2009

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http://ro.uow.edu.au/engpapers/1843

Publication Details

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Geotechnical Assessment of Skin Reinforcement in Underground Mines

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ABSTRACT

Steel mesh has been used successfully for many years to control friable roof conditions and prevent loose roof and rib material from caving into the roadway. Despite its extensive use, the installation of steel mesh is difficult to automate and many other products have been evaluated as an alternative for skin control. Ideally, the properties of these new products should be similar or better than those of the steel mesh. In particular, development of a strong and resistant shell that minimizes movement along the fractured rock and coal surfaces between the bolt anchors is recommended. A strong surface adhesion and the strength of a reinforced polymer skin can provide the necessary toughening mechanism required to enhance roadway surface support by forming a reinforced polymer/rock surface layer. Most of the Thin Spray-on Liners (TSL) evaluated in the mines are weak with slow curing times, and the plastic mesh currently used to support the coal ribs is relatively weak. Therefore, neither material can seriously compete with steel mesh. Currently, a new polymer product that cures in seconds and forms an instantaneous strata binder that surpasses the properties of steel mesh is under development at the University of Wollongong.

INTRODUCTION

A primary goal of the project was to develop a suitable alternative to steel mesh for roadway skin reinforcement; the application of which can be fully automated together with a suitable bolting system. A number of polymeric materials have been investigated and several have been identified as having suitable properties for roadway skin reinforcement.

As movement occurs in underground strata, stress redistribution and deterioration of the roadway skin may be experienced. The ability of a fibre-reinforced polymer skin to carry these loads is a key to effective reinforcement of the mine roadway. A number of key parameters have been identified that can significantly contribute to effective strata skin reinforcement, including high mechanical strength, excellent adhesion to rock/coal surfaces, flexure properties and toughness. The polymer-based system under development at the University of Wollongong and its typical properties, are described in this paper.

PRINCIPLES OF EFFECTIVE STRATA REINFORCEMENT

It is not possible to prevent the formation of mining induced fractures that initiate at some distance from the roadway, but it is possible to improve roadway skin conditions by early application of a polymer skin at the roadway face. Excessive skin failure usually develops when secondary strata movements take place at the roadway surface. The fractured rock mass in its undisturbed phase is relatively stiff while confined by compressive stress. However, loss of ground confinement results in roadway skin softening, bulking and subsequent strata movement into the mine opening. In general, most of the displacement-induced fracture surfaces are of an irregular nature, and excessive displacements along such fractures can cause significant dilation, driving yielded strata into the mine opening. It is common knowledge that reduction of strata movement is desirable for ground stability; therefore, early strata reinforcement measures are essential to minimize roadway skin displacement.

Historically, wooden props, sprags and arches were used to provide strata control of low stiffness that allowed large roof and rib displacements before resistance to movement occurred. Such low stiffness support could not provide effective strata control, and large amounts of support were required in order to control severe ground conditions. These systems resulted in slow mining advance and expensive labour intensive support systems that would not be suitable for today’s modern high production mines.

Modern strata reinforcement of very high stiffness evolved over time with fully encapsulated high capacity steel bolts currently used as the primary roadway reinforcement, while the cable bolting systems are used as the secondary reinforcement of severely deformed ground. High capacity roadway reinforcement provides significant resistance to fracture movement whether in shear, tension or dilation. Today’s reinforcement systems ensure high strata confinement characteristics, reduced ground movement and, therefore, superior ground stability in adverse roadway conditions.

Although the success of steel bolts in ground reinforcement is undisputable, skin reinforcement of the mine roadways has not yet been optimized. Current roadway skin support utilizes steel mesh to control friable roof conditions, but as with the old wooden prop
system support it is purely passive in nature. The steel mesh is primarily used to prevent loose roadway skin material from caving into the roadway.

**ROCK FRACTURE MECHANISMS IN UNDERGROUND ROADWAYS**

Mining induced fractures occur ahead and adjacent to the roadway mining face where the stresses are high. These fractures gradually grow, forming a typical fractured roof as illustrated in Figure 1. The shear or tensile fractures develop in response to the stress change adjacent to the mine opening while bending of bedded strata will result in shear failure along the weak bedding planes. It is impossible to prevent the development of mining induced fractures. However, it is possible to minimize the movement of the rock resulting from the fracture development.

![Figure 1. Typical roof conditions in a mine roadway requiring skin reinforcement.](image1)

For an effective roadway skin control, it is desirable to apply a stiff reinforced coating to the strata at an early stage of the mining process. The fibre-reinforced polymer provides a tough and durable skin, minimizing fracture propagation both within the skin itself and in the surrounding rock.

