pipe. There are no

Table 1 - Borehole and roof bolt specifications for grout mixture tests.

Borehole diameter (mm)	Bolt diameter (mm)	Difference* (mm)	Steel wire
29	19	5.0	Yes
29	19	5.0	No
24	19	2.5	No

*The difference refers to the distance between bolt and borehole wall.

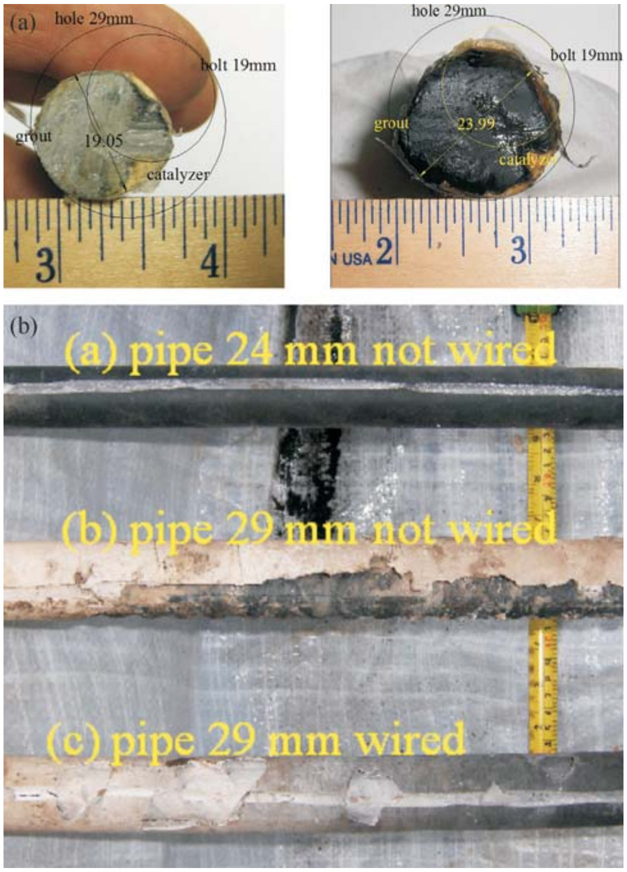

Figure 2 - (a) picture of the cross-section of a resin cartridge, and (b) results for grout mixture tests.

void spaces, and the gray color, which indicates complete mixing of the resin, is more uniform than in the others two tests (29 mm diameter pipe). On the other hand, the tests with the 29 mm diameter pipe contained large voids, and the color was not uniform. The results indicate that the mixture is better for the test bolt with steel wire than the bolt without steel wire.

Therefore, the space between bolt and borehole wall can have a large influence on the efficiency of the grout mixture and the elimination of gloving effects. In this case, the 2.5 mm difference (between bolt and hole wall) was deemed appropriate to obtain a good grout mixture.

The next step is to verify the quality of the contact resin/rock in terms of grout properties using pullout tests, which can be used to calculate the grout stiffness and grout cohesion strength at interface resin/rock.

3. Bolt Pullout Test

The intent of the bolt pullout test is to determine the mechanical parameters of the grout (grout stiffness and grout strength cohesion). The pullout tests were conducted underground in the immediate roof, using the same bolt and borehole specifications described in Table 1, but the bolt length is reduced to 30 cm (1 ft). Figure 3 shows the apparatus for the pullout test.

The chart in Fig. 4 shows the pullout tests results for each borehole and bolt specification. In the pullout test, the grout stiffness is the inclination of the force/displacement

