Investigating the use of polymer-modified cementitious thin spray-on liners as stope face support

M. du Plessis

Gold Fields, South Africa

D.F. Malan

Department of Mining Engineering, University of Pretoria, South Africa

ABSTRACT

This paper investigates the use of a thin spray-on liner (TSL) as stope face support in narrow width tabular stopes. The application of areal support is difficult in these stopes because of the small stoping width and the large area of hanging wall that is exposed by the long face lengths and regular blasting. A simple analytical model of a collapsing block supported by a TSL is explored to determine the parameters to be considered for underground use of the liners. Most literature on TSL focusses mostly on specialised laboratory testing. Almost no large scale testing to determine TSL strengths, when it is applied to blocky rock masses, has been conducted. To simulate the discontinuous nature of the hanging wall in mining stopes, a large scale rig and test methodology was developed. Four different polymer-modified cementitious TSL products were tested and the results are described in the paper. For the particular experimental setup and a curing time of 24 hours, the maximum load carrying capacity of the strongest TSL was 305 kg, while a 50 mm thick shotcrete had a capacity exceeding 1100 kg. The test results indicate that care should be exercised when attempting to use a TSL as a structural element in support systems.

Keywords: Thin spray-on liners, Tabular stopes, Areal support

1. Introduction

A large area of hanging wall needs to be supported when mining narrow reef, tabular ore bodies dipping at a small angle. This is typical of the gold and platinum mines in South Africa. The Leon Commission[1], established in 1994 to investigate mine safety, made the comment that *"…due to the narrow width of mineralisation, a large area must be mined in each year to produce the planned tonnage of gold (e.g. 619 t in 1993). The recovery of this tonnage requires the extraction of reef* *over an area of some 20 to 30 km²"*. The newly blasted stope faces needs to be supported before workers enter these areas.

The unique problems associated with the support of narrow reef, shallow-dipping tabular stopes was recently explored by Malan and Napier[2]. The rock is typically fractured or jointed and fallouts occur between rock bolts and other support units. Areal support is difficult to implement owing to the small stoping width in some areas (< 1.2 m). In stopes prone to rockbursts, this problem is particularly problematic. Kaiser and Chai[3] emphasised that one of the key functions of rockburst support is to prevent fractured blocks from falling between reinforcing elements. As stated by them: *"Under high stress conditions, fractured rocks between reinforcing or holding elements may unravel if they are not properly retained."* Solving this areal support problem is of critical importance to improve the safety in the South African gold and platinum mines. Jager and Ryder[4] stated: *"The predominant cause of falls of ground in stopes is inadequate areal coverage or interaction between support units."* The current approach to mitigate this problem is to use headboards, systematic bolting between elongates and temporary nets[2]. Installation of rock bolts is problematic in the small stoping widths and special drill rigs are typically used. The bolts are limited to short lengths (typically 0.9 – 1.2 m) owing to the small mining height. The use of temporary nets have been partially effective and have saved numerous lives. The nets are attached to other support units, but as a limitation, only cover parts of the face area. The nets are reusable, but it may become a safety hazard if they are not replaced when worn. Although attempts are made to tension the nets, they are deformable and falling rocks may only be arrested after a significant amount of downward movement has occurred (Fig. 1). This is problematic in the small stoping width environments. A more robust and effective permanent areal support system is required for these stopes. Permanent, blast-resistant steel nets have been tested as an alternative (Fig. 2), but these installations are susceptible to damage by the scrapers used for cleaning operations in these mines. It nevertheless provides permanent hanging wall coverage and a much improved support capability when compared to the temporary nets.

Fig. 1. A fall of ground arrested by a temporary net in the face area of a platinum mine.

Fig. 2. Use of permanent blast resistant steel nets in the face area of a platinum stope. Visible in the photograph are the other support elements namely rock bolts and cementitious grout packs.

Thin spray-on liners (TSL) is an alternative areal support type in the face area of these stopes. An important specification of a TSL for this application is early strength development. Workers will enter the face area a few hours after blasting and they need protection against falls of ground while cleaning the broken ore and installing support units such as rock bolts. TSL products have been tested and proposed as areal support in the mining industry for more than 25 years[5-11]. An extensive list of papers on TSL testing and references are also given in Guner and Ozturk[12]. Surprisingly, no consensus has been reached on a standardised testing methodology for these products. This situation is problematic as different support suppliers make claims in terms of the performance of their TSL products and it is difficult to compare these products in the absence of standardised testing methods and independent verification. In a particular case known to the authors, this led to an instruction being issued that all working faces be supported by a TSL. The type of areal support had to have *"long term bonding strength"*, consist of a "*thermo pseudo plastic polymer base*" not be *"brittle"* and that it "*must have biaxial flexural strength with deflection of more than 5 mm over time*". It is not clear what the technical justification for this specification was. EFNARC (European Federation of National Associations Representing for Concrete) produced a document on "Specification and Guidelines on Thin Spray-on Liners for Mining and Tunnelling" during 2008[9]. This document was the result of the work of a Technical Committee on TSL products that was formed in 2004 with the objective of producing a specification and guidelines for these liners to be used as rock support in the mining and tunnelling industry. As stated in the document: "*Whilst the primary support is provided by steel anchors and/or arches and/or reinforced shotcrete, the TSL provides an initial stabilising layer which will contribute to the overall support*." The types of testing parameters required is given in the EFNARC document and it is important to note that no mention is made of "biaxial flexural strength" as specified above.

Regarding the testing of membranes, of which TSL products were considered as one type, Stacey[7] classified the testing requirements into three categories namely:

1. Testing of membrane material to determine material properties (referring to laboratory properties).
2. Testing of the membrane component using a "representative" test method.
3. Testing of the membrane system (combinations of more than one membrane component, e.g. wire mesh and shotcrete) using a "representative" method to test the system.

Stacey highlighted the problem with these test categories owing to the different requirements of membrane components and systems. The "representative" test methods will be different in each case. The last two categories of testing has been neglected for TSL products and this make it difficult for practicing Rock Engineers to predict the behaviour of this support type for underground applications. Shan et al[13] conducted large scale laboratory tests comparing TSL material and welded steel mesh as a confinement medium in coal mines. The TSL consisted of 5 mm polymer sheets reinforced with glass fibre sheet. The rock material was initially simulated using triangular concrete prisms fitted together to form specimen sizes of 400 mm x 400 mm x 800 mm. The second type of specimen consisted of a concrete block of similar dimensions with embedded plastic sheets to simulate weak bedding planes. Four bolts were also used to anchor the blocks. The one side of the specimen protruding from the press was reinforced with mesh or the TSL. It was found that the TSL reinforced block with the bedding planes had a higher peak load than the control specimen, but no comparison with the steel mesh specimen was possible as one of the bolts broke. Shan et al[14] extended the earlier work with a more complex testing setup. The authors noted that previous laboratory tests on TSL sheets larger than 1 m^2 were limited. Their specimen size was 1.4 m x 1.4 m. A concrete slab was artificially fractured and bonded to a prepared TSL sheet with a thin layer of polymer. It should be noted that the TSL tested by these researchers were fibre-reinforced polymer (three different types) and fibre-reinforced polymer-concrete composite materials. It was found that the TSL specimens were stiffer than the steel mesh types tested and provided higher support loads at smaller displacements. Only one sheet of each type of TSL was tested during this study and only one of the sheets was bonded to the rock. The method of preparing the TSL for these tests are questioned in relation to the mining problem presented above. The TSL sheets were cast in stages with two layers of glass fibre sheets inserted at different stages. This will not be a practical support type in the type of stopes shown in Fig. 2 where a spray-on application is required.

