Transaction Paper

Improving rockbolt installations in US coal mines

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Synopsis

The vast majority of the roughly 100 million rock anchors installed in mines in the USA each year use resin cartridges[1]. About 4.5 million of these bolts are installed using a mechanical shell in addition to the resin to create an active (pre-tensioned) bolt. Over 1 million of the bolts are passive cable bolts and typically have an effective grout length of 1.2 m, regardless of the cable length, which could be as long as 6 m. The successful performance of the resin grouted bolts depends on several parameters, including the annular gap between the bolt and hole wall, which should be relatively small, ideally from 3 mm to 5 mm. This requirement, combined with the high viscosity of the resin, produces a high back-pressure that can cause the bolt being installed to buckle or not be installed to standard. It is this back-pressure that limits the effective grout length with passive cable bolts and causes the mechanically anchored bolt failures (typically called 'spinners' where the mechanical shell does not anchor). This creates potentially unsafe conditions and wastes time and money. A purpose, built rig was used to mimic underground installations and record the back-pressures during full scale applications in the laboratory. This information was used, and is still being used, to reduce the failures and sub-standard installations by producing improved designs. In addition, a flow model was calibrated that can act qualitatively to estimate the back-pressures and can be used as a crude screening process before full scale prototypes are built and tested. To date, the results obtained have been used to stop the use of a mechanical shell due to the proven higher rate of failures. A new, improved mechanical shell is being field tested and another system is under development. The use of the rig is therefore ongoing to develop improved mechanical anchor systems. It is too early for real data; however, anecdotal evidence seems to indicate that significant improvements can and will be made.

Keywords

Rockbolt, performance, mechanical anchor, resin, underground support, annular gap, installation pressure, back-pressure, resin ports.

Introduction

Coal is key for energy production in the USA and is actively mined in 33 states. Approximately 90 per cent of this coal production is used to generate 50 per cent of the USA's electric power. Coal mining is responsible for over US $60 billion in annual revenue, and the industry directly and indirectly supports over 750 000 jobs in the US[2]. As Figure 1 shows, annual production has risen at a steady rate since 1960.

In 2007, about 1.15 billion short tons of coal were produced from 1 438 mines. 612 of these mines were underground operations, and they accounted for about 31 per cent of the total coal produced[3].

Underground mining is of more concern than surface mining when considering coal mine safety, for obvious reasons as roof and rib falls have the potential to cause serious or fatal injury to miners. The weak roof strata typically located above a coal seam are prone to skin failure, including massive failure in some cases. Over 1 500 roof falls occur every year in US coal mines[4]. In addition, however, the tight working conditions also make it easy for a miner to become pinned between a piece of machinery and the rib if proper safety procedures are not followed.

2005 was the year when the least fatalities occurred on the coal mines to date. In 2006, however, the coal mining industry was plagued by two major disasters; in January 2006 an explosion at the Sago Mine in West Virginia killed 12 people, followed in May 2006 by five miners being killed in another explosion at the Darby Mine in Kentucky. In August 2007, a further disaster occurred at the Crandall Canyon Mine in Utah in the form of a massive collapse, possibly caused by a coal bump, that resulted in nine miners being killed and a further three more fatalities during rescue operations.

As a result of these disasters, Congress rapidly passed the Mine Improvement and New Emergency Response (MINER) Act in 2006. The primary, relevant support-related provisions of this Act, according to the Mine Safety and Health Administration (MSHA), are:

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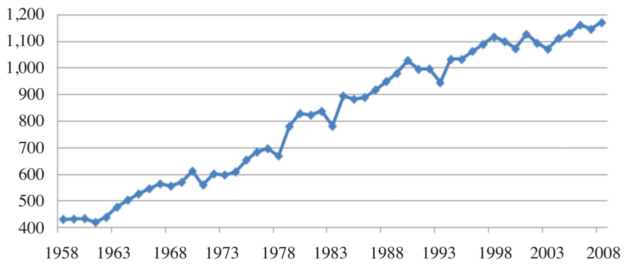

Figure 1—US raw coal production (million short tons)[1]

- Each mine must develop and continuously update a written emergency preparedness plan, which must be recertified by the MSHA every 6 months
- Mines must use equipment and technology that is commercially proven and available if it can improve safety
- Every mine must have 2 trained and experienced mine rescue teams capable of responding within 1 hour of an emergency if required
- Mine operators must report dangerous incidents and accidents to MSHA within 15 minutes or face fines of up to US$60 000
- The criminal penalty cap will be raised to US$250 000 for the first offence and a maximum civil penalty of US$220 000 for flagrant violations of safety regulations and standards
- Within 3 years, all mines must have wireless two-way communication and an electronic personnel tracking system in place
- The MSHA is empowered to shut down a mine that has refused to pay a final order penalty
- A scholarship fund will be created to help pay for the education of more mining engineers, mainly for MSHA.

According to the National Mining Association (NMA), a federal lobbying group representing many mine producers, the mines have reacted positively to this legislation. More than 150 000 new Self Contained Self Rescuers (SCSR) have been introduced; all main escape ways have lifelines; nearly 1 000 refuge facilities that can provide 96 hours of independent air have been commissioned or are on order; 45 new rescue teams have been or are being trained; and redundant communication systems have been installed.