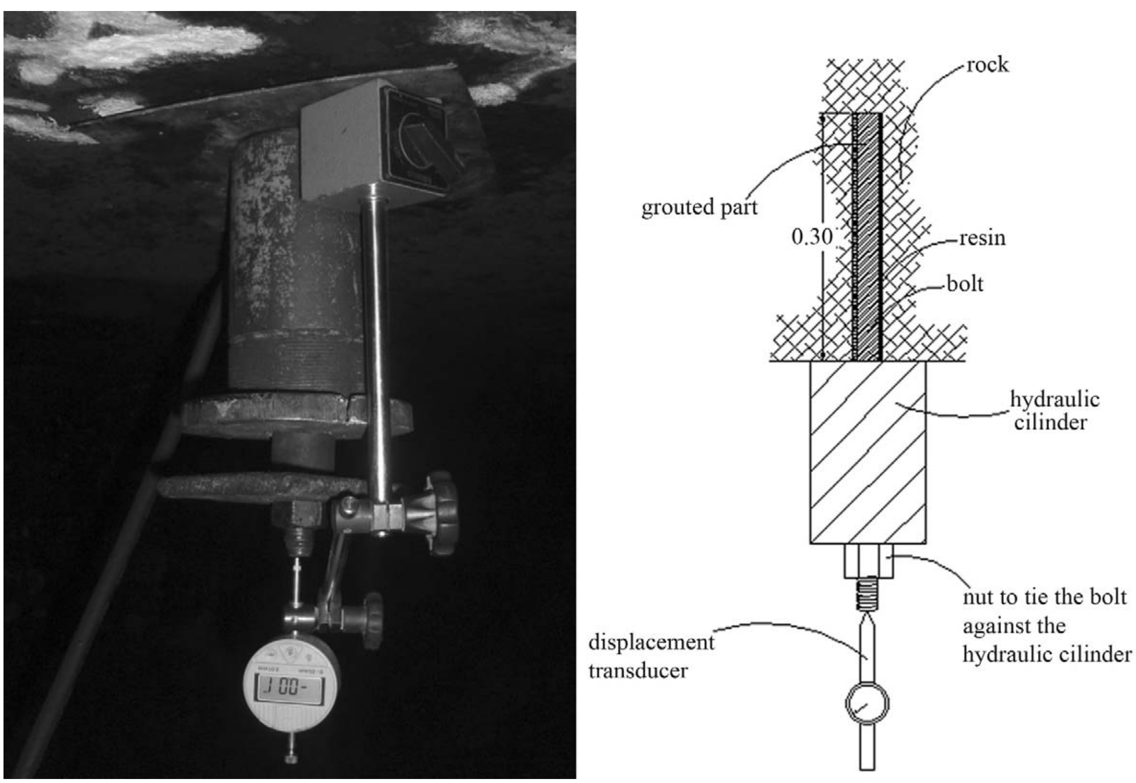

Figure 3 - Apparatus for pullout test.

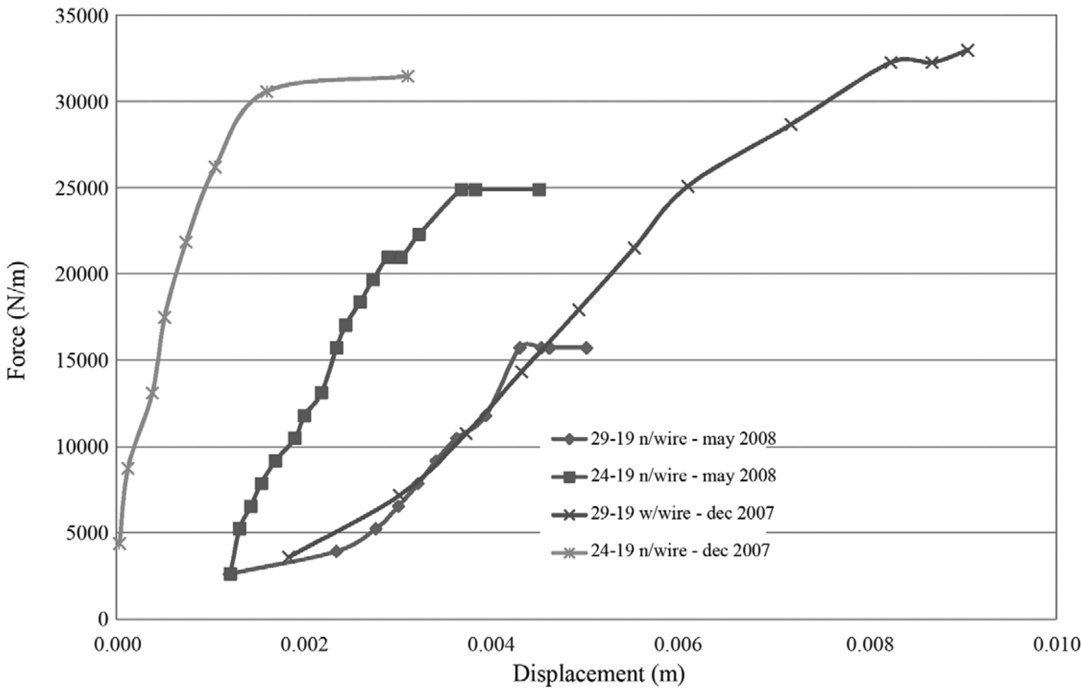

Figure 4 - Force/displacement for pullout tests.

curve (the unit is N/m/m), and the cohesive strength is the maximum force read in the test (the unit is N/m).

