
Development of thin spray-on liners for underground rock support - an alternative to shotcrete?

DIE ENTWICKLUNG VON DÜNNEN, SPRITZBAREN BESCHICHTUNGEN ALS FELSSICHERUNGSMÄßNAHME - EINE ALTERNATIVE ZU SPRITZBETON?

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Schnell abbindende, dünne, spritzbare, polymere Beschichtungsmaterialien als Ausbruchssicherung unterirdischer Hohlräume werden in Kanada und anderen Ländern geprüft. Dünne, polymere Beschichtungen liegen in ihrer Wirkungsweise zwischen jenen von Spritzbeton und Schutzgittern. Spritzbare, polymere Beschichtungen mit üblichen Schichtstärken von 3 bis 6 mm reduzieren im Vergleich zu Spritzbeton erheblich die erforderlichen Ausgangsmaterialmengen.

Einige der Beschichtungen härten innerhalb weniger Minuten aus, im Gegensatz zu Spritzbeton mit Festigkeitsanstiegen im Stundenbereich. Dünnschichtungen sind dort besonders vorteilhaft, wo rascher Auftrag und schnelles Sichern notwendig sind.

Die zukünftigen Herausforderungen liegen in der Entwicklung von Beschichtungsmaterialien mit höherer Zugfestigkeit zu niedrigeren Kosten.

Rapid setting, thin, spray-on polymeric liner materials for underground rock support are being tested in Canada and elsewhere. Thin polymer liners have performance characteristics that lie between those of shotcrete and wire mesh. Spray-on polymer liners are typically about 3 to 6mm thick, greatly reducing the amount of material needed to cover the excavation compared to shotcrete.

Some liner materials cure within minutes instead of hours for shotcrete. Thin liners have a role to play where rapid application and surface support of rock are needed.

Future challenges will be to develop liner materials with higher tensile strength and lower costs.

1. Introduction

Thin spray-on liners are a new form of rock support that is receiving increasing attention by various mines around the world. Various liner materials are currently being developed and tested in Canadian mines. They can all be generically classified as mul-

ti-component polymeric materials. Thin polymer liners have applications in hard-rock mines as a replacement for either wire mesh or shotcrete. They function well as the areal support component in a support system that also incorporates rock bolts.

This paper gives a historical overview of the development and testing of spray-on liner materials and

discusses various mechanisms by which thin liners function to support and stabilize underground excavations in rock. Important liner properties include the tensile strength and the adhesion to the rock, which control the liner's load capacity, and the ultimate strain, which controls the liner's displacement capacity. Various factors to consider when using thin spray-on liners, including advantages and disadvantages when compared to mesh or shotcrete are reviewed. Simple models are used to illustrate various support functions and important design parameters for thin liners. Finally, an example of thin liner use in a Canadian mine is presented.

2. Development of thin liner support

The installation of conventional rock bolts and wire mesh is labour intensive and time consuming. In addition, underground personnel are frequently injured while installing rock support. While the installation of rock bolts or other tendon support elements can be mechanized, mesh installation still requires manual labour. One method for overcoming some shortcomings of mesh is the use of shotcrete, in particular, steel fibre reinforced shotcrete. While the use of shotcrete rapidly gained acceptance within many Canadian mines in the 1990's there are still problems associated with the logistics of transporting large quantities of shotcrete materials to active headings far underground. In addition, it was noticed that deeper drifts in many Canadian mines underwent substantial deformations. These deformations exceeded the displacement capacity of the shotcrete rendering the shotcrete itself a hazard.

As an alternative to rock bolts and mesh or shotcrete, MIROC (Mining Industry Research Organization of Canada) began an investigation of rapid setting, thin, spray-on liner materials for ground support. The first tests on thin spray-on liner rock support technology were initiated in Canada in the late 1980's (Archibald et al. 1992). Initial research led to the development of a polyurethane based product called Mineguard™. Modifications to the chemical formulation of Mineguard and extensive laboratory testing continued throughout the 1990's (Archibald et al. 1997, Archibald & Lausch 1999).

In the 1990's, Canada's largest nickel mining company, INCO Ltd., embarked on a strategy to move toward robotic mining methods. The use of a thin spray-on liner for underground rock support offered INCO numerous advantages in terms of speed of application and minimizing transportation of materials. INCO thus became a key advocate of thin liner research and testing and sponsored numerous laboratory and field tests using Mineguard (Figure 1)

throughout the 1990's (Espley et al. 1995, 1996, Espley-Boudreau 1999, Tannant 1997, Tannant et al. 1999). In the late 1990's, these tests also included a new product based on a hybrid polyurethane/polyurea mixture called Rockguard.

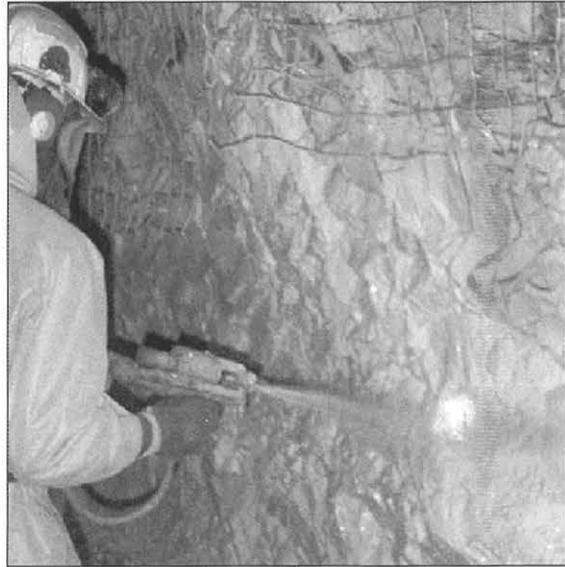


Fig. 1: Manual application of a thin polyurethane (Mineguard) liner to rock

Meanwhile in 1996, researchers from South Africa began exploring the use of another thin liner product that was latex-based. This product was known as Everbond (Wojno & Kuijpers 1997) and has since evolved into another product called Evermine. Researchers in Australia have also been exploring the use of thin liners for rock support and have conducted field tests in Western Australia.