One of the provisions of the MINER Act that does directly impact rock-related safety is that all unplanned roof falls must be reported to a central MSHA office by telephone within 15 minutes of being discovered. MSHA defines an unplanned roof fall as a fall that is at or above the anchorage zone in active workings where roof bolts are in use, or a fall (roof or rib) in active workings that impairs ventilation or impedes passage. This information is then relayed to the relevant MSHA district office, where a decision is made as to whether an investigation is justified and whether the area should be barricaded off to keep all personnel clear.

For the coal industry, MSHA is divided into 11 independent districts, all with a central district office in close proximity to the local coal mining areas. Most districts also have local offices, as each mine must be thoroughly inspected four times per annum by MSHA, aside from other routine visits.

Rock falls remain a significant concern in US coal mines, as illustrated in the Tables I and II.

Roof bolting is a required practice in all US coal mines. Support in US coal mines is generally classified as either primary support, secondary support, or supplemental support. Primary and secondary support are specified in each mines' roof control plan, which must be approved by MSHA. Primary support is generally rockbolts or anchors that are installed in the development cycle. Secondary support typically consists of cable bolts, trusses and/or standing support. Supplemental support is support installed in addition the primary and secondary support when conditions are worse than anticipated, due to weathering, for example, or for rehabilitation of an excavation.

Depending on the particular roof geology and the type and spacing of bolts used, the support provides skin control (key block support), suspension, beam building, or supplemental support (when cable bolts are typically used in intersections). The support density required is influenced by:

- The load bearing capacity of the bolts
- The length of bolts
- The bolt stiffness
- The roof strata and local geology
- The stress state
- The use of bolt ancillaries such as straps or screen.

Tang[5] states that immediate roof geologies can be divided into three types:

(A) The deflection of each stratum is larger than that of its overlying stratum, and each stratum deflects independently
(B) Some strata deflect more than the overlying stratum
(C) The deflection of each stratum is larger than or equal to that of its underlying stratum.

The immediate roof of case (A) is most critical to stability; therefore, an adequately designed primary roof bolting system is crucial. Additionally, the effect of axial loading due to horizontal stresses should be considered in the design of support systems.

The most commonly used bolt type in the USA is resin anchored rebar. A study[6] found that a strong shift in the coal industry's bolt preference has occurred in the last two

Table I

Fall-of-ground fatalities in underground US coal mines

Type of fall	2002	2003	2004	2005	2006	2007	2008	2009
Roof fall	4	2	3	9	7	3	4	2
Rib fall	0	1	1	0	3	9	0	1

Table II

Fall-of-ground injuries in underground US coal mines

Type of fall	2002	2003	2004	2005	2006	2007	2008	2009
Roof fall	249	211	216	457	430	442	381	324
Rib fall	65	49	61	90	100	86	106	86

decades, with fully grouted bolt usage increasing from 40 per cent to well over 80 per cent, and mechanical anchor bolts decreasing from 35 per cent to 8 per cent. A decreasing trend in roof fall rates has been observed during this shift in preference from mechanical to fully-grouted bolts, although there are many factors that may be contributing to this effect. Resin grouted rebar can be considered a far superior system to the mechanical anchor bolt because of the load transfer capabilities and the higher anchorage capacity per unit length, especially in weak strata.

Roof bolt systems are divided into two categories: passive and active bolts. Active bolts are tensioned upon installation, and can be anchored by either using a two-speed resin or a mechanical shell with resin. Passive bolts are un-tensioned on installation and are usually fully grouted with resin cartridges. Active bolts are typically used in laminated strata for 'beam building'. Active bolts using mechanical shells have two advantages over the two-speed resin cartridge option:

- In narrow seams, the forged heads used with the mechanical shell active bolts protrude less from the coal roof than the threaded two-speed resin system. This has obvious safety advantages.
- In long-term excavations, the bolts with forged heads are much less susceptible to long-term corrosion than threaded bolts.

Intersections are of particular concern regarding roof stability because the span across the diagonal is large, typically 40 per cent more than the room width. The diagonal span can be even larger if the pillar corners are rounded or incorrectly edged during their development, or if the pillar corners are damaged due to stress. Approximately 71 per cent of all roof falls occur in intersections, even though they account for only 20 to 25 per cent of the total development, so a fall is 8 to 10 times more likely to occur in an intersection than an entry on a unit length basis. Numerical modelling and statistical analysis have shown that although four-way intersections are 1.28 times more likely to fail than three-way intersections, it takes two three-way intersections to replace a single four-way intersection. This makes the potential remedy of replacing three-ways with four-ways ineffective in reducing the total number of roof falls in these areas[7].

Problems can arise because primary rock anchor systems are not successfully installed 100 per cent of the time. With a mechanical shell and resin bolt, the result of a failure is either a non-tensioned bolt (commonly referred to as a 'spinner') or a totally failed installation that requires another complete installation. The spinner is often the result of a damaged anchor shell leaf. Both these results are undesirable because they create potentially hazardous conditions and increase support costs. It has been estimated[8] that around 2 per cent of the resin bolts with mechanical shells are not installed correctly. Based on the annual usage, this represents about 90 000 bolts.