Yilmaz et al[15] conducted a study of TSL products and found that the support mechanism of these membranes are not well understood. They also lamented the fact that no standard test methodology existed for TSL products. Of importance is their statement that assessing TSL performance would only be possible once the design requirements are determined. Regarding testing, they quoted earlier researchers and recommended that a TSL testing program should have the attributes of being simple (easily prepared samples), cost effective, repeatable, practical, representative of relevant properties, relate to in-situ performance and that statistically valid data should be generated. Testing should be conducted to examine the TSL material itself or could consider both the TSL material and the substrate to understand the interaction between these two. The following mechanical properties, which can be tested, were considered relevant for characterising TSL properties:

- Tensile strength,
- Adhesion strength,

- Tear strength,
- Creep behaviour,
- Impact strength (abrasion)

Recent work on the creep behaviour of TSL material was done by Guner and Ozturk[16,17]. Of importance is that temperature and humidity should be recorded during the tests listed above. Of all these tests, only two were accepted by the delegates to the International Seminar on Surface Support Liners in Australia in 2001 namely tensile and direct adhesion tests.

Kanda and Stacey[18] presented a lengthy list of difficulties when conducting tests on TSL products for underground mines. Some of the key limitations, which are related to this current paper, are as follows:

- The test results of support behaviour in the field are not generally the same as those obtained from laboratory tests.
- The ability of a TSL to support the rock mass depends on the number of mobilised blocks and the amount of displacement in the rock mass. A TSL should not be applied on rock surfaces that have a large number of mobilised blocks.
- TSL products are not structural support elements and this is a limitation in their adoption by users.
- The conditions in the mines should be simulated in the laboratory to determine if the TSL tensile and bond strength can increase the energy absorption capacity of the support system.
- The method of preparation and application of a TSL can substantially affect the performance of the product. Mixing of the material, rock surface condition and applied thickness can play a role.

One particular aspect that has been largely ignored in relation to the testing of TSL products, and referred to by Kanda and Stacey[18], is the performance of a TSL when applied to a number of mobilised blocks. Fig. 3 illustrates the extreme blocky conditions that are encountered in some of the gold mining stope faces owing to the extensive fracturing at great depths. The rock mass behaviour in the shallow and intermediate depth platinum mines is dominated by joint sets and this can lead to large intact blocks being dislodged. This was illustrated in Fig. 1. The engineering question that needs to be asked is to what extent a TSL will be beneficial as areal support in these conditions, what the load carrying capacity of the liner will be and what type of tests and quality assurance need to be conducted to verify its performance? Shan et al[14] suggested that TSL have the potential to replace steel mesh in certain cases, such as the support the rock between rock bolts and to prevent the formation of guttering. Steel mesh may, however, be better in areas prone to seismic events owing to a higher energy absorption capacity.

Fig. 3. Blocky hanging wall conditions in a deep gold mine.

To address these questions, large scale tests on TSL products may be beneficial, but very few of these tests are described in literature. The recent tests conducted by Shan et al.[13,14] are described above. Espley et al[6] coated a series of interlocking 50 mm thick hexagonal concrete paving blocks with TSL and conducted large-scale pull tests. The TSL was applied onto the concrete blocks from above and left to cure for about an hour to test a reactive TSL and between four and eight hours to test a non-reactive TSL. Load was applied to a 100 mm square steel plate positioned in the centre below the coated blocks. The load was increased until the TSL failed. The results obtained were affected by the interlocking effect of the bricks when a force was applied to the plate. The researchers concluded that a TSL is able to enhance the interaction between loose blocks and a significant portion of the supporting function depends on the block-to-block interaction. Swan and Henderson[19] performed a TSL baggage capacity test to measure adhesive strength at different curing times. The artificial beam was created by pieces of rock debris coated with a TSL from the top, resulting in the penetration of the product between individual rocks. Load was applied onto the inverted sprayed mass until the liner ruptured. The test measured rupture load and maximum deformation of the applied liner. The authors proposed that tension and adhesive strength properties contributed to the support capacity of the deformable TSL. It is not clear to what extent the adhesive strength played a role, as the load-bearing capacity could have been controlled mainly by the tensile properties of the liner and interlocking effect of the blocks.

In summary, in the large volume of TSL literature, a number of laboratory tests are described in detail. The objective of this current paper is not to focus on additional results from laboratory testing, but rather to investigate the suitability of these products for the conditions shown in Fig. 1 and Fig. 3. No guidelines are currently available to Rock Engineers under which conditions a TSL can be used safely to mitigate the fall of ground problem. These engineers typically struggle to understand the specifications and application limits of the available areal support types. There is no design methodology to select between the option of permanent steel nets (Fig. 2), temporary nets (Fig. 1) or the application of a TSL. In terms of a TSL, it is important to determine which of the wide range of laboratory tests is necessary when considering the suitability of a product as a practical support component. The objective of this paper is not to address all these aspects, but rather to clearly illustrate that large scale testing, under conditions that can simulate the underground application of the product, is indispensable for the comparative evaluation of TSL products. A simple analytical model also proved to be useful to illustrate some of the important TSL properties for practical applications.

2. Simplified support mechanism provided by thin spray-on liners

The previous section discussed the large number of laboratory tests that are proposed for TSL products. It is important to determine which of these laboratory parameters are important when considering the use of a TSL for practical mine support problems. To assist in this regard for the narrow reef tabular stopes, consider the simplified support problem shown in Fig. 4. The assumption of tributary area theory, where each elongate supports the area of rock in its immediate vicinity, dominated the support design methodology in the South African mining industry for many years[2]. The typical fallout height h depends on local conditions and it is frequently defined by a weak parting in the hanging wall. For example, in the platinum mines, there is a series of chromitite stringers in the hanging wall where the UG2 Reef is mined and the height of these stringers typical determines the fallout height. In the gold mines, there is not a persistent parting at a fixed height in the hanging wall and the rock that needs to be supported is determined by keeping a record of the typical fallout heights over a period of time. This support design approach is described in detail in Ryder and Jager[20]. A graphical method is used to determine whether particular support units at a particular spacing meet the support resistance and energy absorption criteria at a specified distance from the face. The requirement of areal support between adjacent elongates or roof bolts is not explicitly included in the design methodology. This may lead to a hazardous situation, as illustrated in Fig. 4, where a block of rock may become dislodged between two adjacent support units.

The current support design approach was reasonably successful as it appears that the horizontal stress σ_h present in the hanging wall of these tabular stopes at great depth appear to knit the rock mass into a stable beam. The horizontal clamping stress in an underground gold mine stope was measured by Squelch[21] and was found to be of the order of 1 to 10 MPa. As an apparent contradiction, the elastic solution of a simple tabular stope indicates that the hanging wall should be in tension. It seems, however, as if the dilation caused by the fracturing ahead of the stope faces generates compression in these hanging walls[22]. In the shallow to intermediate depth platinum mines, the fracturing of the stope face is largely absent. Ryder and Jager[20] nevertheless note that the occurrence of horizontal tensile stresses is unlikely in shallow platinum stoping, because the horizontal to vertical stress ratio at these depths is usually very large. Gravity-induced falls of ground are nevertheless frequent in the platinum mines and large scale instabilities may be significant, depending on the prevailing geological conditions[23,24]. The exact figure of σ_h is unfortunately not known for every stope.