By the mid to late 1990's news of spray-on liners being used in Canada's hard-rock underground mines reached many other interested manufacturers and vendors of a wide variety of spray-on products. Falconbridge Ltd. (another large Canadian mining company) began its own research effort to find appropriate liner materials. While many products were tested, it was found that most did not possess adequate physical or chemical properties. One product called TekFlex (a water-based, polymer modified cementitious material) was found to show promise and field trials of this material were initiated in cut and fill stopes (Pritchard et al. 1999, 2001).

New products are in the development and testing stages. These include a polyurea-based product called RockWeb and a methacrylate-based product called Masterseal 840R01 or Superskin (Spearing & Champa 2000). As of 2000, there are about six different manufacturers of spray-on materials for thin liners that are competing in the market for underground rock support in Canada. Currently about

55 mines around the world are considering the use of thin liners for rock support. The greatest interest is in North America, Australia, and South Africa. Given that thin liner technology is still in its infancy, it is likely that other products will come forward for testing and evaluation.

3. General characteristics of liner materials

Shotcrete, polymer liners, and steel mesh mobilize support resistance at different displacements. Materials that are sprayed onto the rock such as shotcrete or liners are able to generate support resistance at small rock deformations (in the order of millimetres). Mesh is a truly passive support and requires substantial displacement (in the order of 100's of millimeters) before it offers a support resistance (Tannant 1995, Tannant et al. 1997). Mesh is effective at catching and holding small falls of rock, but it provides minimal resistance to the initiation of the rockfall itself. Sprayed materials operate differently because they are able to offer support resistance at small displacements. Therefore, they can prevent rockfalls from happening in the first place. Shotcrete, especially reinforced shotcrete, can generate much higher support resistance than thin polymer liners. However, in situations where large ground convergence occurs, the more flexible thin liners may provide superior support over the full range of rock deformations. For example, insitu pull tests using a 250 mm diameter plate pulled through 70 to 100 mm thick steel fibre-reinforced shotcrete showed that the shotcrete could only sustain 5 to 10 mm of relative displacement before the shotcrete ruptured and failed (O'Donnell & Tannant 1998).

Laboratory pull tests on 1.5 m square panels made from concrete blocks coated with 50 to 60 mm of steel-fibre reinforced shotcrete also showed a limited displacement capacity (Tannant & Kaiser 1997, Kaiser & Tannant 1997). The shotcrete panels attained peak strength and fractured after relative displacements of 5 to 10 mm. In comparison, concrete blocks coated by a polyurethane membrane tested in similar conditions did not reach peak load until 40 to 50 mm of displacement and the load was maintained for up to 100 mm of displacement (Tannant 1997).

Figure 2 shows schematically the different load-displacement performance for various areal support types. Liners are expected to have performance characteristics that lie between mesh and shotcrete.

The mass of loose rock that can be safely held in place depends on the liner adhesion to the rock and the polymer's tensile or shear strength. Another pa-

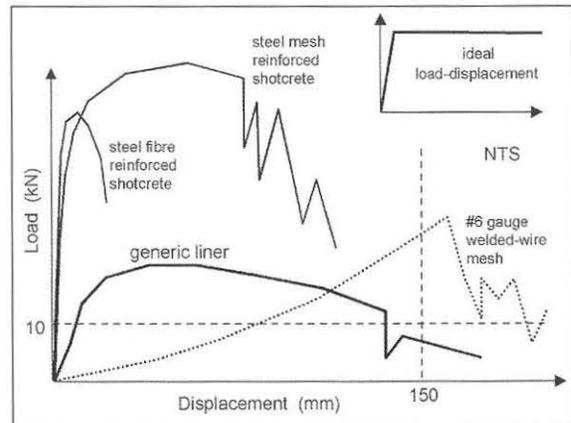


Fig. 2: Load versus displacement capacities from pull tests on various areal support types

parameter, which is difficult to determine, is the adhesive bond width. The effective bond width dictates the area over which the membrane acts while carrying a tensile load. The estimated properties for a polyurethane-based liner and a liner made from polymer-modified cement are listed in Table 1. The newer methacrylate products have strength properties between those of polyurethane and cement-based polymers. Note the strength values in Table 1 are estimates of strength that should be consistently achieved in the field and hence are appropriate for support design. They may be less than some published values.

Polyurethane	
Tensile strength, σ_t	10 MPa
Adhesive strength, σ_a	1 MPa
Bond width, ω_b	5 mm
Polymer cement (after 4 hrs)	
Tensile strength, σ_t	1 MPa
Adhesive strength, σ_a	1 MPa
Bond width, ω_b	8 mm

Tab. 1: Typical liner material properties assuming a 4 mm thickness

4. Rock support provided by thin liners

A principal objective of support is to assist the rock mass in supporting itself. It is difficult for a support system to hold up the dead weight of rock once the rock mass has loosened (Hoek & Brown 1980). This is particularly true when using thin liners, because they have a limited load capacity. In jointed or fractured rock masses, a thin liner prevents the rock mass from dilating, loosening and unraveling, thus forcing fragments of the rock mass to interact with each other creating a stable beam or arch of rock. To be effective at helping establish a stable zone of

rock, a liner must be able to limit the movement of individual rock blocks.