When any rockbolt is installed through resin cartridges, the effect is the creation of a high back-pressure that can be significant and can create failures, especially when a mechanical shell or cable bolt is used. For optimum resin mixing and performance, a small annular space is needed between the bolt and the hole, typically less than 6 mm (ideally about 4 mm). After the hole is drilled, the correct volume of resin in cartridge form is inserted in the hole and the bolt is inserted, using the roofbolter chuck, through the resin to the back of the hole; the bolt is then spun to mix the resin for the specified time. If the bolt is passive, it is then held motionless until the resin has set and the chuck is lowered, leaving the bolt in place. If the bolt is active and a mechanical shell is used, the spinning to mix the resin also locks the shell in place, so the roofbolter stalls at the maximum torque set on the machine as the mechanical shell locks. A typical twin boom roofbolter is shown in Figure 2.

Secondary support is installed mainly in intersections because of the larger effective span. The effective bond length with the resin is only 1.2 m, as mentioned earlier, because of the back-pressures and the flexible nature of the cable. These cables are installed essentially as passive supports, and attempts to fit a mechanical shell on the end of the cable have been unsuccessful because the increase in back-pressure cause the cables to bend and the insertion to fail.

Rockbolting materials and ancillaries in the USA are specified in ASTM F432[9]. The coal mining industry uses rebar with typical properties as listed in Table III.

The grade specified in Table III refers to the minimum yield stress in imperial units, as defined in ASTM F432. Therefore, by definition, a Grade 40 steel has a minimum yield stress of 40 000 psi (276 MPa).

The steel used for cable bolts is given in Table IV.

The cable bolts typically use bulbs ('birdcages') to assist with the resin mixing and final anchoring.

The research bolt installation testing apparatus

The causes of the back-pressure are complex and depend mainly on the annulus between the bolt and the hole, the resin viscosity, the fillers (both quantity and size), the cartridge skin, and possibly even the resin cartridge staples. A total installation failure occurs when the insertion back-pressure exceeds the buckling strength of the bolt, which typically bends before it is completely inserted into the hole.

Small laboratory test apparatus exists to investigate some aspects of resin bolt installation, but is not able to handle realistic bolt and equivalent resin lengths, so the results are mainly qualitative. In order to truly quantify the insertion problems, a custom designed apparatus was built at the Coal Research Center at Southern Illinois University Carbondale.

Figure 2—JH Fletcher twin boom rock bolter

Table III

Commonly used steel for rockbolting and the hole diameters used

Steel material (diameter and grade)	Minimum yield stress (MPa)	Recommended anchor hole diameter (mm)	Annulus (mm)
16 mm (#5 - ⅝ inch diameter) Grade 60	414	25.4	4.7
19 mm (#6 - ¾ inch diameter) Gr 40	276	25.4	3.2
19 mm (#6) Gr 60	414	25.4	3.2
19 mm (#6) Gr 75	517	25.4	3.2
22 mm (#7 - ⅞ inch diameter) Gr 40	276	28.6 to 34.9	3.3 to 6.5
22 mm (#7) Gr 60	414	28.6 to 34.9	3.3 to 6.5
22 mm (#7) Gr 75	517	28.6 to 34.9	3.3 to 6.5

Table IV

Cable properties and recommended hole diameters

Steel material (diameter and grade)	Minimum yield stress (MPa)	Recommended anchor hole diameter (mm)	Theoretical annulus (mm)
15 mm Gr 270	1862	25.4 to 34.9	5.2 to 10.0
18 mm Gr 270	1862	25.4 to 34.9	3.7 to 8.5

This apparatus measured the back-pressures created when different rock bolts were forced through resin cartridges. The conditions create significant back-pressures, in the same way as a syringe does, especially since the resin mix is viscous. The resin component of an anchor cartridge has a viscosity range of typically 200 000 to 400 000 centipoise (mPa.s), about 200 000 to 400 000 times the viscosity of water.

Research[10] was conducted to understand and quantify the issues causing the failures, improve current designs, and try to establish design parameters such that the percentage of failures can be reduced significantly, thus improving safety and reducing costs.

The test apparatus (Figure 3) was designed to install 1.2 m rock anchors (cables or bolts) into steel pipes with nominal internal diameters of 25 mm and 35 mm, which are the typical hole diameters used in US coal mines for rock anchoring. The length selected is a common, effective resin grout length (especially for cable bolts) and it kept the overall height of the test rig within manageable limits based on the height available for the rig.

Figure 4 is a diagram of the hydraulic system for the test apparatus.

The cylinder is hydraulically powered and extended at a rate of 150 mm/sec. This is close to the actual installation speed used by a rockbolter underground. The maximum up-thrust capacity of the cylinder is 5.5 tons. The hydraulic power pack was borrowed from an old MTS load frame.

The installation distance was measured using a string potentiometer, and the insertion back-pressure was recorded as a voltage and converted to a load in the standard manner.