The simplified scenario shown in Fig. 4 assumes that the stope is supported by elongate support units at a regular spacing and a TSL was applied to the hanging wall. There is a loose square block of width *w*, not supported by an elongate, and it is held in place by the frictional forces, horizontal clamping stresses, σ_h , and the TSL. The clamping stresses in the two horizontal directions are assumed to be equal in magnitude.

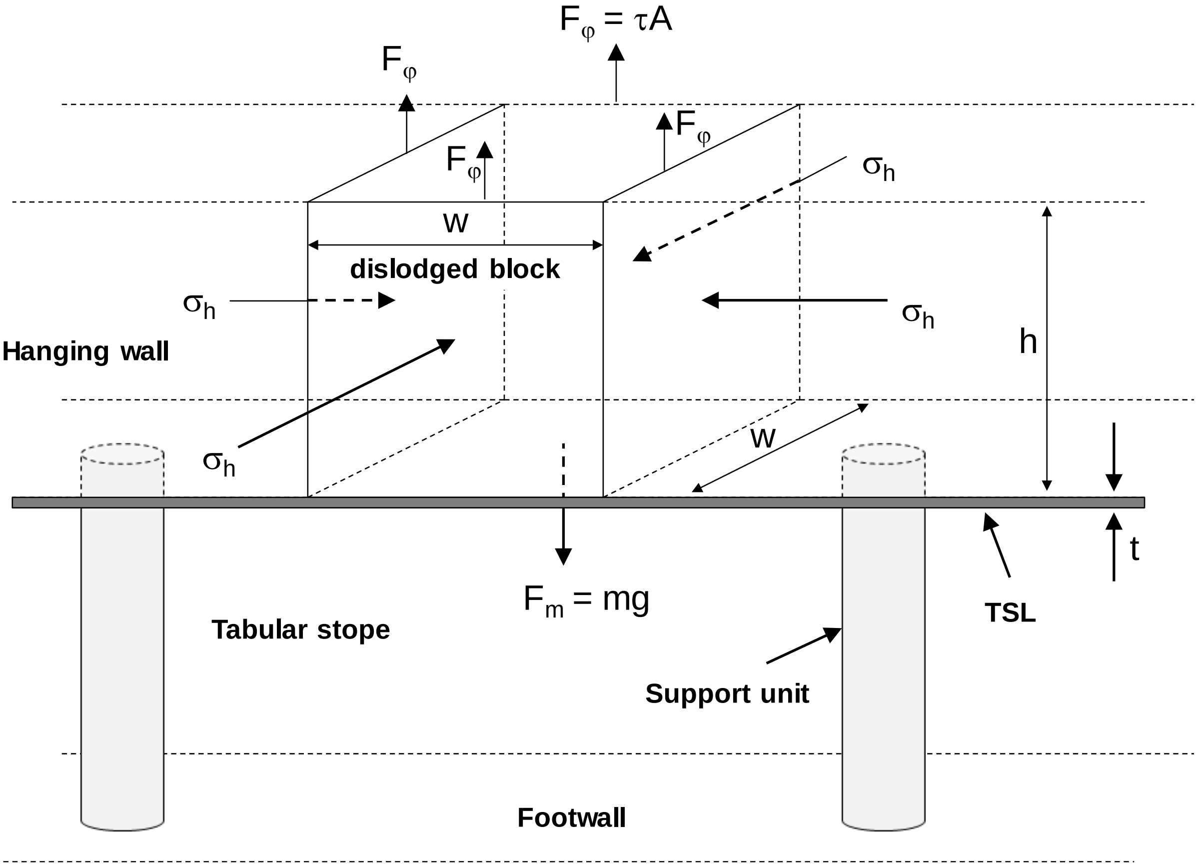

Fig. 4. Loose block of rock between two support units.

Ignoring the contribution of the TSL as a first step, the block with mass *m* shown in the figure will be stable if the following force-equilibrium condition is met:

$$F_m = 4F_\varphi \tag{1}$$

Considering that $F_m = mg$ and $F_\varphi = \tau A = tan\varphi\sigma_h A$, where g is gravitational acceleration, τ is the shear stress, φ is friction angle and A is the area. It therefore follows from Eq. (1) that

$$mg = 4tan\varphi\sigma_h A \tag{2}$$

and the mass of block that can be supported by the clamping stress and frictional interfaces is

$$m = \frac{4tan\varphi\sigma_h wh}{g} \tag{3}$$

where w is the width of the block and h is the fallout height.

As a second step, consider the contribution of the TSL. Of particular value in this regard is the theoretical work of liner failure modes presented by Tannant[11]. The work below is an extension of his original model by adding the effect of the frictional contacts acting on the block. The frictional contacts were added to illustrate the subtle risk of considering a TSL as a structural element of the support system which is intended to prevent large blocks from failing. In many cases, the blocks are held in place by the clamping stresses or joint interlocking mechanisms and not by the application of a liner. Tannant[11] distinguishes between TSL failure at small deformations (< 1 mm) and large deformations (>> 1 mm).

Failure at small deformations: Liners with a high stiffness can fail in two modes after a small deformation. Failure of the adhesive bond does not occur in this case. The two failure modes (direct shear versus diagonal tensile) are shown in Fig. 5 and these are most likely to occur if the liner adhesive strength is similar to the tensile strength. For these failure modes, the support capacity (expressed as force per unit length around the block perimeter) is a function of liner thickness and either the shear or tensile strength of the liner (Eq. 4). Owing to a lack of test data[11], the shear strength was previously assumed to be equal to the tensile strength, σ_t. The equation below therefore applies to both tensile and shear failure. The strength of the liner F_t is given by:

$$F_t = \sigma_t A_t \tag{4}$$

The area A_t of the liner where the failure occurs is the thickness t multiplied by the perimeter of the block. Therefore:

$$F_t = 4\sigma_t tw \tag{5}$$

Eq. (1) can be modified to add the contribution of the TSL to the force balance equation:

$$F_m = 4F_\varphi + F_t \tag{6}$$

By inserting Eq. (5), it follows that

$$mg = 4tan\varphi\sigma_h wh + 4\sigma_t tw \tag{7}$$

The mass of the block that now can be supported is given by

$$m = \frac{4w(tan\varphi\sigma_h h + \sigma_t t)}{g} \tag{8}$$

When examining the term in brackets in Eq. (8), the relative contribution of the compressive stress acting on the frictional contact is significantly larger than that provided by the liner. For typical practical values, it can easily be shown that $tan\varphi\sigma_h h \gg \sigma_t t$. The implication, as suggested above, is that application of a TSL in stope faces may lead to a false sense of security. The natural stability of the rock mass caused by the clamping stresses and the interlocking blocks may keep the hanging wall intact and not the application of a TSL. A sudden loss of clamping stress caused by a fall of ground in a different part of the stope may cause the loose block in Fig. 4 to collapse. The function of the TSL during underground applications and the expected mechanism of failure must therefore be better understood.

To investigate the theoretical capacity of the liner in terms of the height of the block that can be supported, consider the worst case scenario where $\sigma_h = 0$ and insert $m = \rho w^2 h$ in Eq. (8) where ρ is the density of the rock. This gives:

$$h = \frac{4t\sigma_t}{\rho g w} \tag{9}$$

This is intuitively correct as it indicates that the height of the block supported is inversely proportional to the width of the square block, *w*. In terms of quality assurance during underground applications, Eq. (9) is important as it illustrates the sensitivity of the TSL support capability to its tensile strength and thickness of application. For a square block of 1 m width, a density of 3100 kg/m^3, a TSL tensile strength of 4 MPa and t = 4 mm, the height of block that can be supported is 2.1 m. When the thickness is decreased to t = 3 mm, the block height that can be supported decreases to 1.5 m. The thickness of application underground will therefore have to be monitored extremely carefully. This may be a difficult problem owing to the small thickness of application inherent to a TSL. This aspect, coupled to other possible quality assurance problems, such as incorrect mixing, may render it unsuitable as a structural support element. For example, for the rough hanging wall profile shown in Fig. 3, it will not be possible to guarantee that the correct thickness is applied to the entire hanging wall. Once displacement occurs and tensile cracks develop, it will also significantly affect the ability of the TSL to provide support resistance. The shear and tensile strengths for this mode of failure is important and it needs to be carefully measured in the laboratory.