If conditions allow the rock mass to loosen excessively, then the liner's function can switch to retaining the loose rock in place between rock bolts. But it is important to remember that the overall objective is to have tight, sound rock present before the liner is sprayed. Otherwise, a sufficient portion of the rock mass's self-support capability has already been compromised before the liner is applied.

Conventional support in the hard-rock mining industry makes use of rock bolts or other tendon support to hold large key-blocks in place while wire mesh is used to retain the small rock pieces between the tendons. In some cases, shotcrete is used in a dual role for supporting both larger key-blocks as well as smaller pieces of loose rock.

Most support design focuses on the load capacity of the support. It is equally important to consider the support's displacement capacity, especially in situations where large ground convergence and significant relative displacements or shear displacements between adjacent rock blocks are expected. Only through knowledge of the displacement capacity of various support types can proper design and selection of support be made for a given application.

4.1 Support for drifts - Membrane action

For general rock support across the back of a drift, the liner performs a support role by resisting relative movement between individual blocks of rock and possibly acting as a suspended membrane in tension carrying rock loads (Espley et al. 1999). A thin liner applied to the excavation surface, especially at the locations of fractures and discontinuities, is effective at resisting relative movement between individual blocks of rock. The liner performs this function through a combination of a gluing action and a membrane action. The membrane action becomes more important if the liner is forced to experience larger deformations.

A liner is most effective when applied to the rock before significant movement takes place. In some cases, the liner can 'lock' the blocks together keeping relative block displacements small (<1 mm) and thus function to stabilize the rock mass around the excavation. In other cases, when rock mass conditions, stress levels, and the excavation geometry combine to generate larger rock deformations or convergence, a thin liner may not be able to suppress relative displacements and a zone of unstable rock will develop. Under these conditions, the liner typically acts like a deformable membrane to retain and hold the rock in place.

The support function required by a thin liner depends on the amount of the rock involved and the magnitude of relative displacements between adjacent rock blocks. It is important to recognize that large convergence may not be a problem so long as the rock moves inward in a uniform manner.

4.2 Potential liner support failure modes

The model shown in Figure 3 can be used to analyze the support capacity of a liner with thickness t holding a loose rock block that undergoes either small or large displacements. The surface area of the block coated by the liner is assumed square in shape with width s . The block is assumed to move vertically downward a distance d thus inducing stress in the liner. The first check is to determine whether the liner ruptures at small displacements due to either shear or diagonal tensile stresses around the perimeter of the block (Figure 4).

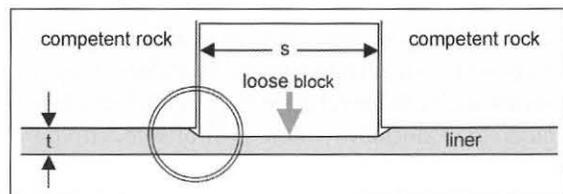


Fig. 3: Model for rock support by a liner assuming a square block moving vertically downward

4.3 Small deformations (<1 mm relative rock movement)

Thin liners can resist shear displacements of up to a few millimetres. They achieve this by using a combination of shear, adhesive, and tensile strength. Relatively high liner stiffness is probably beneficial in this case. At small rock displacements the liner functions to prevent unraveling of small rock fragments, lock small rock blocks or wedges in place (key blocks), prevent loosening of the rock mass, mobilize interactions between rock blocks, and establish a stable arch of self-supporting rock. At small block displacements, a thin liner acts like shotcrete in an active manner.

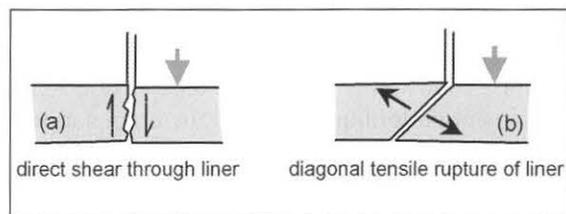


Fig. 4: Liner failure modes at small displacements caused by shear or diagonal tensile rupture

The liner can fail in two modes *Figure 4*. It is assumed that failure of the adhesive bond does not occur. Given that a typical liner is only a few millimetres thick, direct shear failure or diagonal rupture of the membrane must occur within the first few millimetres of relative rock displacement. These two failure modes are most likely when the liner adhesive strength is similar to the tensile strength. Note that this is the situation for unreinforced shotcrete, which is why shear or diagonal tensile failure modes occur in shotcrete.

For the failure modes shown in *Figure 4* the support capacity (expressed here as force per unit length around the block perimeter) is a simple function of the liner thickness and either the shear or tensile strength of the liner. Given lack of test data, the shear strength will be assumed equal to the tensile strength.

$$F = t \cdot \sigma_t \text{ per metre} \quad (1)$$

Assuming a liner thickness of 4mm and tensile strengths of either 1 or 10 MPa (*Table 1*), Equation 1 yields a support capacity in range of 4 to 40 kN/m. If the block size was 1m by 1m, with a density of 2600 kg/m³, then the liner could theoretically hold the weight of a block that was 0.6 to 6 m high. Note, it is overly optimistic to expect a 4mm thick liner to hold up the weight of 6m of rock. In a real excavation, the loading conditions would be irregular and would greatly reduce the membrane's support capacity.