The test regime and procedure

The test procedure was simple and the results surprisingly repeatable. Where possible, the resin cartridges used were from the same batch, so that the viscosity was as consistent as was practical. A steel pipe, 1.2 m long with an internal diameter of either 25 mm or 35 mm (matching the bolt hole diameters drilled underground) is clamped in place, and the appropriate resin cartridge is placed in the tube. A bolt is fitted into the socket on the end of the insertion cylinder, and the cylinder is activated upwards, forcing the bolt into the

Figure 3—The test apparatus

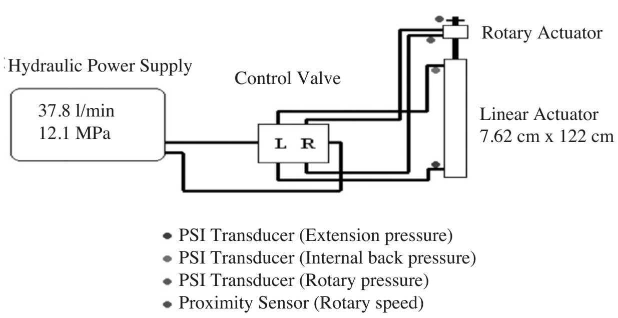

Figure 4—Test apparatus hydraulic schematic

steel pipe through the resin. After being fully inserted, the bolt can be rotated using the motor attached to the cylinder, as shown in Figure 5. This procedure closely mirrors the actual underground bolt installation.

The following tests were carried out to quantify the parameters that influence bolt insertion through the resin and establish which combinations of mechanical shells and bolts install reliably:

- Number 5 and number 6 rebar in 25 mm holes (mainly to calibrate the rig, check on the repeatability of the tests, and obtain an idea of the back-pressure magnitudes)
- Parameter testing (resin viscosity and annular gap)
- Mechanical shells with number 5 rebar in 25 mm holes
- Mechanical shells with number 6 rebar in 37 mm holes
- The back-pressures when inserting a typical cable bolt.

Based on the results from the procedures outlined, a new generation mechanical shell was tested that could improve the load performance, diminish installation back-pressures, and possibly even reduce production costs.

All tests were repeated at least once to help ensure reliable findings.

Results

Repeatability tests

Number 5 and number 6 rebar feature the most common diameters used in US coal mines. Figure 6 gives the insertion loads (back-pressure) results for the number 6 bars in a 25 mm hole with a standard resin.

It can be seen from Figure 6 that the results are repeatable and consistent. It is interesting to note that after about 1 m of bolt insertion (0.2 m from full insertion), the force required is over 1.6 tons. The bolt does not buckle, however, because of the short length remaining out of the hole and the resulting high effective buckling strength.

Since the failures are due to the back-pressures causing the rockbolt to buckle before it can be inserted into the hole, the buckling strength of the most commonly used rebar (number 6) was tested. Total installation failures where the rebar buckles during installation are less common than 'spinners', where the shell is damaged during insertion through the resin cartridge due to the pressure. The buckling strength of number 5 and number 6 rebar was measured at different lengths, and the results are given in Table V. The spread of results is significant and is mainly due to the fact that ASTM F432 specifies only a minimum tensile strength and not a range. This data can be used to design bolt systems using resin to reduce the likelihood of a total failure on installation. Such a failure would require an additional bolt to be inserted, wasting both time and money and potentially increasing the safety hazard.

In most US coal mines (except in the west coalfields), the rebar extends less than 1.5 m from the bolter chuck to the rockbolt hole in the roof, and the pressure on initial insertion is very low, as the cartridge is less than the hole length (designed usually to create a full column bond in the hole, taking account of the bolt volume).

Figure 5—The motor to spin the bolts after insertion

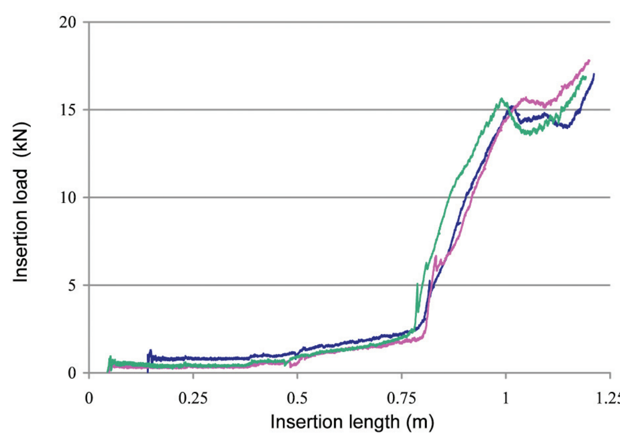

Figure 6—Repeatability tests with number 6 rebar, 1.2 m grout length in a 25 mm diameter hole

Table V

The buckling strength of rebar as a function of length

Rebar length (m)	#5 buckling load (kN)	#6 buckling load (kN)
1.1	7.1 7.8 5.5 Ave: 6.8	10.7 9.6 12.3 Ave: 10.9
0.9	8.1 8.7 9.9 Ave: 8.9	21.2 18.7 15.9 Ave: 18.6
0.6	18.4 23.2 28.2 Ave: 23.3	50.2 40.5 45.2 Ave: 45.3
0.3	64.7 55.4 62.9 Ave: 61.0	109.4 105.6 114.1 Ave: 109.7

The effect of resin viscosity

The effect of resin viscosity in 25 mm diameter holes, using number 5 and number 6 rebar, is shown in Figures 7 and 8. Resin cartridges normally have viscosities between about 250,000 cps and 450 000 cps. To extend the viscosities tested, some expired cartridges were found with a very high viscosity. The results are of interest because the back-pressure increases with increasing viscosity to a certain level, and then tends to reduce. The reduction in back-pressure when using the extremely high viscosity resin (900 000 cps) was not an intuitive result and all the tests were repeated at least twice. This result is difficult to explain and is probably due to the relatively coarse limestone fillers, which make the flow properties of the resin cartridge mix more complex.