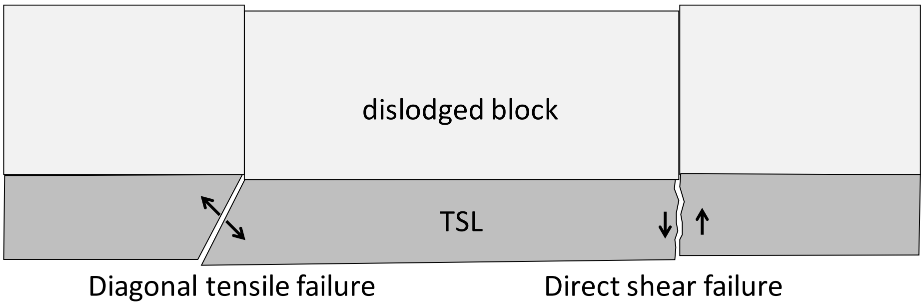

Fig. 5. An illustration of the TSL failure modes at small displacements as proposed by Tannant[11].

Failure at large deformations: For TSL failure at large deformations (>> 1 mm), adhesion loss typically occurs and this allows the TSL to stretch before failure. The failure mode is therefore adhesion loss followed by tensile rupture of the TSL. This will typically occur if the adhesive strength of the liner is less than the tensile strength. Note that not all types of TSL may experience this mechanism of failure as discussed below. The proposed mechanism of failure is shown in Fig. 6.

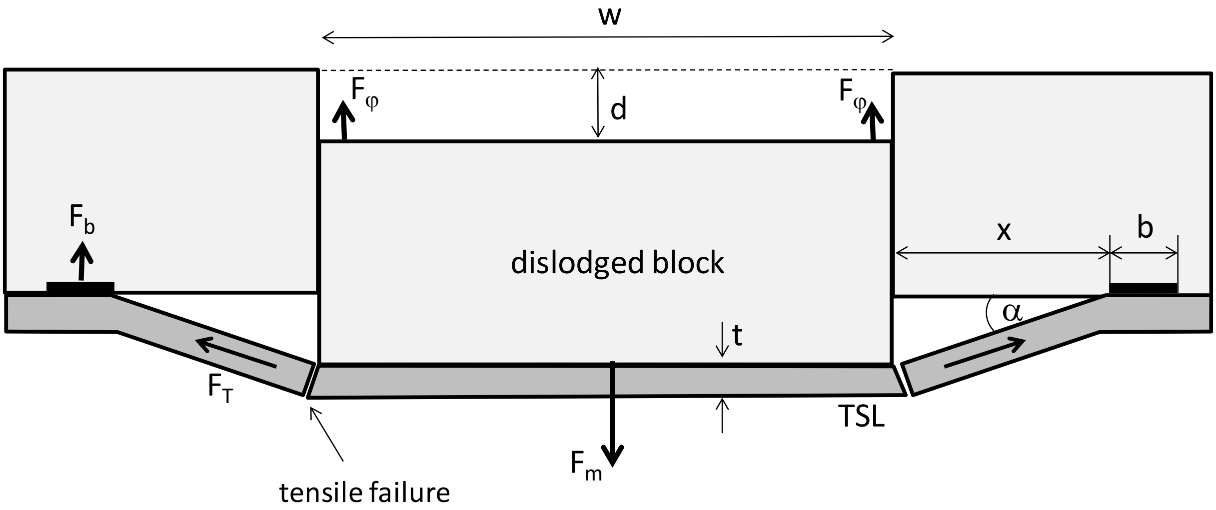

Fig. 6. A section through the block in Fig. 4 illustrating the failure mechanism caused by a loss of adhesive strength and eventual tensile failure of the TSL.

During the failure process, the adhesive bond progressively fails around the dislodged block. The loose portion of liner is subjected to tension. Force equilibrium is achieved when the vertical component of the tensile force and the friction forces acting on the block (also see Fig. 4) equals the downward force exerted by the weight of the block. De-bonding will progress away from the edge of the block. This increases the area over which the adhesive force F_b acts as the perimeter length increases. This area grows until the liner fails in tension or the block is arrested after a displacement d by the force equilibrium condition to which the block is subjected to.

To investigate the mechanism of failure, assume the block moved downwards for a distance *d* and modify Eq. (6) to illustrate the contribution of this TSL mechanism to the force balance equilibrium. The following condition needs to be met:

$$F_m = 4F_\varphi + F_b \tag{10}$$

The bond width, *b*, is a critical parameter and the area of liner where the force F_b is exerted is the perimeter at the edge of the debonded liner multiplied by the bond width. Therefore

$$F_b = 4(w + 2x)b\sigma_a \tag{11}$$

where σ_a is the adhesive strength of the liner acting over the bond width, *b*. Note that the relationship of bond width relative to the TSL thickness is not well understood. Tannant assumed the two parameters to be approximately equal based on research conducted on shotcrete. Ozturk[25] estimated an average effective bond width of 0.7 mm from tests conducted on a polymer-modified cementitious TSL applied on various substrates. Further testing is required to investigate and quantify the bond width for various TSL products. Eq. (2) and (11) can be inserted in (10) to give

$$mg = 4tan\varphi\sigma_h w(h - d) + 4(w + 2x)b\sigma_a \tag{12}$$

The mass of block that can be supported for this mechanism, provided the tensile strength in the debonded liner is not exceeded, is given by:

$$m = \frac{4[tan\varphi\sigma_h w(h-d)+(w+2x)b\sigma_a]}{g} \tag{13}$$

Again, consider the worst case scenario where the clamping stresses are zero, $\sigma_h = 0$. This gives:

$$m = \frac{4(w+2x)b\sigma_a}{g} \tag{14}$$

It is difficult to evaluate Eq. (14) and also the height of fall that can be supported from the mass if the debonded length x is not known. To make the problem tractable, consider the tensile strength of the liner and assume the tensile failure occur near the edge of the dislodged block. The maximum tensile force in the liner was already given by Eq. (5). This equation is only applicable to this problem if tensile failure occurs close to the edge of the dislodged block. The vertical component of the tensile force must equal the block weight at equilibrium in the absence of frictional forces on the block ($\sigma_h = 0$). Therefore

$$F_m = F_b = F_T sin\alpha \tag{15}$$

where F_T is the force in the liner. The block displacement at equilibrium is:

$$d = x(tan\alpha) \tag{16}$$

Considering the model in Fig. (6) and by inserting Eq. (5) and (11) in (15), at the point of tensile failure when $F_T = F_t$, the following relationship must hold:

$$(w + 2x)b\sigma_a = \sigma_t tw(sin\alpha) \tag{17}$$

It is problematic using these equations to calculate the height of rock, h, that can be supported. The debonded length x will depend on the weight of the loose block. Iterative techniques using Eq. (5), (15) and (16) needs to be used with different estimates of h to meet the condition in Eq. (17). Tannant also suggested the following relationship which should not be violated for the type liners that fails according to this mechanism (this can be derived from the diagram given in Fig. 6:

$$\sqrt{x^2 + d^2} < (1 + \gamma)x \tag{18}$$

where γ is the elongation at peak strength for a liner as determined in the laboratory and a typical value suggested by Tannant may be 0.2. Note that this value will not be applicable for the stiff cementitious type liners discussed in this current paper.