From the geometry shown in *Figure 4b*, one could argue that for diagonal tensile rupture, the true thickness of the liner carrying stress is greater than the liner thickness by roughly $1/\sin 45^\circ$. However, given the uncertainty in the parameters, this effect is ignored.

While the approach presented here is illustrative, rigorous liner design is nearly impossible given the complicated geometry of the interacting rock blocks and the unknown nature of all the forces acting through the stabilized rock mass. Clearly, sprayed polymer materials are capable of holding in place small rocks. But support design for a whole drift should be a philosophy or approach that dictates the need to maintain the inherent rock mass strength. The application of a liner is just one of many activities that can be used in this regard. For example, careful blasting practices are important too. In blocky rock masses, the use of a polymer liner may aid in the development a stable Voussoir beam or arch.

Observations gathered from field and laboratory pull tests indicate that neither of the two failure modes depicted in *Figure 4* are common for polyurethane liners.

4.4 Large deformations (≈ 1 mm relative rock movement)

When conducting large pull tests on liners, the block displacements observed at the peak load are typically much greater than the thickness of the membrane. This demonstrates that the membrane is able to deform and stretch before it fails. In order for significant stretching to occur, some adhesion loss must also occur, providing a debonded length of membrane for stretching. Therefore, adhesion loss followed by tensile rupture is an important process from a design point of view.

These observations are consistent with the physical properties and liner thicknesses in use today (*Table 1*). Using the data for a polyurethane liner, the force needed to shear through a liner is about the same as the force needed to rupture the liner in tension and is 40 kN/m for a 4mm thick liner. The force required to initiate adhesive debonding ($\sigma_a \cdot w_b$) is 5 kN/m. Therefore, when the adhesive strength to the rock is significantly less than the liner tensile strength and the effective bond width is roughly the same as the liner thickness, adhesive failure around the displaced rock must occur first.

When the adhesive strength is less than the tensile strength, the liner adhesive bond may progressively fail around the displacing block. By debonding, a section of liner rotates and begins to act in tension to resist the weight of the moving block as shown in *Figure 5*. Under these conditions, the liner can tolerate relatively large block displacements. Force equilibrium can be achieved when the vertical component of the tensile forces acting in the liner equals the weight of the block (assuming no frictional resistance along the sides of the block).

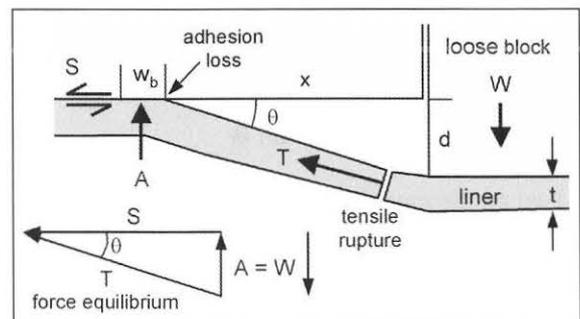


Fig. 5: Interaction between liner adhesion and tensile strength to support the weight of a displaced block (only half of the model is shown)

The model first looks at the adhesive capacity of the membrane. If the block movement causes progressive adhesive failure, the debonding will progress away from the edge of the block (*Figure 5*). In doing

so, the area over which the adhesion acts grows because the perimeter length increases. It is assumed that the area eventually becomes large enough to create an adhesive force A that satisfies force equilibrium with the weight of the block. The width of the debonded zone x at equilibrium or when tensile rupture occurs is calculated from:

$$A = 4\sigma_a(s + 2x)w_b = W \quad (2)$$

where W is the weight of the block, σ_a is the average adhesive strength of the membrane acting over the effective bond width w_b , and s is the width of the block. Equation 2 can be used to determine the width of the debonded area.

Adhesive support from the liner has now been fully mobilized so attention can now turn to the tensile strength of the liner. It is reasonable to assume that the tensile rupture will occur near the perimeter of the block, in which case the maximum tensile force T that can be carried in the plane of the membrane is:

$$T = 4s \cdot \sigma_t \cdot t \quad (3)$$

The vertical component of the tensile force must equal the block weight at equilibrium. There is a geometric relationship between the block's weight and the tensile force in the liner. By estimating the block weight and knowing the maximum allowable tensile force in the liner, the minimum angle θ can be determined.

$$\theta = \arcsin (W/T) \quad (4)$$

This angle will define the minimum vertical block displacement needed to ensure that the vertical component of T is equal to the block weight W . The vertical block displacement at equilibrium is:

$$d = x \tan \theta \quad (5)$$

Based on the model shown in Figure 5, when tensile rupture occurs the following relationship must hold true.

$$\sigma_t \cdot s \cdot t \cdot \sin \theta = \sigma_a (s + 2x)w_b \quad (6)$$

It is useful to note that the greater the angle θ or for larger displacements and liner elongation, the greater the capacity. However, there is a limit to the allowable displacement that is governed by the elongation capacity of the liner. In this model, the following relation must not be violated.

$$\sqrt{x^2 + d^2} < (1 + e)x \quad (7)$$

Where e is the elongation at peak strength for a given liner product determined from laboratory tests. A typical value for e might be 0.2 to 0.5.

4.5 Discussion

The two models shown in Figure 4 and Figure 5 illustrate the interaction between adhesive and tensile properties of a liner. Equations 2 to 7 can be used to predict the block height that can be supported by a liner before it ruptures in tension at a given block displacement. In Figure 6, the block height and width (square cross-section) are plotted against the vertical block displacement at equilibrium.