The grout stiffness for the test in a 24 mm borehole diameter is higher than the tests in a 29 mm borehole diameter, regardless of whether a steel wire is installed around the bolt or not. It is also possible to see that the grout stiffness is quite similar for the bolts with and with no steel wire around the bolt in a 29 mm diameter borehole. However, the cohesive strength is twice as much for bolts with steel wire around them. Table 2 shows the pullout tests results.

Numerical models were developed to simulate the pullout tests that were made in the field. The bolt and borehole specifications were considered in these models, and the models were also adjusted to grout stiffness and cohesive strength determined from the field tests. The numerical models were built using FLAC-2D version 5.0 of Itasca Inc., in which the models geometry is a rock block (laminated sandstone), and the rock bolt with the same specifications detailed in Table 1.

The results of the models suited the field tests very well, confirming the mechanical parameters of the grout for each test. Figure 5 shows the charts that compare the numerical models on pullout test simulations with the pullout tests made in the field.

The results from the numerical simulations were applied to the roof support numerical models at the entries intersection.

4. Roof Support Design

One of the challenges to underground coal mining is the roof support design for the entries intersections. The intersection dimensions (diagonals) are difficult to control due to the lack of mining operator control and pillar corners sloughed due to stress concentration. In this case, the diagonal dimensions can vary from 9 to 11 meters, instead of 8.6 m.

The roof support for the intersections consists of 2.2 m long roof bolts, while the entry height is about 1.8 m.

Table 2 - Results of the pullout tests.

Borehole diameter (mm)	Bolt diameter (mm)	Diff.* (mm)	Steel wire	Grout Stiffness (N/m/m)	Cohesive Stiffness (N/m)
29	19	5.0	Yes	3.95×10^6	3.2×10^4
29	19	5.0	No	3.60×10^6	1.6×10^4
24	19	2.5	No	6.78×10^6	2.5×10^4
24	19	2.5	No	2.37×10^7	3.1×10^4

*The difference refers to the distance between bolt and borehole wall.