The equations shown above were used together with the parameters in Table 1 to calculate the block height that can be supported at various values of displacement d. As iterative techniques need to be used, the "Goal Seek" function in Excel provided a simple solution, together with Eq. (5), (15) and (16), to modify the value of h to meet the condition in Eq. (17). Fig. 7 presents an example of the output generated following the methodology. Of importance is that the results for this simple model indicate the sensitivity of the load-carrying capacity of the liner to its adhesive strength. This emphasises that care should be exercised when using an adhesive strength obtained from testing on a particular substrate as other rock types may result in different values and substantially smaller load carrying capacities. The influence of the rock type, environmental conditions and the liner thickness on adhesive strength were studied by Ozturk and Tannant[26,27]. The importance of proper TSL and surface preparation and product application is vital to ensure improved bonding to the rock medium. It is not clear if this type of preparation will be possible in a production stope. Furthermore, the effect of bond width, *b*, is critical to estimate the performance of a TSL. When considering the results in Fig. 7, the estimated block height that can be supported will reduce further if the bond width is reduced to a smaller value, say 1 mm. This uncertainty regarding the performance and load carrying capability of a TSL makes it questionable if it can be safely used as a structural support element in mining stopes.

Table 1. Parameters used to investigate the effect of adhesive strength.

Parameter	**Value**
Tensile strength, σ_t	4 MPa
Adhesive strength, σ_a	2 MPa and 1 MPa
Bond width, b	5 mm
Block width, w	1 m
Gravitational acceleration, g	9.81 m/s^2
Rock density, ρ	3100 kg/m^3
Thickness of TSL, t	4 mm

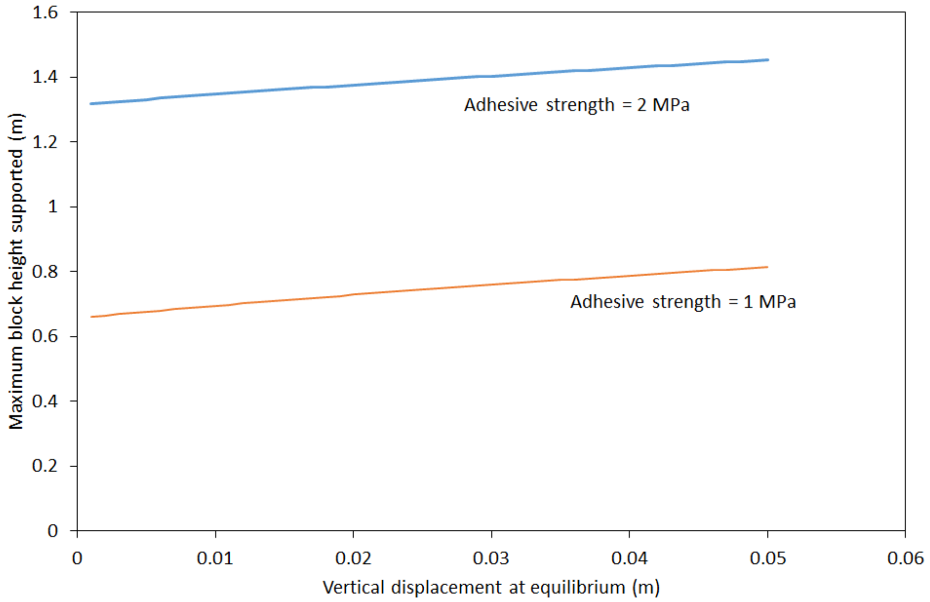

Fig. 7. Effect of adhesive strength on the height of block that can be supported.

3. Large scale testing methodology

As described above, only limited large scale testing of TSL products, and almost no attempts to simulate the blocky rock mass conditions underground, can be found in the literature. Preliminary experiments were therefore conducted on an assembly of cement blocks covered with a TSL for this study. These experiments were not conducted under controlled environmental conditions similar to those recommended for the laboratory work. Although the importance of controlling humidity and temperature is emphasised by many workers[15,18], it was not possible to do this owing to the large-scale nature of the tests. It can also be argued that if large areas are to be covered with a TSL in underground stopes over extended periods of time, these applications will occur under a variety of humidity and temperature conditions. Any product taken underground will therefore have to be robust enough not to be affected by subtle changes in environmental conditions.

Four products that are commercially available in South Africa were tested and these are simply labelled as A, B, C and D. All four products were two-part "cement dominant", polymer-modified, non-reactive, spray-on liners. In terms of this naming terminology, in the early days, there were attempts to develop a pure polymer TSL. This quickly evolved to TSL products containing both polymers and cements. The "polymer dominant" products typically has a higher elongation to failure compared to the "cement dominant" products. In terms of the failure modes described above, the "cement dominant" TSL tested in this study probably relates mostly to the small deformation type (< 1 mm) and associated mode of failure (Fig. 5) as described by Tannant[11]. This was confirmed by the testing results below.

To determine the typical characteristics of the four types investigated, laboratory testing was conducted on the TSL material. The type of tests and results are given in Table 2. The test methodologies for the various types of tests have been described extensively by Yilmaz[8,28,29,30]. Yilmaz also conducted the tests for this particular study and the methodology followed is similar to that described in his references. Note the low tensile strength of most products after one day of curing and this appear to be a characteristic of the "cement dominant" TSL. This behaviour is problematic in terms of underground applications considering the re-entry time of workers into a hypothetical stope face area that is only supported by a TSL.

For the large scale tests, a 1.5 m x 1.8 m test rig was built (Fig. 8). An artificial rock surface was constructed using 100 mm thick, 300 mm x 600 mm lightweight (16 kg) reinforced cement blocks. These cement blocks are commonly used to build packs in the South African mines and is referred to by the supplier as "*…lightweight concrete blocks, reinforced with annealed steel wire* *mesh, stirrups and polypropylene fibres…"*. The blocks are engineered so that a pack constructed to a size of 0.6 m x 0.6 m and a height of 1.5 m would typically fail at a constant load of 1200 kN over a large deformation range. These blocks were convenient to be used in the TSL test setup as they are readily available in large quantities, their size and weight were considered ideal and their strength properties are engineered and therefore constant for every test conducted. It should be noted that the results of the tests may be affected by the various boundary conditions imposed by the blocks, for example, the friction angles at the interfaces. These parameters were constant between the various tests, however, and the blocks were therefore considered suitable to do comparative testing of the different types of TSL.

Table 2. Average laboratory test results for the different TSL products labelled A, B, C and D. The tensile adhesive strength was done on material with a thickness of 8 mm and norite was used as a substrate.

Test parameter	Curing interval (Days)	A	B	C	D
Tensile strength (MPa)	1	0.70	0.70	0.52	2.95
	3	1.48	1.48	2.25	3.87
	7	2.71	2.71	3.04	4.06
	28	2.81	2.81	3.54	4.84
Tensile adhesive strength (MPa)	1	1.45	1.21	0.83	2.66
	3	2.06	1.14	1.12	4.00
	7	0.80*	0.82*	1.67	4.09
	28	0.81*	1.28	1.86	3.65
Shear bond strength (MPa)	1	0.40	0.35	0.14	3.90
	3	1.55	0.95	1.10	5.05
	7	2.10	1.25	1.30	5.50
	28	2.35	1.90	1.90	6.95
Material shear strength (MPa)	1	2.13	2.48	1.52	5.52
	3	7.81	4.55	4.91	7.19
	7	12.56	6.82	8.60	7.85
	28	13.45	12.83	16.29	11.35

*These values for the tensile adhesive strength of products A and B seem anomalous.