For all data plotted in Figure 6, the maximum liner elongation was less than 10%. Based on this simple model and assumed liner strengths it appears that elongation capability greater than roughly 10% may not be needed. However, if the liner's tensile strength is close to the adhesive strength, then it is advantageous to have a higher elongation capacity.

The curves plotted in Figure 6 implicitly assume a perfectly plastic material response for the liner at a tensile stress equal to the liner's tensile strength. Larger block displacements at equilibrium may occur if the liner has a strain-hardening response.

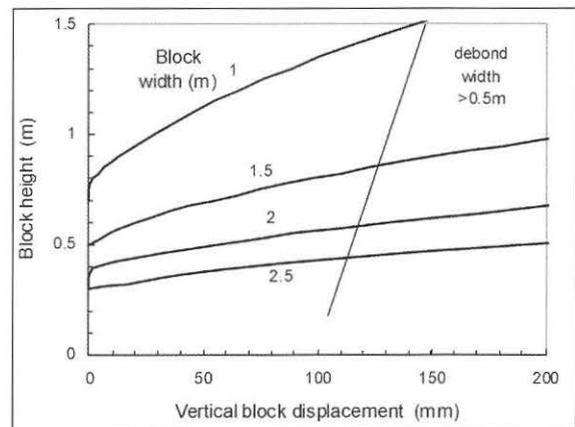


Fig. 6: Block height vs vertical block displacement at equilibrium for a thin liner with $\sigma_a = 1\text{MPa}$, $w_b = 5\text{mm}$, $\sigma_t = 8\text{MPa}$, $t = 4\text{mm}$, rock density = 2.6g/cc . Points plotting beyond the thin line indicate situations where the debonded width exceeds 0.5m

The block heights shown in Figure 6 at displacements of zero refer to blocks that do not cause progressive adhesive debonding and hence the block is stabilized at very small displacements by the shear and/or diagonal tensile rupture support mechanisms shown in Figure 4. For example, the force re-

quired to initiate adhesive failure is 5 kN/m, which for a 1 m by 1 m block is equivalent to a 0.78 m block height. At block heights below 0.78 m, the model shown in *Figure 4* applies and liner failure will be unlikely if the tensile/shear strength is higher than the adhesive strength. For heights greater than 0.78 m the model shown in *Figure 5* applies, but only up to a point. Because once debonding initiates, the debonded width can quickly exceed 0.5 m with further increase in block height or weight. The suspension support function illustrated in *Figure 5* is quite sensitive to the debonded width. In practice, effective support from a liner is probably lost once the debonded width exceeds about 0.5 m.

It is the combination of adhesive and tensile strengths that fundamentally controls the load the liner can support. Higher adhesive strength shifts the liner support function toward failure modes of shear or diagonal tensile rupture (*Figure 4*) and hence results in smaller displacements at failure. The adhesive strength to the rock must be about the same as the liner's tensile strength to use, most effectively, the tensile strength of a liner.

The tensile stresses in a liner can only counteract gravitational forces in loose rock blocks when the liner is either applied or is deformed such that a component of the tensile forces act vertically. The liner in the model presented in *Figure 5* starts in a horizontal orientation and hence has no support capacity until vertical block displacement changes the liner orientation around the perimeter of the block. In a real excavation, perfectly flat backs are unusual and hence non-horizontal sections of liner may be oriented to hold more effectively loose rock.

The issue of liner failure modes and the corresponding displacements has important implications for support design and further studies should be conducted to verify the actual failure modes under field conditions. For now, based on pull tests and limited field observations, it appears that liner failure begins as adhesive bond loss near the displaced rock. As displacements continue, the zone of adhesion failure propagates away from the block and tensile stress builds in the liner. Ultimate liner failure occurs as tensile rupture and/or adhesion loss at larger block displacements.

4.6 Adhesion and effective bond width

Increasing the adhesive strength and/or the effective bond width increases the load capacity of the membrane. At present, the effective adhesive bond width for most liner materials is unknown although it may be back calculated from laboratory tests. For example, two punching tests (Archibald et al. 1993) performed on three concrete blocks coated with

Mineguard may be used to give a rough estimate of the effective bond width for a polyurethane liner. The setup for the testing was similar to the conditions shown in *Figure 3*. The force required to displace the centre block relative to the two side blocks was 1.73 and 1.10 kN. The centre block was 180 mm long and adhesion was mobilized on each side of the block. Therefore, the effective bond width w_b assuming an adhesive strength of 0.9 MPa is found from:

$$w_b = \frac{\text{load}}{\sigma_a \cdot L} = \frac{\text{load}}{0.9 \text{ MPa} \cdot 2(0.18 \text{ m})} \quad (8)$$

The estimated bond widths are 5.3 and 3.4 mm. It is quite likely that the effective bond width varies depending on the polymer type, applied liner thickness, and substrate conditions. Thicker and stiffer membranes probably have larger bond widths. For comparison, work by Fernandez-Delgado et al. (1979) and Hahn and Holmgren (1979) suggest that the effective bond width between rock and shotcrete for good adhesion is in the order of 50 mm.

The load capacity calculated based on adhesion is probably also a function of liner thickness because thickness probably affects the effective bond width. However, the lack of tests precludes assessment of this effect. Simple laboratory testing techniques similar to those presented by Tannant et al. (1999) are needed to better quantify liner material properties.

Plated rock bolts installed after a liner is applied can function to increase the effective bond width or the adhesion and hence help mobilize the full tensile capacity of the liner at smaller block displacements.