It is apparent from these tests that the resin viscosity alone is not a major contributor to the installation back-pressure.

The effect of resin ports

The annular gap is half the gap between the diameters of the bolt and the hole. The gap is also considered to be an important parameter affecting the back-pressure on installation. When mechanical shells are used, the gap between the mechanical shell and the hole is clearly the limiting factor. The dimensions of the shell plug are dictated by the performance requirements of the shell. Therefore, the only way to make additional passage for the resin is by machining flow grooves (referred to as resin ports) in the shell plug. Resin ports in a mechanical shell plug are critical to the successful installation of bolts with mechanical shells through resin because they increase the effective flow cross-sectional area for the resin during installation. The effect of the resin ports in shells had not been quantified in the past.

Figure 9 shows the plugs used to establish the effect. The first set of plugs had no resin ports, the second was a standard commercially available design with six resin ports and the third set had twelve resin ports to try to facilitate the resin flow around the shell.

Three tests were undertaken for each plug design (without the leaves) using 1.2 m of equivalent resin from the same resin batch in a 37 mm internal diameter hole (steel pipe). Each plug design was tested three times to ensure consistent and repeatable results.

Figure 10 shows the results, and the difference in the insertion pressures is dramatic. Basically, effective resin ports are essential for successful installations using mechanical shells. The plug without resin ports failed each time during installation (this means that the insertion back-pressure exceeded the buckling strength of the bolt and it bent). The shells with the 6 resin ports had insertion loads above 8.8 kN and peaked at 15.7 kN. In contrast, the insertion loads using the 12 resin ports had loads generally below 9 kN with a peak of about 10.8 kN.

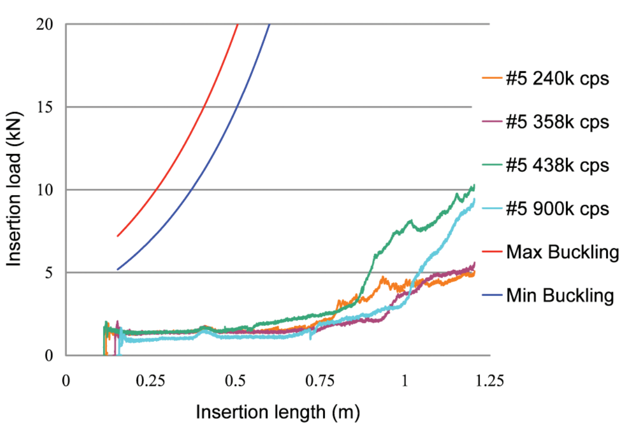

Figure 7—The effect of resin viscosity with number 5 rebar in a 25 mm hole

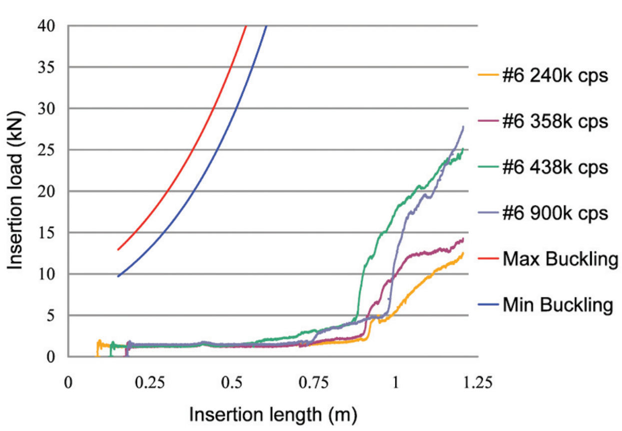

Figure 8—The effect of resin viscosity with number 6 rebar in a 25 mm hole

Figure 9—The plug tests for resin port quantitative assessment

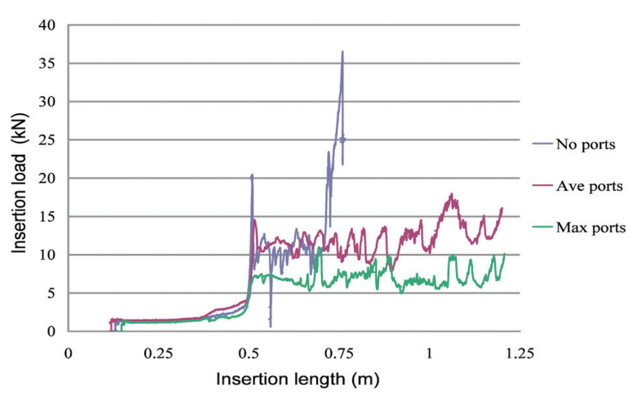

Figure 10—The effect of resin ports on insertion pressures

Resin ports are therefore considered the key to reducing the installation back-pressure and improving the bolt installations.