The blocks were clamped into the rig, placed onto a 2 m high steel structure and sprayed with TSL from below (Fig. 9). This was done to simulate the underground application of TSL and these tests are therefore different compared to the methodology used by Shan et al[14] where a pre-manufactured TSL sheet reinforced with glass fibre sheets was glued to concrete blocks. A TSL layer was applied in all tests onto this artificial surface representing a blocky rock mass. The applied thickness was verified by randomly probing the TSL across the applied surface area. The thickness of the layer depended on the skill of the operator, but on average, it was in the order of 8 mm. The objective was to simulate the underground application of a TSL. Typical practical applications of TSL is less than 5 mm thick (e.g. Tannant[11]), but 8 mm was selected for the tests owing to claims made by a supplier that an 8 mm thick application of TSL will provide a load carrying capacity of 6 and 14 tonnes/m^2 after 24 hours and 14 days of curing respectively.

After various curing intervals, the clamped blocks covered with the TSL on the bottom, was placed on robust supports spaced 1.5 m x 1.5 m apart. This is a typical support spacing used underground in the South African tabular stopes. The clamping rig was then removed. A 1 m^2 area on top of the blocks was loaded (Fig. 10) with increasing mass to determine the load at which the liner would fail. Unlike underground conditions, the tests were repeatable and could therefore provide comparative results for the four different TSL products.

Regarding the loading of the panel, if the sprayed panel could support itself, the surface would be incrementally loaded on top of a 1 m^2 base plate in the centre of the assembly. A static load would be applied by carefully lowering the weight on the assembly of blocks. If the blocks did not fail, the applied mass would be increased and the loading repeated. Testing would be conducted until failure occurred. Fig. 10 illustrates the loading of the sprayed cement blocks.

Fig. 8. Test rig to clamp a number of cement blocks before spraying it with a TSL.

(a) (b)

Fig. 9. (a) Photograph illustrating the rig elevated on a frame with TSL being applied from below. (b) The blocks photographed from below.

Fig. 10. Test configuration showing the sprayed cement blocks suspended on the rigid supports. A 1 m^2 area is being loaded in the middle of the blocks.

4. Test results

As a starting point, testing was conducted using product A. The product was applied and allowed to cure for 4 hours. The intent of the 4 hour tests was to determine the performance of the product after a short underground re-entry period after supporting an area with a TSL. While the clamping forces on the rig were reduced, the TSL failed along the block joint interfaces (Fig. 11). The failure was as a result of direct shear through the liner. There was no indication of adhesion loss between the liner and the block surfaces and the mechanism of failure is therefore similar to that shown in Fig. 5 on the right. Adhesion pull tests conducted on the sprayed blocks (8 mm thick TSL) confirmed the apparent strong adhesive bond (Fig. 12). The photograph indicate tensile failure of the cement material below the TSL/surface interface.

New panels were sprayed to determine if a longer curing period would result in better results. The testing was conducted after 3 and 14 days of curing using the same product. The test results and TSL behaviour were identical to the first test. Products B and C were also tested after 7 days of curing. Both these products failed in a manner similar to product A.


(a) (b)

Fig. 11. Failure of the blocks during the first test with product A. a) Shear failure along the block joint interface while the clamping stress was reduced. b) Collapse of the assembly of blocks while the rig was still being removed.

Fig. 12. Adhesion pull tests to determine the tensile adhesive strength for various curing intervals.

The final product tested was product D. A successful test was conducted after 5 days of curing. The cement blocks and TSL layer was self-supporting after the rig was removed (Fig. 10). The assembly of blocks was then loaded with a gradually increasing mass until failure occurred. This was the first successful test and was used to investigate the most suited loading technique to apply for subsequent testing. Subsequently, more tests were conducted on this product at various curing intervals.

Prior to failure, and once the sprayed artificial surface was statically loaded, a deflection of approximately 1 mm could be measured along the centre of the fully loaded panel. During the failure process, the liner would fail along the block interfaces running through approximately the centre of the sprayed panel. Almost no debonding of the material occurred and the failure mode is therefore similar to that shown in Fig. 5. The tensile strength and material shear strength are therefore important parameters for this TSL and type of failure. Table 2 illustrated the laboratory test results and the strengths of the 8 mm thick material. Tests were conducted on Norite samples. It seems contradictory that in the laboratory, the adhesion values are smaller than the tensile and shear strengths of the TSL material, but in the large scale tests, the tensile/shear type failure mechanism dominates and not one involving adhesion loss. The substrate material for the laboratory and large scale tests were different and the mode of failure in the large scale tests, described in the next section, seemed to have played a role as well. It is important to note that product D has the highest material tensile and shear strength of the four products tested. It is also the only TSL that was able to provide the support to bind the blocks together and carry a substantial load.

The results of the various tests conducted are summarised in Table 3. Somewhat disappointing is that not a significant load could be carried, even by product D. Of interest was the strength of panels coated with product D which were left in the rain during a 3 and 7 day curing interval period. The presence of water during the curing period resulted in premature failure once the rig was removed from the sprayed blocks. It therefore significantly impacted the strength of the liner. Espley et al.[31] performed underground adhesion tests of a liner on rock and shotcrete for various curing times and for various moisture levels. The application surfaces were cleaned prior to the liner being applied. It was found that adhesion strength decreased with increasing surface moisture. This is problematic for underground applications in wet areas as it will result in a weakened layer. This may result in a significant risk of rock falls occurring.

As the large scale TSL tests indicated a small load carrying capacity, shotcrete tests were also conducted to serve as a verification of the test methodology. This indicated that a different type of sprayed liner can indeed provide a substantial load carrying capacity for this particular test methodology. Using the same method as described above, the cement blocks were sprayed with 25 mm and 50 mm thick, 40 MPa, accelerated oxi-fibre shotcrete. The tests were conducted after a 4 and 24 hour curing interval. Only the 24 hour cured 50 mm thick shotcrete assembly remained intact and could be tested. The assembly of blocks with this shotcrete succeeded in carrying a load of 1 100 kg. This is substantially more than the capability of the TSL product D. A 2 000 kg mass resulted in the failure of the assembly (Fig. 13). This was caused by the cement blocks breaking and not the because of failure of the shotcrete-cement block adhesion strength. This contradicts a popular belief in the South African mining industry that shotcrete does not bond well to rock or other substrates.

The preliminary testing was valuable as a number of products could be tested under similar conditions. Disappointing is that none of the TSL products applied to a thickness of approximately 8 mm could match the performance of the 50 mm shotcrete cured for a short period of time. Additional testing needs to be conducted before TSL products can be considered for underground use, especially where early strength is required and when applications are considered in areas where no other support is present. The rock type and surface condition should also be tested for suitability of TSL application. The work in Ozturk and Tannant[27] is valuable in this regard.


(a) (b)

Fig. 13. Cement blocks, covered by 50 mm of shotcrete, was a) able to carry a load of 1100 kg after 24 hours of curing. B) The panel failed after it was loaded with a 2 000 kg mass.

Table 3. Large-scale test data for the different TSL products. The average load for successful tests are given in brackets.