5. Practical considerations

Thin polymer liners have a number of attributes that warrant special attention when evaluating, designing, or applying a liner.

5.1 Timing of liner application

To gain maximum benefit from thin liner support it is important to apply the liner as soon as possible in newly blasted headings. The objective is to minimize rock mass loosening in a proactive manner. Thin liners are not very effective at 'tightening up' a rock mass that has been allowed to loosen.

The ability to rapidly apply a thin spray-on liner near the face of a newly blasted heading permits installation of support before the rock mass has time to loosen. In fact, a thin liner can be sprayed on the back of a fresh round before the blasted muck pile is removed. The rapid application rates achievable

with thin liners means this type of support can be applied sooner to the rock than any other support type currently in use.

5.2 Rock-support interaction

Thin liners or shotcrete are superior to wire mesh in terms of their ability to have intimate contact with the rock and to mobilize rock interactions at small deformations. Mesh is largely a passive support that often only carries the dead weight of small rocks that have fallen between rock bolts. While a thin liner can perform a similar holding function to mesh, it is better suited to mobilizing rock-support interactions at small displacements (millimetres to centimetres). In contrast to some forms of shotcrete, the compliant nature of liners allows them to continue to function over a wider displacement range. One interesting application is the use of a combination of mesh and sprayed-on liner. Although this support is expensive, it offers superior strength and deformation properties.

5.3 Continuous coverage versus web

Experience to date suggests that creation of an unbroken thin membrane over the entire rock surface provides the best support. The liner follows the contour of the rock surface although the liner thickness is usually greater near open fractures or sharp concave depressions in the surface.

Intelligent spraying equipment may be developed to identify the location of joints and fractures and then only spray the liner material in these locations thus creating a liner that functions like a spider's web. This could significantly reduce polymer material consumption and decrease application times. A web of liner material bridging across the joints and fractures would help prevent relative rock displacements. However, if ground conditions become so severe that the polymer web cannot prevent these displacements, it is likely that a liner consisting of a continuous membrane would perform better. A continuous liner is simply more robust and has higher load carrying capacity than a web of polymer material. Nevertheless, where ground conditions are appropriate, a web of polymer material is likely to be effective and economical.

5.4 Performance near blasts

Field observations have shown that thin liners perform well in close proximity to blasts. When mesh and bolts are used within a metre of an advancing heading it is usual to see extensive damage to the mesh after each blast. The mesh is torn by the fly

rock. A typical drift round will damage the mesh over a distance of roughly 3 to 5m from the blast-hole collars. When supporting the back in preparation for the next round, some of the damaged mesh must be removed and new mesh installed. This time consuming process exposes personnel to hazards from small falling rocks as well as cuts from torn mesh.

Thin sprayed-on liners can be used up to the face, and on the face itself if needed. After a round is blasted, portions of the liner further than one metre from the face typically sustain only minor damage such as small nicks, cuts and abrasions. The damage is most pronounced where the supported surface protrudes into the drift or on surfaces that face the blast. As expected, the worst damage occurs immediately adjacent to the face. At these locations, the liner can be peeled back about 0.3 to 0.5m from the face by the blast. Further from the face, the liner typically experiences only small nicks and cuts.

Near the face, where the liner has been torn from the rock there will normally be flaps of liner material adhering to the rock. These flaps of material must be cut away in preparation for the next application of the liner. In small headings, the flaps of liner material pose a problem. For example, when mucking out a drift, a scoop can accidentally catch a flap of liner and pull off quite a large section of the still good liner. Further equipment development is needed to simplify the process of trimming away flaps of liner material created by the blast. One operational procedure that has minimized this problem is to taper the thickness of the liner toward the face. The thinner liner near the face is more likely to tear without peeling off the rock. This leaves a narrow zone where the liner is destroyed by the blast but there is a clean transition to essentially intact liner.

5.5 Eccentric and cantilever loading

There are often situations where a liner is not uniformly loaded by the deforming rock mass. Tannant et al. (1999) described two case histories where liner failure occurred because of progressive tearing caused by large slabs of rock that rotated and cantilevered from the back. In one case, a Mineguard liner was used to support a narrow drift (2m span) in highly stressed rock. A problem occurred near the advancing face where loose fractured rock caused the liner to sag between two bolts; this material was easily knocked down by a scoop bucket. A key factor contributing to the problem was the fact that the liner was not continuous to the drift face, i.e., the back at a distance of one round from the face was only supported on three sides by the liner because the newly excavated round had not been coated

yet. The lack of a liner allowed roof displacements (sagging) to initiate near the edge of the blast-damaged liner and propagate away from the drift face. This created a cantilever effect in terms of the loads imposed on the liner. One positive aspect was that the liner gave ample visual warning that excessive displacements had occurred.

The other case history involved application of Mineguard to two rounds in a 3.0 to 4.3 m span drift that was driven along a swarm of sub-parallel, steeply dipping veins. The drift was excavated as part of a drift-and-fill mining method for the narrow veins and it was the third cut in a bottom-up mining sequence. While washing and scaling the roof after blasting the second round it was evident that stress-induced fracturing was occurring from the sound of "rock noises" in the roof and shoulders of the drift. The stability of the roof decreased over time due to the progressive nature of the creation of stress-induced fractures. The rock fracturing led to a fall of a large slab of rock located in the roof of the second round, which had not yet been totally coated with the liner. In total, roughly two tonnes of rock fell from the roof. The fall of ground also peeled some of the liner from the back.