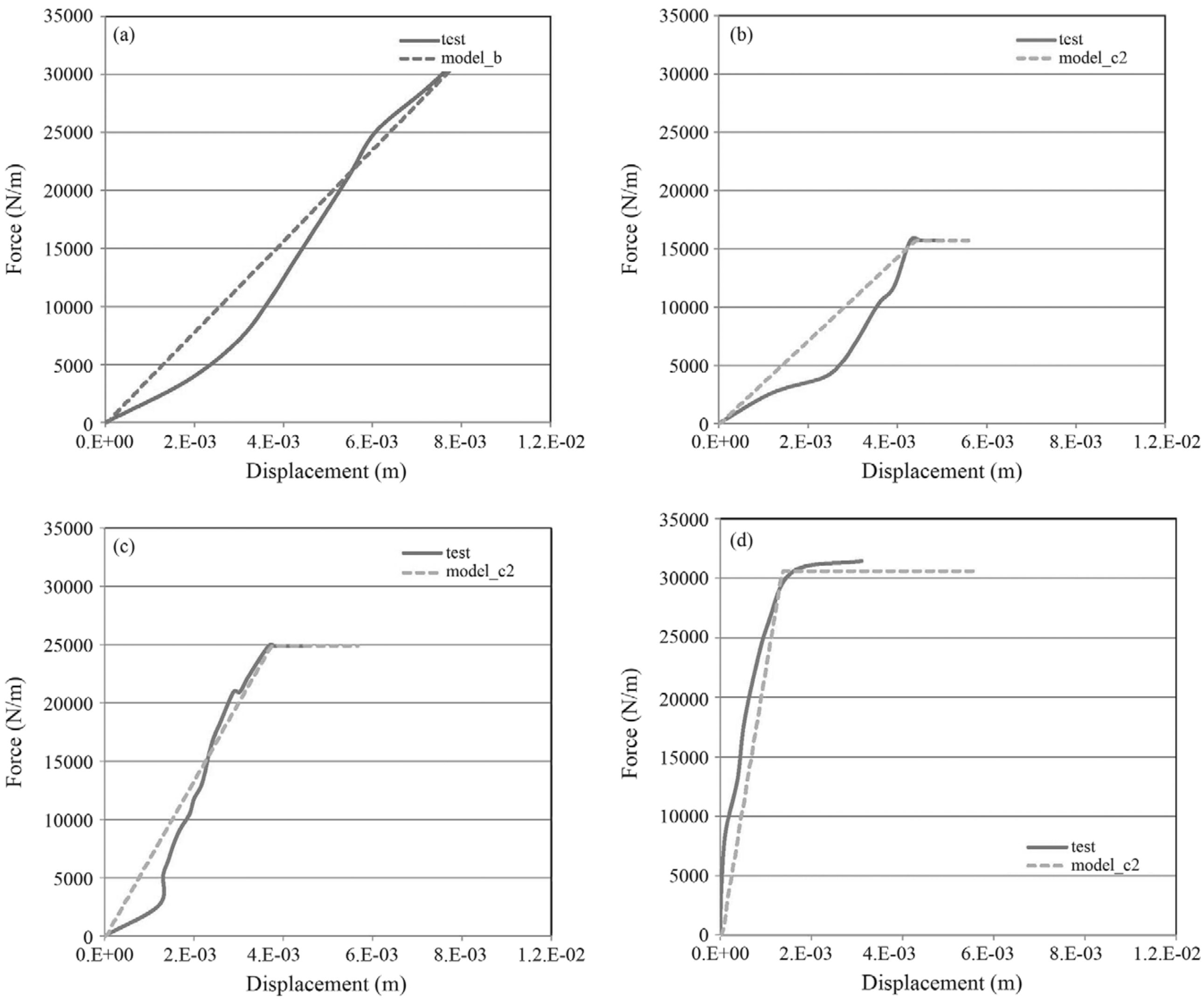

Figure 5 - Results of the numerical simulation for pullout tests compared to the field tests. (a) Borehole 29 mm and bolt with steel wire; (b) Borehole 29 mm and bolt with no steel wire; (c) and (d) Borehole 24 mm and bolt with no steel wire.

Bolt lengths longer than entry heights make roof bolt installation very difficult and impacts productivity negatively. Therefore, the challenge is to determine if a roof bolt length less than 1.8 m would provide adequate and safe support.

The new support design was taken into account using the empirical methods proposed to Unal (1983) and Bieniawski (1989), where the length of the roof bolt is calculated based on the load height in the immediate roof. For intersection roof support the diagonal dimensions must also be considered.

Considering the RMR (rock mass rating) for laminated sandstone (Table 3), and the maximum diagonal dimension (11 m), the support spacing was determined for roof bolts with 19 mm diameter and 1.8 m long. For this roof bolt dimension, the bolt spacing was estimated at 0.85m in the diagonal direction, which resulted in a safety

Table 3 - Material properties.

Rock	RMR	Young's Modulus (Pa)	Poisson's ratio	Internal friction angle (degree)	Cohesion (Pa)
Laminated sandstone	65	2.99E+10	0.17	35	8.00E+06
Massive sandstone	80	2.99E+10	0.17	20	5.00E+06
Siltstone	50	9.90E+09	0.25	15	1.80E+06
Coal	55	4.00E+09	0.25	15	1.40E+06