Mechanical shells with #5 rebar in 25 mm holes with resin

The two commercially available 25mm shells were tested and Figure 11 shows the results. Only one of the shells is suitable for use with resin cartridges, as shell B caused the number 5 rebar to buckle during installation.

Based on these results, shell B is no longer used with resin in rock bolting, and is used only as a mechanically anchored temporary rock bolt now.

Mechanical shells with #6 rebar in 37 mm holes with resin

Most of the mechanical shells used in US coal mines are installed in holes with a diameter of 37 mm. Not all commercially available mechanical shells perform in the same manner, and certain designs appear more satisfactory than others when used in combination with resin cartridges, as shown in Figure 12. Of the five commonly available designs, only four were consistently successful with different insertion loads. Clearly the lower the insertion load the better, given that once installed, all the shells provide an effective pre-load as designed, based on *in situ* tests.

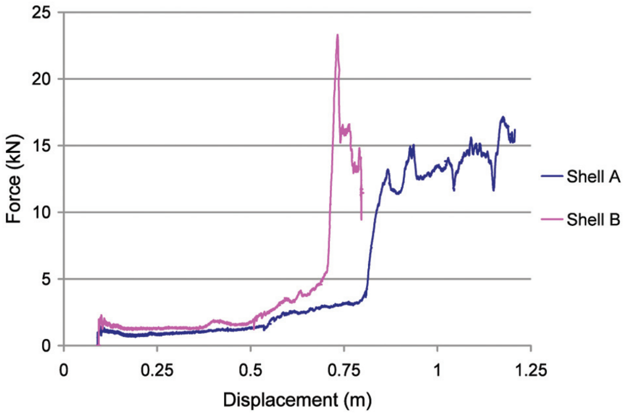

Figure 11—Performance comparison of mechanical shells with number 5 rebar in 25 mm holes

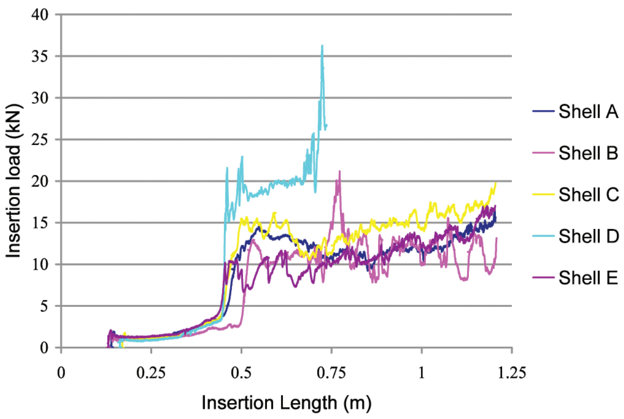

Figure 12—Insertion back-pressures with different shells and number 6 rebar

Figure 13 shows the buckling strength of the number 6 rebar and the insertion back-pressures obtained using the different mechanical shells. The reason for the failure is apparent from the photograph. Other designs should be improved because underground, the bolter and hole are not always properly aligned, and this reduces the effective buckling strength range of the bolt, as given in Table V.

It should be noted that the buckling strengths used in Figure 13 are higher than the effective buckling strength during an installation in a hole. During a bolt installation, only the one side of the bolt (in the bolter chuck) is fixed; the other has some freedom in the hole, permitting non-axial loading, which will significantly reduce the buckling strength of the bolt.

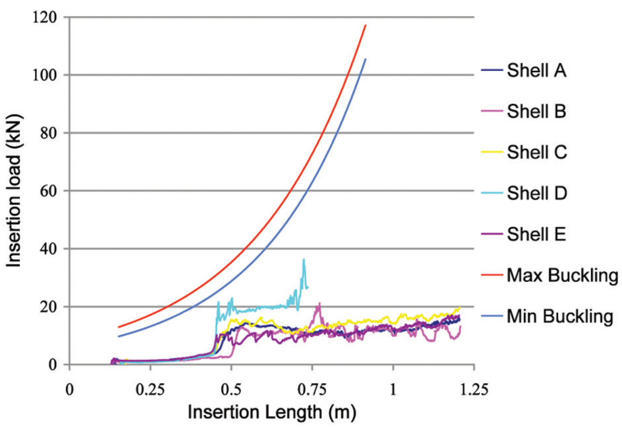

Figure 13—Insertion loads and number 6 rebar buckling strengths

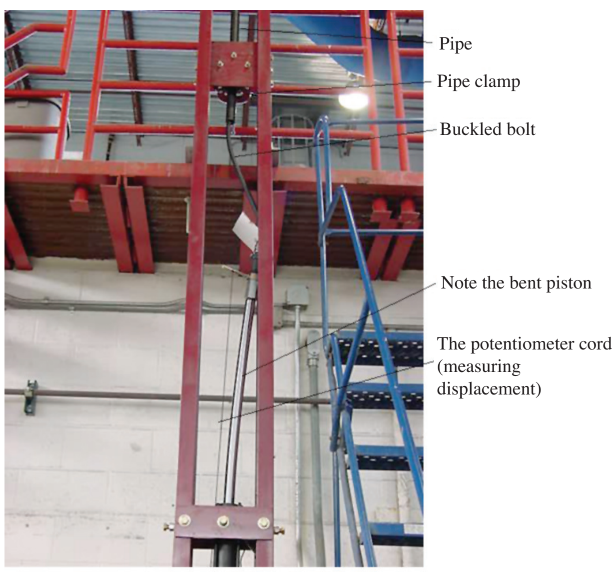

Figure 14—The failed installation using shell D (result shown on Figure 13)