In fractured strata, gradual displacements reduce the compressive stress until equilibrium is reached. The remnant compressive stresses within the strata must provide enough confinement to arrest any further movement along the fractures. If the strata are severely broken and the compressive stresses are totally dissipated (as is often the case adjacent to the roadway), strata will lose their self supporting capability and disintegrate. Typically, displacements will accelerate when the fractured rock mass is stress free. Just prior to a fall, accelerated fracture displacements and fragment rotations may occur that will “unlock” the rock structure and eventually cause the yielded rock zone to fall. For this reason even a small confining stress may be enough to arrest significant rock displacements and subsequent falls of “loose” rock material. An inadequately supported roadway surface can slowly deteriorate and affect the ground stability between the bolts, as illustrated in Figure 2. Ideally, it is the function of the reinforcing members, such as the rock bolt together with the appropriate skin reinforcement, to prevent the last phase of rock de-fragmentation between the bolts.

![Figure 2. Partial roof failure between bolts compromising roof stability.](image2)

**COMPARISON OF THE POLYMER SKIN REINFORCEMENT AND STEEL MESH SUPPORT**

The fundamental difference between the polymer skin and the steel mesh support is similar to the difference between a point anchor and a fully encapsulated bolt system. A fully encapsulated bolt provides immediate resistance to any fracture movement via its continuous anchorage to the surrounding strata, while the point anchor bolt without pre-tension needs to stretch significantly over its entire length to provide comparable strata confinement. The reinforced polymer skin bonded to the strata surface provides immediate resistance to any crack movement that occurs at the strata surface, while the steel mesh will support the strata only after significant roof deformation occurs. Adhesion of the reinforced polymer skin to the strata provides a stiff reinforcing mechanism to complement the fully encapsulated bolt reinforcement system, and contributes to the overall stability of strata adjacent to the mine roadway. If the strata are severely broken before the polymer skin is applied, the polymer will provide a stiff restraint to excessive strata movement.

**EXPERIMENTAL MEASUREMENT OF POLYMER SKIN BEHAVIOUR**

To study the fibre reinforced polymer properties and its influence on strata skin reinforcement, several laboratory tests were designed and conducted. These include polymer adhesion normal to the rock surface, flexure, and shear strength along the polymer-rock interface.

**Normal Adhesion**

The laboratory data indicate high adhesion strength of the polymer skin to various types of coal and rock. To simulate the in situ strength between the polymer skin and the excavation surface, a test was designed (shown in Figure 3) whereby the polymer sample bonded to the rock surface is pushed directly away from the rock surface. The rock surface is cut with the diamond saw and a 30mm hole drilled in the centre of the rock surface. The reinforced
polymer 100x100mm in size is cast onto the flat rock surface and force applied onto the polymer through the hole until the polymer disbands from the rock surface.

Figure 3. Adhesion test method.

A number of coal and rock surfaces were prepared in this way and the adhesion of the polymer to the rock was tested. To study how the pH influences polymer bonding strength a number of coal surfaces were treated to change their pH. The results are summarised in Figure 4 and Table 1 below.

Figure 4. Laboratory tests of polymer adhesion to the coal and rock surfaces.

The laboratory results indicate that the polymer adhesion to rock surfaces is substantial and can provide a significant reinforcing component to the rock skin. When testing polymer adhesion to coal (Figure 4a), in all test cases the failure occurred within the coal and not at the bonded surface. It can be assumed that in all tests the polymer bond to the coal surface was greater than the tensile strength of the coal sample and was equal to approximately 4 – 6.9 tonnes/m². The pH or water saturation did not seem to influence the polymer bond. The test showing the polymer adhesion to sandstone (Figure 4b) indicated a higher tensile strength of the bond of approximately 10.3 tonnes/m². However, failure occurred at the rock/polymer interface. Further work needs to be undertaken to investigate the in-situ variations in adhesion strength that may occur due to the uneven nature of the roadway surface.

More tests are scheduled to verify the polymer adhesion to various rock surfaces.

Flexure

Flexure (bending) test was carried out in order to simulate the polymer’s ability to flex under an increasing load until total skin failure is experienced. The 3-point bend test was used to load a fibre reinforced polymer specimen of 5 mm thickness until failure occurred. The test arrangement is shown in Figure 5.

Maximum tensile stress at the polymer skin wall was calculated for the peak load value using equation (1).

\[ \sigma_{\text{max}} = \frac{3FL}{2bh^2} \]  

(1)

Where: \( F = \) applied force, \( L = \) length of the sample (110mm), \( b = \) width of the sample (13mm), \( h = \) sample thickness (5mm).

The laboratory polymer flexure test results shown in Figure 6a indicate that the non-reinforced polymer cannot sustain large loads or deformation and exhibits sudden and catastrophic brittle failure (at about 30 MPa for this particular sample). In contrast, the glass reinforced polymer can sustain a much larger load with greater displacement, gradually failing with an audible warning.