Curing period	No. of tests - TSLs	No. of tests - shotcrete	Product A		Product B		Product C		Product D	
4 hours	3	1	0 kg 0 kg	Failed test Failed test	Not tested		Not tested		0 kg	Failed test
8 hours	1		Not tested		Not tested		Not tested		0 kg	Failed test
1 day	2	2	Not tested		Not tested		Not tested		340 kg 270 kg	(305 kg)
3 days	6		0 kg 0 kg 0 kg	Failed test Failed test Failed test	Not tested		Not tested		400 kg 250 kg Sample in rain 0 kg	(325 kg)
7 days	6		Not tested		0 kg	Failed test	0 kg 0 kg	Failed test Failed test	450 kg 300 kg Sample in rain 0 kg	(375 kg)
14 days	3		0 kg 0 kg 0 kg	Failed test Failed test Failed test	Not tested		Not tested		Not tested	
28 days	2		Not tested		Not tested		Not tested		500 kg 400 kg	(450 kg)

5. Discussion of failure mode during the large scale testing

Products A, B and C appear to be considerably weaker than product D when comparing the material properties as tested in the laboratory (Table 2). During the large-scale tests, the three weaker products resulted in premature failure and the liners could not support the weight of the blocks in the absence of any external loading. The failure mode was typically direct tensile/shear failure of the liner along the block intersections.

During the tests of product D, a small amount of bending of the assembly of blocks (approximately 1 mm) was typically measured. This bending would have resulted in tensile stresses being induced in the liner. Minor tensile cracking could be observed along the block intersections as shown in Fig. 14. Once significant failure occurred along any position of the loaded surface, it would result in extensive failure of the liner and collapse of the structure. Buckling of the assembly occurred across approximately the centre of the panel as can be seen in Fig. 14b. Failure was predominantly as a result of a combination of tensile failure and direct shear failure of the liner (Fig. 15). The failure mode is therefore similar to the theoretical model discussed above for small deformations. The tensile strength and shear strength of the TSL are important parameters to resist this mechanism of failure of a discontinuous rock mass. There were instances where minor debonding could be observed and this is also visible in the photograph. From adhesion pull tests conducted on the surface of the cement blocks, it was observed that debonding did not occur along the block-TSL interface, but rather within the material of the cement block (Fig. 12). Loss of adhesive strength was therefore not an important failure mechanism for the polymer-modified cementitious TSL.

(a) (b)

Fig. 14. Product D being tested after a 7-day curing period. a) During the incremental loading cycles, minor cracks could be observed in positions below the block intersections. b) Typical buckling failure through the centre of the assembly of blocks.

(a) (b)

Fig. 15. TSL shear failure along the block interfaces. a) Minor debonding is visible along the edge of this block. The liner was approximately 8 mm thick. b) The more common direct shear/tensile failure observed along blocks.

From the tests conducted, the typical failure mode can be described as follows:

1. As the blocks covered by the liner was loaded, minor bending of the "plate" was observed. This was small and in the order of 1 mm at the centre of the plate.
2. The liner expanded and was subjected to tensile forces as the surface is deflected downwards.
3. Tensile fractures developed either where the tensile stress was the largest or where the liner was the weakest.
4. In areas where the blocks were displaced the most, the liner experienced minor debonding and further shear/tensile failure. Owing to the complex interaction of the blocks and the loading arrangement, direct shear was also observed in some areas.
5. During the final collapse, the liner and blocks buckled approximately along the centre of the plate.

Although the test methodology may possibly be criticised for producing a complex interaction of block movement and liner behaviour, it is considered a useful representation of the underground conditions where the hanging wall consists of a number of interacting blocks. The tests can be repeated under similar conditions to compare different TSL products. It can be argued that if a TSL product does not even succeed to support a number of lightweight cement blocks between support units, it will never be able to support the large fall of ground shown in Fig. 1. In contrast, Tannnat[11] argued that the role of a liner is to assist the rock mass in supporting itself. If conditions allow the rock mass to unravel excessively, then the liners function should be to retain the loose rocks in place between rock bolts. The type of collapse shown in Fig. 1 is, however, a different failure mechanism consisting of a large single dislodged rock and it is not clear if a liner would be able to prevent this type of collapse. What was evident from the large scale tests conducted, once the cementitious TSL material experience tensile crack initiation and excessive deformation, failure is inevitable.

It is important to understand the underground loading conditions that will be imposed on a liner. Barrett and McCreath[32] proposed that the maximum size block, which an areal support system should be able to arrest, can be estimated by a pyramidal shape with side angles of 60° and a basal area defined by the square support pattern. By assuming this shape, a 1.5 m x 1.5 m support spacing and a rock density of 3100 kg/m^3, this is a weight of approximately 2.5 tons. From the testing conducted on the TSL products available, an 8 mm thick liner will not be able to support such a block. Caution should therefore be exercised when attempting to use a TSL as a structural support element to mitigate the fall of ground problem.

6. Summary

This paper investigated the use of a TSL for stope face support in narrow reef tabular stopes. The application of areal support is a difficult problem in these stopes because of the small stoping width and the large areas of hanging wall that is exposed by the long face lengths and regular blasting. A simple analytical model of a collapsing block supported by a TSL was studied to evaluate the important parameters when considering the underground application of liners. The tensile strength, shear strength and adhesive strength of TSL products are important for the two modes of failure investigated. The analytical models illustrated the sensitivity of the load-bearing capacity of the liner to these parameters and specifically its thickness. Controlling these parameters in underground tabular stopes, where large areas need to be covered with a TSL on a daily basis, is a difficult problem to solve. The required quality assurance may render the liners unsuitable as a structural support element.

Most literature on TSL products focusses mostly on specialised laboratory testing and almost no large scale strength testing has been conducted. To simulate the blocky conditions of the hanging walls in the tabular mining stopes, a large scale test methodology was developed. An assembly of cement blocks of size 1.5 m x 1.8 m was clamped in a rig and sprayed with a TSL. This assembly was then incrementally loaded until failure occurred. For this study, four different polymer-modified cementitious products were tested. The study proved the value of the large scale tests as only one of the products performed satisfactorily. The tests also indicated that the cementitious TSL have a much smaller load carrying capacity than a 50 mm thick, high strength, accelerated shotcrete.

It is concluded that additional testing needs to be conducted before TSL products are considered for underground use as a structural support elements, especially in areas where early strength is required. Certain rock types and surface conditions may also not be suitable for the application of a TSL.

Further work needs to be done on refining the large-scale test methodology. Different types of blocks need to be tested to investigate how a change in rock conditions affects the behaviour of the TSL. Numerical modelling with a distinct element code that can simulate the effect of the liner and the assembly of blocks may also provide additional insight.

References

1. Stanton DW. LEON - Volume 1 1995 - Report of the Commission of Inquiry into Health and Safety in the Mining Industry. Chamber of Mines, South Africa, Electronic copy prepared from the 1995 report; 2003.
2. Malan DF, Napier JAL. Rockburst support in shallow-dipping tabular stopes at great depth. *Int J Rock Mech Min Sci*. 2018;112:302-312.
3. Kaiser PK, Cai M. Design of rock support system under rockburst conditions, *J Rock Mech Geotech Eng*. 2012;4(3):215-227.
4. Jager AJ, Ryder JA. *A handbook on rock engineering practice for tabular hard rock mines*. SIMRAC; 1999.
5. Archibald JF, Mercer RA, Lausch P. The evaluation of thin polyurethane surface coatings as an effective means of ground control. In: *Proc. Int. Symp. on Rock Support – Rock Support in Mining and Underground Construction*, Balkema, Rotterdam, 1992;105-115.
6. Espley S, Tannant DD, Baiden G, Kaiser PK. Design criteria for thin spray-on membrane support for underground hard rock mining. In: *Canadian Inst. Of Mining and Metallurgy Annual Meeting*, Calgary 1999.
7. Stacey TR. Review of membrane support mechanisms, loading mechanisms, desired membrane performance, ad appropriate test methods, *J. S. Afr. Inst. Min. Metall.* 2001;343-351.