The stress fractured slabs were observed to extend over both rounds because, coincident with the fall of ground, the roof above the first round suddenly moved downward about 50mm. However, the presence of rock bolts prevented the slabs from ultimately falling to the floor in the first round. This example shows that the addition of rock bolts may be required in many situations where a spray-on liner is used. In particular, rock bolts are probably needed in addition to a thin liner where the drift span exceeds 3 to 4 m or where the rockmass quality is less than good ($Q=10$ or $RMR=60$). When installing rock bolts the use of a robotic rock bolt machine is recommended.

The two documented falls of ground occurred where the liner was not present up to the face of the drift because a new round had been previously excavated. In both cases, slabs of rock in the roof were able to move downward near the face because they were unsupported thus forming a cantilevered slab. Ultimately the slabs of rock tore through the liner at some distance from the face. In these cases, the loading on the liner was concentrated at the liner's edge. High tensile stresses caused by the rotational displacement of the slab progressively ripped the liner until the slab was able to fall.

Full areal coverage by the liner is needed to minimize local straining and progressive tearing mechanisms. A continuous membrane that is firmly adhered to the rock creates effective support. Careful rock scaling and cleaning are essential for good

adhesion. Smooth liner overlap between rounds and adequate liner thickness (to bridge all rock fractures/joints) are essential for creating a continuous membrane. The use of a robotic spray arm removes the risk to personnel from rock falls while building up a continuous liner over the roof and upper parts of the walls.

5.6 Long-term performance

Polymer liners have not been used for more than a few years in routine mining applications. Therefore, little operational evidence exists concerning their longevity in a mining environment. Initial research suggests that most materials in use today have very good resistance to acids and bases (Archibald & DeGagne 2000). Some polyurethane liner materials alter their colour and appear to degrade when exposed to sunlight. This should not be a concern in the underground environment.

One concern with polymer liners is their creep characteristics. Simple tests have demonstrated that most liner materials will creep and rupture at stresses much less than the values quoted for their tensile strengths. The impact of creep on the load capacity of a liner in conditions where a liner is supporting the gravitation load from loose broken rock is unknown. Further research is needed to evaluate the performance of polymer liners under sustained loading conditions. The Canada Centre for Mineral and Energy Technology CANMET is working with Falconbridge to address this issue. Fortunately, most liner materials can sustain large strains before rupturing. This allows for visual identification of areas experiencing problems and allows remedial actions to be taken before a fall of ground occurs.

5.7 Safety

Mine accident statistics demonstrate that the activities associated with the installation of mesh are relatively hazardous. Mesh installation is a labour intensive and manual operation and personnel are exposed to small rock falls, cuts, slips and strains in the process. In contrast, liner spraying is amenable to robotic application, which essentially eliminates these hazards.

5.8 Rock visibility

Thin liners can be sprayed on the face of an advancing drift to provide support against hazards such as small rockbursts. One advantage of thin liners compared to shotcrete is the ability to still see major rock structure and bootlegs after application of the support. The bootlegs from previous blastholes can

be easily identified such that the new blastholes are not collared near the bootlegs.

It is also easy to identify features such as joints and rock type where the rock 'roughness' varies from one type to another.

Liner materials that are white in colour provide a major improvement in the general lighting conditions in an underground environment.

5.9 Dirty or weak, crumbly rock

Thin liners have not been used successfully on weak, crumbly rock. Where the rock is weak or covered in dust, it is impossible to create good adhesion between the liner and the rock. Without good adhesion a liner does not work. There have been cases where small pockets of high-grade sulphide ore have been coated by liners. High-grade sulphide ore can have a sugary, crumbly texture and little tensile strength. As expected, the liner did not adhere to this rock type. The rock itself must possess sufficient tensile strength.

Recent experiences from Australia and US have shown that liners can be used with success when sprayed over coal pillars. In these applications, it is important to ensure that the rock surface is not dusty.

5.10 Contamination of ore

When mining through supported areas, the ground support becomes mixed with the blasted ore. Some studies have indicated that the presence of shotcrete in ore may cause detrimental effects in the milling and mineral recovery process. It is not known if this is an issue with the various types of liner materials. Fortunately, the quantity of liner material needed to support a given area will be substantially less than for shotcrete.

5.11 Application rates

INCO completed costing and time studies for the activities needed to install various support types (Espley-Boudreau 1999). The studies were based on a 4.9 m by 4.9 m drift with a 3.7 m drilled round achieving 3m advances. It was assumed that bolts and mesh were installed using a scissor-lift truck with hand-held stoper and jack-leg drills. The shotcrete was applied manually with dry-mix equipment, and the polymer liner was sprayed with a hand-operated spray gun. The application rates were found to be 0.11 to 0.15 m²/min for 1.8 m long mechanical rock bolts and welded-wire mesh; 0.1 to 0.33 m²/min for manual application of 50 mm thick fibre-reinforced shotcrete (no rock bolts); and

1.8 to 2.3 m²/min for polymer liners (no rock bolts). When the labour component is included, the study found that polymer liners can be applied at a rate of about 60 m²/man-shift versus 20 m² or 40 m² per man-shift for bolts and mesh or shotcrete respectively.

The application rate for shotcrete can be increased by an order of magnitude by adopting the wet-mix method and using remote semi-automated equipment. Similar productivity improvements are expected for thin spray-on liners once they become more widely used and specialized spray equipment is developed.