The aim of the tests shown in Figure 6b was to use flexure data to select the optimum polymer to be used for the skin reinforcement. The results indicate that various polymer products can be made to suit the mine support requirements. The ‘strong and tough’ behaviour of two samples shown in Figure 6b indicate the optimum selection of fibre-reinforced polymer that may be suitable for underground applications.

Shear Tests

The direct shear tests were designed to simulate the in situ shearing resistance of the polymer skin along the excavation surface. The test schematic, and an example of a polymer sample after testing, is shown in Figure 7. Several carbonaceous rock specimens with naturally polished surfaces, and sandstones with fractured planar surfaces, were collected for testing. A square (50 mm x 50 mm) polymer sample was cast onto the rock surface inside an aluminium frame in which was mounted a steel hook. The polymer sample was then loaded in shear by pulling on the steel hook imbedded in the sample (see Figure 7) and the failure load was recorded. To date only one sample has been successfully tested as most rock samples disintegrated during testing. This sample, a medium-grained sandstone, gave a maximum shear load at failure of 550 KPa.

Static Load Test

The deformation of a 1.0 x 0.8m piece of steel mesh consisting of a 5mm welded wire in 100mm square pattern and a 5mm thick
Table 1. Adhesion of polymer skin to rock surface – test results.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Rock surface description</th>
<th>Surface preparation</th>
<th>Max tensile Load (kPa)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Cut smooth surface</td>
<td>Dry &amp; clean</td>
<td>69</td>
<td>Tensile failure in coal</td>
</tr>
<tr>
<td>Coal</td>
<td>Cut smooth surface</td>
<td>Wet pH 1</td>
<td>48</td>
<td>Tensile failure in coal</td>
</tr>
<tr>
<td>Coal</td>
<td>Cut smooth surface</td>
<td>Wet pH 7</td>
<td>40</td>
<td>Tensile failure in coal</td>
</tr>
<tr>
<td>Coal</td>
<td>Cut smooth surface</td>
<td>Wet pH 13</td>
<td>40</td>
<td>Tensile failure in coal</td>
</tr>
<tr>
<td>Sandstone</td>
<td>Cut smooth surface</td>
<td>Dry &amp; clean</td>
<td>103</td>
<td>Rock-polymer bond failure</td>
</tr>
</tbody>
</table>

Figure 5. 3-point bending test of reinforcement polymer sheet.

Figure 6. Polymer skin flexure test results.

polymer skin sample of a similar size were compared under a one tonne load as shown in Figure 8.

Deflection of the fibre reinforced polymer mesh under the 1 tonne load was considerably smaller (20mm) than the steel mesh (35mm). In addition, 90% of the polymer sheet deflection recovered after the load was removed, while only 60% recovery was measured for the steel mesh.

Polymer Tensile Properties

In the search for a suitable roadway skin reinforcement, many unreinforced polymer formulations (dogbone samples 110mm long, 13mm wide and 5mm thick) were tested in tension and compared to the steel mesh. Since the continuous polymer sheet occupies a 25-fold greater volume than steel mesh of the same thickness, the overall properties of the steel were scaled down appropriately to represent the overall mesh strength. The strength vs strain results are shown in Figure 9. A sample under test is also shown. It can be seen that a wide range of polymer properties can be obtained. The figure also shows the strength of steel mesh for comparison. This comparison was conducted as an initial screening test, allowing the
Figure 8. Deflection of reinforced polymer sheet and steel mesh loaded with 1 tonne of bricks.

selection of a small number of polymer formulations for further investigation.

Figure 9. Polymer and steel mesh testing procedure and tensile strength test results.

CONCLUSION

The above investigations indicate that a reinforced polymer may provide a strata skin reinforcement system superior to the currently used steel mesh. Benefits of the polymer skin can arise from the ability to adhere well to rock/coal surfaces and provide significant early resistance to strata displacements and fracture opening. The adhesion is not negligible and would have a positive influence on the overall roof support. The reinforced polymer skin is fundamentally a different type of support to the passive steel mesh, providing resistance to any small movement as soon as movement begins to occur. The localized de-bonding of the polymer from the rock surface during fracture movement is unavoidable and may not significantly disturb the polymer reinforcing capabilities.

The tough nature of the polymer mesh will resist even the severe strata displacements in a manner similar to that of steel mesh, while the reinforcing fibre will give an audible warning of imminent failure reminiscent of the sound made during yield of the old wooden prop system.

Further benefits of the polymer skin include automated application where continuous or intermittent applications of polymer skin of various thickness and patterns are possible. The polymer skin can be applied on the roof and rib strata close to the working face or as required. The fully automated fast setting polymer application can be incorporated together with the automated bolting system with the aim of speeding up roadway development and remove mine personnel from the working face area.

REFERENCES