8. Yilmaz H. Shear-bond strength testing of thin spray-on liners. *J. S. Afr. Inst. Min. Metall*. 2007;107:519-530.
9. EFNARC. *Specification and Guidelines on Thin Spray-on Liners for Mining and Tunnelling*. July 2008.
10. Kuijpers JS, Sellers EJ, Toper AZ, Rangasamy T, Ward T, Van Rensburg AJ, Yilmaz H, Stacey TR. Required technical specifications and standard testing methodology for Thin Sprayed Linings, SIMRAC Final Report, SIM 020206, 2004.
11. Tannant D. Thin spray-on liners for underground rock support, In: *The 1st International Seminar on surface support liners: membrane, shotcrete and mesh*. Perth, Australia, 22-24 August 2001; 2001:1-12.
12. Guner D, Ozturk H. Experimental and numerical analysis of the effects of curing time on tensile mechanical properties of thin sray-on liners, *Rock Mech. Rock Eng.* 2016 (49); 3205-3222.
13. Shan Z, Porter I, Nemcik J, Baafi E. Comparing the reinforcement capacity of welded steel mesh and a thin spray-on liner using large scale laboratory tests, *Int J. Min. Sci.Tech.* 2014(24); 373-377.
14. Shan Z, Porter I, Nemcik J, Baafi E, Zhang Z. Investigation on the rock surface support performance of welded steel mesh and thin spray-on liners using full-scale laboratory testing, *Rock Mech. Rock Eng.* 2020 (53); 171-183.
15. Yilmaz H, Saydam S, Toper AZ. Emerging support concept: Thin Spray-on Liners, In*: 1st Int. Min. Cong. Exhibition*, Turkey; 2003:65-72.
16. Guner D, Ozturk H. Creep behaviour investigation of a thin spray-on liner, *Int. J. Rock Mech Min. Sci.* 2018(108); 58-66.
17. Guner D, Ozturk H. Experimental and modelling study on nonlinear time-dependent behaviour of thin spray-on liner, *Tunneling and Underground Space Technology* 2019 (84) 306-316.
18. Kanda MJ, Stacey TR. Review of the practical effectiveness of thin spray-on liners based on information from suppliers and observations from the mining industry. *Mining Geomechanical Risk*, 2019;443-458.
19. Swan G, Henderson A. Water-based spray-on liner implementation at Falconbridge Limited. In: *Proceedings CIM/AGM*, Calgary; 1999.
20. Ryder JA, Jager AJ. *A textbook on rock mechanics for tabular hard rock mines. Johannesburg*: SIMRAC; 2002.

21. Squelch AP. The determination of the influence of backfill on rockfalls in South African gold mines. *M.Sc. Dissertation*. University of Witwatersrand. Johannesburg; 1994.
22. Kuijpers JS, Napier JAL. The effect of loading history on stress generation due to inelastic deformations around deep-level tabular stopes. *J. S. Afr. Inst. Min. Metall.* 1991;91:183-94.
23. Roberts MKC, Clark-Mostert V. Is there some commonality between the geological structures in the Bushveld Complex and the Great Dyke?. In: *The 4th International Platinum Conference, Platinum in transition 'Boom or Bust'*, The Southern African Institute of Mining and Metallurgy; 2010.
24. Hartzenberg AG, Du Plessis M. Investigating the mechanism contributing to large scale structurally driven hanging wall instabilities on the UG2 Reef horizon. In*: Proceedings of Eurock*, Saint Petersburg, Russia; 2018:293-297.
25. Ozturk H. Work of adhesion of thin spray-on liners. *Rock Mechanics and Rock Engineering.* 2012.
26. Ozturk H, Tannant DD. Thin spray-on liner adhesive strength test method and effect of liner thickness on adhesion, *Int. J. Rock Mech. Min. Sci.* 2010 (47); 808-815.
27. Ozturk H, Tannant DD. Influence of rock properties and environmental conditions on thin spray-on liner adhesive bond, *Int. J. Rock Mech. Min. Sci.* 2011 (48); 1196-1198.
28. Yilmaz H. Comparison of mechanical properties of shotcrete and thin spray-on liner (TSL). In: *Shotcrete for Africa Conference*, March 2009, ITA, SAIMM and SANCOT; 2009: 251-265.
29. Yilmaz H. Tensile strength testing of thin spray-on liner products (TSLs) and shotcrete. *J. S. Afr. Inst. Min. Metall.* 2010;110:559-569.
30. Yilmaz H. Development of testing methods for comparative assessment of thin spray-on liner (TSL) shear and tensile properties. *PhD thesis*, University of the Witwatersrand; 2011.
31. Espley S, Gustas R, Heilig J, Moreau LH. Thin spray-on liner research and field trials at INCO. In: *1st international seminar on Surface Support Liners: Membranes, Shotcrete and Mesh, Australian Centre for Geomechanics*, Australia; 2001.
32. Barrett SVL, McCreath DR. Shotcrete support design in blocky ground: towards a deterministic approach. *Tunnels and Deep Space*. 1995;10(1):79-89.

List of figures

Fig. 1. A fall of ground arrested by a temporary net in the face area of a platinum mine.

Fig. 2. Use of permanent blast resistant steel nets in the face area of a platinum stope. Visible in the photograph are the other support elements namely rock bolts and cementitious grout packs.

Fig. 3. Blocky hanging wall conditions in a deep gold mine.

Fig. 4. Loose block of rock between two support units.

Fig. 5. An illustration of the TSL failure modes at small displacements as proposed by Tannant[11].

Fig. 6. A section through the block in Fig. 4 illustrating the failure mechanism caused by a loss of adhesive strength and eventual tensile failure of the TSL.

Fig. 7. Effect of adhesive strength on the height of block that can be supported.

Fig. 8. Test rig to clamp a number of cement blocks before spraying it with a TSL.

Fig. 9. (a) Photograph illustrating the rig elevated on a frame with TSL being applied from below. (b) The blocks photographed from below.

Fig. 10. Test configuration showing the sprayed cement blocks suspended on the rigid supports. A 1 m^2 area is being loaded in the middle of the blocks.

Fig. 11. Failure of the blocks during the first test with product A. a) Shear failure along the block joint interface while the clamping stress was reduced. b) Collapse of the assembly of blocks while the rig was still being removed.

Fig. 12. Adhesion pull tests were conducted to estimate the tensile adhesive strength for various curing intervals. The photograph indicate tensile failure of the cement material below the TSL/surface interface.

Fig. 13. Cement blocks, covered by 50 mm of shotcrete, was a) able to carry a load of 1100 kg after 24 hours of curing. B) The panel failed after it was loaded with a 2 000 kg mass.

Fig. 14. Product D being tested after a 7-day curing period. a) During the incremental loading cycles, minor cracks could be observed in positions below the block intersections. b) Typical buckling failure through the centre of the assembly of blocks.

Fig. 15. TSL shear failure along the block interfaces. a) Minor debonding is visible along the edge of this block. The liner was approximately 8 mm thick. b) The more common direct shear/tensile failure observed along blocks.