5.12 Costs

The material costs for some polymer liner materials are presently quite high, ranging between Euro 17/m² and 33/m² for an assumed application thickness of 4mm. These costs on a per metre basis are similar to 50mm of steel fibre reinforced shotcrete. The materials for rock bolts and mesh cost the least, at about 7 to 9 Euro/m². However, it must be recognized that the installation of conventional mesh and bolts is both time consuming and labour intensive. In all cases, the total support costs involving labour and equipment were much larger than the material cost. It is important to remember that the material costs do not control the overall economics of the support selection.

The economic benefits from using thin sprayed polymer liners are realized by the higher productivity created by reduction of the time needed for support installation. Further gains are possible when material transportation and handling cost are considered. Compared to shotcrete, a lot less material needs to be moved underground to the working face when using thin polymer liners.

Studies by INCO indicate that the total support cost using polyurethane liners (roughly Euro 83/m²) is similar to bolts and mesh and cheaper than mesh-reinforced shotcrete (Espley-Boudreau 1999). This cost does not account for substantial productivity improvements that are forecast to occur once semi-automated spraying of thin liners is implemented.

6. Example of thin liner use in a candian mine

Falconbridge Ltd. is making routine use of TekFlex as mesh replacement in cut and fill stopes and permanent development drifts at the Fraser Mine (Figure 7). Thin liners combined with systematic mechanized rock bolting are being used to help support the back of 80 to 85% of all headings. Mesh is still used in the areas that experience stress-driven fracturing resulting in the generation of slabby rock

(Pritchard per. comm. 2001) or in areas where the surface roughness of the rock is high thus requiring excessive quantities of liner per metre of drift (Pritchard et al. 2001).

Three key factors contributing to successful imple-



Fig. 7: TekFlex spraying at Fraser Mine

mentation of thin liners at Fraser Mine were (1) adopting stricter blasting and site preparations procedures, (2) better use of mechanized bolters, and (3) improved materials handling capabilities (Pritchard et al. 1999). One challenge that was overcome was the implementation of strict quality control procedures for site preparation, which included washing and scaling the back. When operators failed to follow the site preparation procedures, poor adhesion of the liner to the back resulted.

Perimeter control blasting techniques involving improved attention to blasthole location and alignment were found necessary to produce good quality ground conditions for a liner application. Once the operators realized the importance of a smooth, sound, clean rock surface, better care was devoted to the drilling of blastholes.

The support installation procedure is as follows. Once a heading is mucked out, the area is mechanically scaled to bring down large loose material. The round is then bolted with a mechanical bolter. Before spraying begins high pressure water scaling is performed. Once scaling is completed, the liner materials are mixed and readied for application. A calculated quantity of the liner material is sprayed onto the surface. Two hundred litres is sprayed in a 4.6m wide by 3.5 m high drift (4.2 m advance), and down the walls to a height of 2.5 m from the floor. About 300 litres is sprayed in a cut and fill environment where the breasting width is 11m, with 4.2 m advance. TekFlex is sprayed with a mobile boom arm to cover the back to a thickness of about 4 mm, and the walls to a thickness of 3 mm.

One benefit from adopting a thin liner was increased awareness of the importance of high quality work. This resulted in improved perimeter control,

drill hole alignment, and a reduction in bootlegs. Furthermore, rock bolts are now being placed where they are needed most to support the rock rather than restricted to specific locations in order to hold sheets of mesh in place. When mesh is used, the bolting pattern is eight bolts per (1.8m x 3.4m) sheet of welded-wire mesh on a 3-2-3 pattern resulting in a bolt density of about 1.6 bolts/m², accounting for mesh overlap. Use of mesh often results in the installation of more bolts than are required for the ground conditions. Elimination of the mesh has allowed a wider bolt spacing (1 bolt/m²) thus nearly doubling bolter productivity. The use of a thin liner enables the bolting density to match the ground conditions.

7. Conclusions

Thin liner support is an emerging technology that is applicable to underground support of blocky rock masses. A variety of different liner materials are currently being investigated and some are now being used in routine support applications within Canadian mines.

Thin polymer liners have performance characteristics that lie between those of shotcrete and mesh. They are a welcome addition to the 'tool box' of support types and have a role to play where rapid application rates and areal support of rock are needed.

The liner must adhere well to the rock and hence, the use of thin spray-on liners is not recommended where the rock surfaces are dirty or can not be cleaned or where the rock has a crumbly texture. A continuous liner that is firmly adhered to the rock creates effective rock support.

Various approaches were used to examine the load capacity of a liner. Interpretation of the available test data and introduction of simple support models show that the two likely failure modes are adhesion loss and tensile or shear rupture of the membrane. Different failure modes occur depending on the relative tensile and adhesive strengths of the liner and the anticipated magnitude of the rock displacements.

Virtually all liner materials are very effective at holding in-place small pieces of rock. When a liner is used to support a larger area it can do so through a combination of adhesion and shear strength at small (<1mm) relative block displacements. If excavation conditions generate larger block displacements, the liner acts like a supporting membrane and a combination of adhesive strength, tensile strength, and liner elongation serve to eventually create force equilibrium in a displaced loose block. More research is needed to determine design va-

lues for the tensile, shear, and adhesive strengths of different liner materials. It is equally important to gain a better understanding of the effective bond widths that carry adhesive stress during progressive debonding of a liner from the substrate material. Field trials are useful for identifying liner performance and potential failure modes and aid with the development of reasonable models for liner design. There are many factors that must be considered before adopting wide spread use of thin sprayed on liners. Fortunately, it appears in some cases that liners offer increased safety, better productivity, and lower overall mining costs compared to conventional bolts and mesh or shotcrete.

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