Improving rockbolt installations in US coal mines

Cable bolt installation

Due to high back-pressures, cable bolts are difficult to install if full column grouted. This fact has led to the current US industry standard of using a 1.2 m equivalent bond length, regardless of the cable bolt length. Cables are clearly weak under buckling conditions; hence the need for the stiffener tube and the 1.2 m bond length. Using this test rig, methods to reduce the back-pressures can be investigated, and this would permit longer resin bond lengths if technically required. Figure 15 shows the results for 15.2 mm diameter cable bolts with one and two birdcages in a 25 mm diameter hole. The appropriate resin viscosity for cable bolts with a 1.2 m effective bond length (as recommended by suppliers) was used.

Mechanical shell optimization

Frazer and Jones (www.frazerandjones.com) is the only significant iron foundry in North America still producing mechanical shells for bolts.

A direct result of this research has been the development of an improved mechanical shell by Frazer and Jones that has the potential (once completely field-tested) to improve performance, reduce insertion loads, and maintain or possibly reduce the cost. Figure 16 shows the results to date, but as the design is 'patent pending', an illustration is not included. It is interesting to see from the graph that during insertion, the viscous drag (hence, load) declines, which should reduce the percentage of failures during installation.

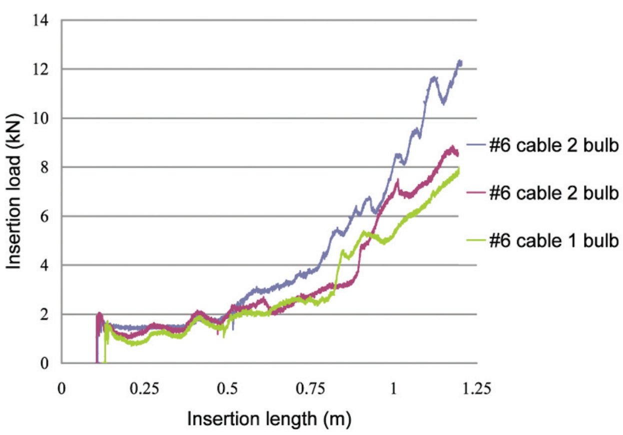

Figure 15—Insertion loads for 15.2 mm diameter cable bolts in a 25 mm hole

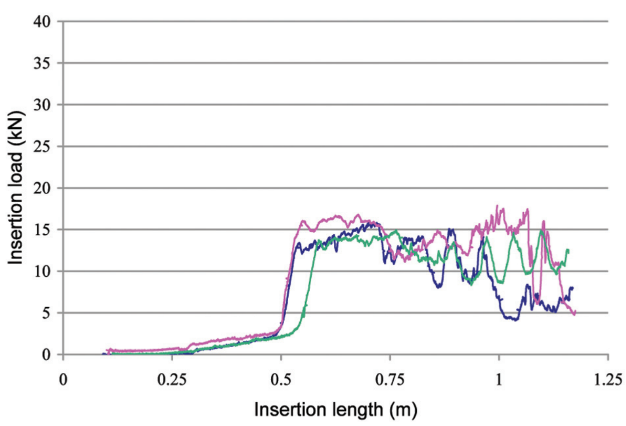

Figure 16—Insertion loads of the first improved shell prototype

Computer flow simulation

The production of prototype shells for testing is time consuming and costly. It was therefore desirable to try to use a computer flow simulation package to act as a screen to isolate those designs that appeared to have more potential (i.e. produce lower insertion back-pressures).

FloXpress (from Solidworks) was used to simulate the insertion loads qualitatively with the resin port tests (the details of which are shown in Figures 9 and 10). The effect of the resin grooves is an increase in the equivalent hydraulic diameter of the annulus. The velocity streamline plots produced by simplified Newtonian flow analysis (water) illustrate the pressure gradients where velocity is high; hence, pressure is high and pressure affects velocity in the reverse manner as well.

The two-component polyester resin cartridges appear to behave as pseudo-plastic, non-Newtonian fluids. It is difficult to simulate flow, as the back-pressure during installation depends not only on the geometry and resin fluid flow (viscosity, etc.), but also on the resin cartridge material, which contains the resin and catalyst mixes, the component ratios, and even the cartridge clips.

Using this simple program, the relative resin velocities around the mechanical shell plug are as follows, assuming the same arbitrary volume flow rate of 295 cm³/s. The pressure and the insertion force are directly related to the velocities calculated by the flow simulation package. The relative maximum flow rates around the plug were modeled to be:

- No ports—maximum velocity 2.5 m/s
- Average ports(6)—maximum velocity 1.9 m/s
- Maximum ports (12)—maximum velocity 1.7 m/s.