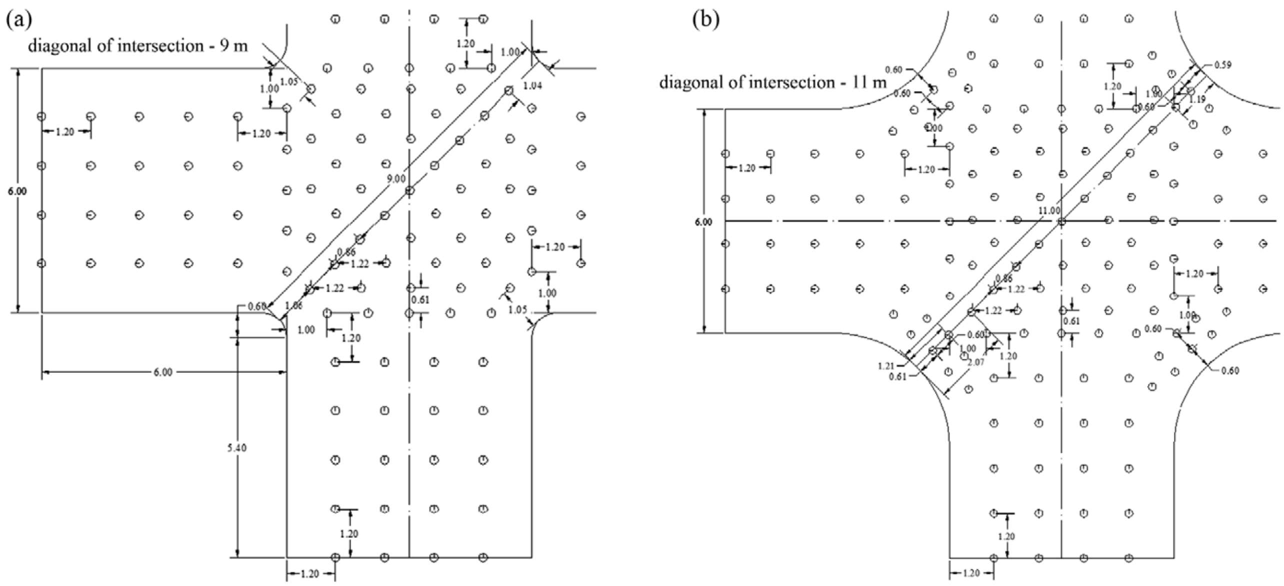

Figure 6 - New roof support design for intersection, considering 1.8 m long roof bolt for diagonal (a) 9 m, and (b) 11 m.

factor of 1.7. Considering the grout mixture and pullout tests, the borehole was designed for a 24 mm diameter. Figure 6 shows the configurations of roof support design for intersection diagonals of 9 and 11 m.

A monitored intersection test was established with instruments to evaluate the roof convergence with the intention of determining whether the new roof support design would eliminate separation above the roof bolt support horizon. For comparison purposes , another intersection was instrumented and evaluated, which utilized the traditional support systems so the convergence between two roof support designs could be compared.

Figure 7 shows the readings of the convergence at the center of the intersection for the two monitored intersections, which the anchor depths in the roof of the instruments are 1.5 m (5 ft), 3.0 m (9.8 ft), and 4.5 m (14.7 ft). The charts shows that both intersections reached equilibrium, and there werent any problems with roof stability.

It can be observed that the extensometer anchor 4.5 m above the roof has more convergence than the other two extensometers for both roof support designs. This happens because the extensometers are anchored in the siltstone layer (Fig. 1). The two anchor depths (1.5 and 3.0 m) are in the laminated sandstone layer.

The charts show different roof convergences, in which the current roof support gets less convergence than the new roof support design, and it also reached equilibrium in shorter time. There are two hypotheses for this behavior: (i) the beam built by the used roof support is stronger than the new one because the roof bolt is longer (2.2 m), or (ii) the time elapsed between the intersections excavation date and the beginning of monitoring were different for both.