The lower flow rate indicates less resistance (i.e. more volume or gap for the same overall flow rate).

The simulation results followed the actual back-pressures qualitatively, and this simulation has been used to conduct preliminary screening tests on designs before making prototypes for actual testing. This saves time and money in the product development process.

Comparing actual tests with the test rig (utilizing the plug only), the increasing insertion load using the complete mechanical anchor (plug and leaves) seems to indicate the presence of fluid or viscous 'drag'.

Fluid drag is probably a major factor as well, especially when the whole mechanical shell is considered. Fluid drag has three components: pressure drag (normal force acting against wedge advancement), viscous drag (fluid friction in annular area), and hydrodynamic drag (resulting from shape of object/anchor within the flow stream).

The results were sufficiently encouraging for this type of analysis to be used in preliminary design optimization before prototypes were made for actual testing in the rig. It is believed that with further simulations and calibration, the results may become a quantitative indicator.

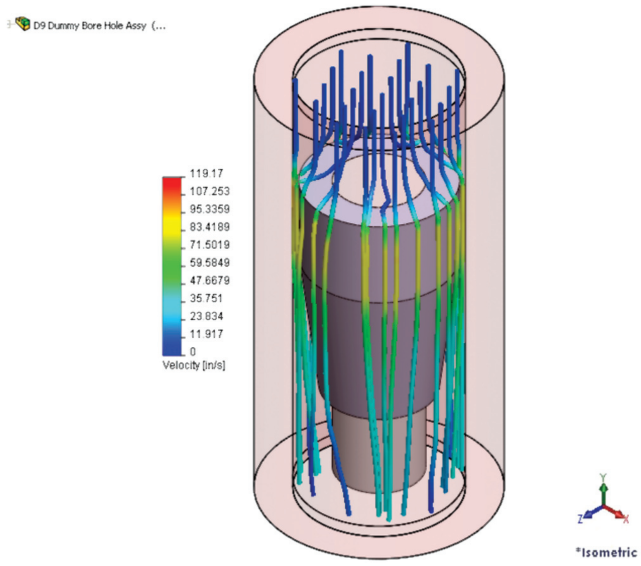

Figure 17—Flow model of the plug without resin grooves and with 12 resin grooves

Conclusions

The following conclusions can be made:

a) The research has been useful in that it has identified and quantified the main parameters affecting the resin insertion back-pressure; the effective annular gap and the installation speed, and has shown that the resin viscosity is not a major factor. Reducing the installation speed is not desirable, however, as in most coal mines, bolting is the production bottleneck and slowing down the bolt installation cycle is counter-productive.

b) The magnitudes of the insertion pressures associated with common bolt and resin combinations have been quantified, and this data has been used to identify the more effective mechanical shells that are commercially available.

c) The need for shell plugs with ports has been demonstrated, and a design using more ports has been tested and proven more effective.

d) A simulation fluid model/method for the better approximation or calibration of design variables and back-pressure has necessitated the use of a 'high-end' simulation package, for which refinement activities are continuing.

e) The test apparatus is also being used to investigate and optimize the pre-load, depending on the applied torque. To investigate this, a hydraulic motor that can rotate and tension the bolts during installation and record the rotational speed, number of revolutions, and applied torque has been fitted to the installation cylinder.

This research and testing should lead to fewer failures ('spinners' where mechanical shells are used) when installing cables or rebar with shells, and should reduce costs and improve safety.

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References

1. Tadolini, S. and Mazzoni, R. Understanding roof bolt selection and design still remains priceless. *25th International Conference on Ground Control*, July 2006. Morgantown, WV, USA. 2006. pp. 382–389.
2. US Energy Information Administration. *Annual Coal Report*. DOE/EIA-0584. 2008.
3. US Energy Information Administration. *Coal Mining Productivity by State and Mine Type*. September 2008. DOE/EIA-0584. 2008.
4. Mark, C. and Iannacchione, A. Ground control issues for safety professionals. *Mine Health and Safety Management*, 2001. pp. 347–367.
5. Tang, D. and Peng, S. Methods of designing mechanical roof bolting in horizontally bedded strata. *25th Symposium on Rock Mechanics*, 1984, Chapter 63. pp. 615–626.
6. Dolinar, D.R. and Bhatt, S.K. Trends in roof bolt application. NIOSH: Proceedings: *New Technology for Coal Mine Roof Support*, 2000. pp. 43–51.
7. Molinda, G., Mark, C., Bauer, E.R., Babich, D.R., and Pappas, D.M. Factors Influencing Intersection Stability in U.S. Coal Mines. *Proceedings, 17th International Conference on Ground Control in Mining*, July 2008. pp. 267–275.
8. Su, D. Personal communication. Consol Energy, 2008.
9. ASTM Standard F432. Standard Specification for Roof and Rock Bolts and Accessories, 2004. ASTM International, West Conshohocken, PA, DOI: 10.1520/F0432-04.
10. Spearing, A., Reilly, M., and Greer, B. The back pressures associated with resin rock bolt installations and methods to control and predict it. *28th International Conference on Ground Control*, July 2009. Morgantown, WV, USA. pp. 53–58. ◆