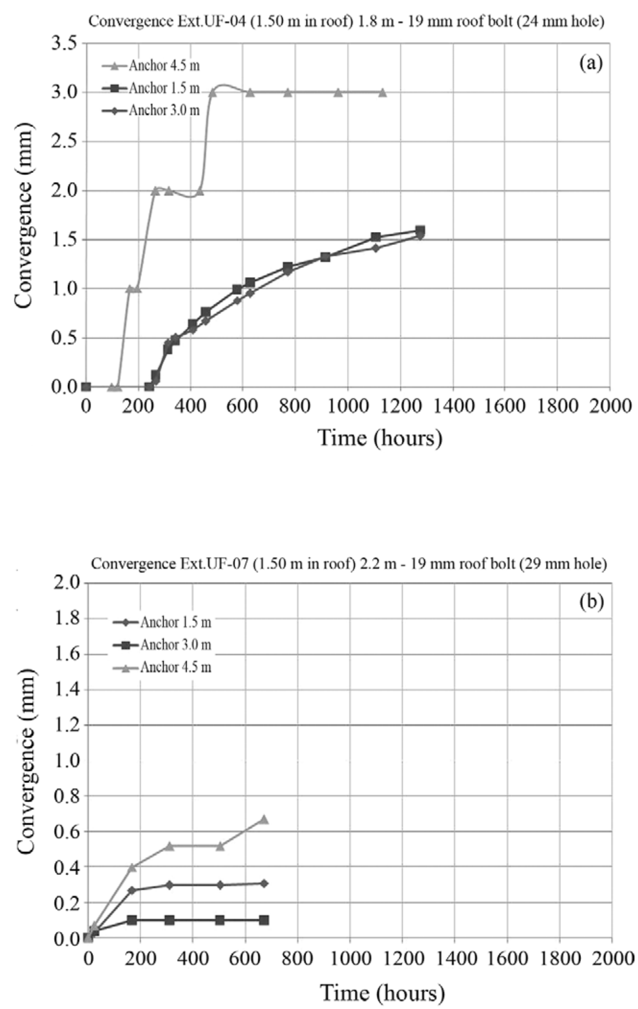

Figure 7 - Roof convergence for (a) new roof support design, and (b) old roof support design.

Numerical models were built to check which of these hypotheses is more reasonable. These models were 3-D models of an entry intersection.

These models were built using the design geometries of the entries and intersections, which were 6 m wide and 1.8 m high. The geology and material properties are based on Fig. 1 and Table 3, respectively. The initial stress field considered that the horizontal and vertical stresses are the main stresses with a stress rate of one, and the depth of the coal seam is 150 m.

Table 4 shows the vertical displacement of the immediate roof, and 1.5 m (5 ft) into the roof, which is the same depth of the extensometer anchors of the monitored intersections. Figure 9 shows the vertical roof displacements for the roof with no installed support.

The vertical displacements at the immediate roof at the intersections center are 6.42 mm (0.25 in.) and 6.80 mm (0.27 in.) for new and traditional roof support, respectively. The new roof support design had less vertical displacement than the traditional roof support, but the difference is minimal. Therefore, the difference that was observed in the field monitoring was most likely caused by the second hypothesis; the time differences between the installed instrumentation and subsequent development.

It must be emphasized that the difference between the in-situ monitoring and numerical modeling convergence happens because the in-situ convergence measuring does not suffer the deformation and the roof sagging right after the excavation of the intersection.

Table 5 shows the maximum stress that the grout and bolt are subjected to for the three roof support specifications (Table 1). The larger grout stress is observed when the resin annulus is smaller, as expected.

The grout stress for the 1.8 m (6 ft) long bolt is almost double than that of the 2.2 m (7 ft) long bolt, because the amount of bolt for 1.8 m (6 ft) bolt is less than for the 2.2 m (7 ft) bolts, and the annulus thickness of grout is also smaller (2.5 mm *vs.* 5 mm). Also, the bolt stress is much higher than in the 2.2 m bolts. However, no yield was observed in any of the examined bolts.

5. Conclusions

The objective of this work was to verify the influence of the annulus thickness between the bolt and borehole wall on the grout mixture and the effect of gloving; and also its influence on the grout properties and roof support quality.

The grout mixture and pullout tests showed that a smaller annulus thickness provided a better grout mixture and no gloving effects were observed. In this case study a 2.5 mm annulus thickness appeared to be enough to eliminate any adverse effects of gloving.

Operations staff should be warned that bolt installations can be adversely impacted by over drilling or when continuing to rotate the drilling steel after the adequate length has been achieved.

Therefore, the roof support efficiency in underground coal mining must take into account the quality of roof bolting installation operations, and also the quality of grout mixture.

Simple tests, like grout mixture and pullout tests can provide important information for roof support design and roof bolting operation installation controls.

The mining company is changing to the new roof support design, which will increase the bolting operation productivity, even with the number of additional bolts required in the intersections In the same way, the cost of the roof bolting operation will be reduced due to reductions in bolt borehole and bolt lengths and reduced resin usage. Additional savings will be achieved by eliminating the steel wire and the additional manufacturing required for coupled bolts.

Table 4 - Vertical roof displacement for the three roof support specifications.

Borehole and Bolt diameter (mm)	Bolt length (m)	Immediate roof (mm)	1.5 m in the roof (mm)
29-19	2.2	6.79	4.91
29-19 wired	2.2	6.80	4.91
24-19	1.8	6.42	4.89
No Bolt	-	6.82	4.91

Table 5 - Grout stress and bolt stress for the three roof support specifications.

Borehole and Bolt diameter (mm)	Bolt length (m)	Max. Grout stress (Pa)	Max. Bolt stress (Pa)
29-19	2.2	1.72×10^5	6.09×10^6
29-19 wired	2.2	2.13×10^5	7.52×10^6
24-19	1.8	4.06×10^5	2.22×10^7

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