Evaluating the behaviour of stiff polymer-modified cementitious thin spray-on liners from small and large scale testing

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Abstract. The application of permanent areal support is recognised as a measure to either retain or prevent the mobilization of potentially unstable keyblocks between installed support elements. Various areal support methods have been developed to provide support to the freshly exposed area created by the blast and to provide support between existing support elements. These methods consist of either shotcrete, thin spray-on liners (TSL), blast resistant mesh or temporary (removable) nets. This paper focuses on the application of polymer-modified cementitious TSLs which is the type predominantly applied in South-African underground mines. Significant amounts of research has been conducted on TSLs. The majority of the research consisted of predominantly laboratory testing. The results of the tests only provide an output which can be used to measure a specific characteristic (i.e. tensile strength) against other products. The output obtained from laboratory tests are not understood, cannot be benchmarked against good or poor performing products or quantitatively related to the performance of the product when applied in-situ on a large scale. This situation is problematic as different support suppliers make claims in terms of the performance of their products based on a material property or small scale testing. The behavioural mechanism of a rockmass supported by TSLs is not understood. It is therefore not clear what critical TSL parameters will affect rockmass stability. Very little work has been conducted locally to test the in-situ behaviour of TSLs once applied. An extensive testing program was developed to establish how the material properties of a TSL as tested in a laboratory would relate to small and large scale in-situ behaviour. This paper discusses the testing conducted and the high level findings.

1. Introduction
In the South African narrow tabular platinum mines, fall of ground (FOG) incidents can occur as a result of the failure of either support elements or keyblocks present between support elements. In most cases, the reinforced hangingwall will prevent the unravelling of the hangingwall. The face area has been the focus of best practice initiatives to ensure that workers are not injured in this “high risk” area. For more than two decades the need for permanent areal support has been recognised as a measure to either retain or prevent the mobilization of potentially unstable keyblocks between installed support elements [1][2].

From the mid-to late 1990’s, in-stope tendons were introduced on some narrow tabular platinum mines in an attempt to reduce the fall of ground risk due to challenging geotechnical conditions (i.e. UG2 triplet package). The technology significantly improved the fall of ground instances on the mines which introduced this application. Due to implications on cost, labour, equipment restrictions and
cycle time, the application was not embraced by the greater mining industry. During the 2000’s, improvements in bolting systems (type), and methods (remote or mechanised installations) as well as the development of temporary removable hangingwall face nets (areal support) continued on some operations which had the foresight to develop or embrace new technology to reduce the fall of ground risk. In 2013 only, bolting with netting was introduced to the platinum industry as a leading practice and compliance enforced through the mining charter. Since 2011 various attempts have been made to develop and install permanent blast resistant mesh in narrow tabular stopes to stop all falls of ground and establish a next leading practice. Unfortunately, the mining industry does not always embrace new technologies or recognize leading practices [3].

In 2017, the application of additional areal support was advocated by the mining regulator in the Platinum Region of South Africa in an attempt to reduce the injury of persons entering the unsupported face area. Consequently, an instruction was issued to all mines in the specific region to ensure that all active mining areas are supported additionally by means of an appropriate support system with overall area coverage. Although the instruction to introduce an additional system to prevent falls of ground was novel, the lack of understanding and the misguided conception construed the development or application of fit for purpose interventions. The instruction specified that this additional support system must have; (i) long term bonding strength, (ii) consists of a thermo pseudo plastic polymer base, (iii) must not be brittle, (iv) must have biaxial flexural strength and (v) allow for deflection of more than 5 mm over time. The instruction being specific, pertained to the application of TSLs. As a result, areal support systems with known strength characteristics were not considered as suitable support systems to provide the additional areal support required as per the instruction. This eliminated considerations such as shotcrete, temporary or permanent nets or mesh which have been well researched, tested and applied as integrated areal support systems for various geotechnical applications across the globe.

TSLs on platinum mines have in most instances only been applied as a secondary support medium to long term excavations. The application was intended to provide a rock consolidation or sealing function which would at best contain small (fist size) keyblocks exposed along the surface of a previously developed and supported excavation. Platinum mines in South Africa are predominantly characterised as being low-to medium stress environments subjected to deadweight loading. Keyblocks are most commonly formed as a result of the intersection of steep dipping planar joints (pegmatite veins or joint clusters) and shallow dipping discontinuities which can also include large scale ramp structures [4]. In addition, the presence of high horizontal stresses across the Bushveld Complex [5] result in the exposed excavation hangingwall being in tension [6]. In most cases, inadequate areal coverage or interaction between support units result in FOG incidents. Open joints are uncommon unless as a result of large scale instability. The potential block interlock mechanism [7] or joint penetration effect [8] will have questionable relevance in this specific environment.

Unfortunately, unproven performance capabilities claimed by manufacturers as a marketing strategy were sold to a disillusioned and uninformed industry. Statements were made that an 8 mm thick application of TSL could provide a support resistance of 6 and 14 tonnes / m² after 24 hours and 14 days of curing respectively. This information was misleading and could contribute to unpredictable rockmass instability. It was therefore an attractive option for the mining regulator to implement as a strategy to reduce the fall of ground risk. However, TSL characteristics such as support resistance capabilities, blast resistance, mining cycle compatibility or health impacts for large scale and high volume applications at a mining face in a narrow tabular application has never been considered or quantified.

Although TSLs have been tested and used as areal support in the mining industry for more than 25 years, no consensus has been reached on a standardised testing methodology. While parameters such as tensile and tensile adhesive (bond) strength has been identified as the dominating performance characteristics, almost no work was done on the mechanism of failure of an in-situ rockmass supported by TSLs. It is therefore not clear what critical TSL parameters will affect rockmass stability.
Additionally, attempts have also been made to apply numerical modelling techniques (finite element modelling) to simulate the impact of material properties on the support action of TSLs. This paper summarises the extensive testing program conducted to establish how the material properties of a TSL as tested in a laboratory may relate to large scale in-situ performance characteristics.

2. Testing
The site preparation and underground application of a liner is the most critical component to ensure the product could perform as anticipated. Generally, the rock surface is dirty and needs to be cleaned before application. The product must also be prepared and applied according to the specified method. The underground application of TSL in the South African platinum mines are mostly reliant on unskilled labour and therefore, in most cases, the proper application process is not followed. Also, the underground environment is subjected to heat, humidity, ventilation, water, different rock types (surfaces) and geology (jointing) which may also impact on the product performance. A significant degree of uncertainty therefore exist regarding the in-situ performance of the applied product, which must be further investigated.

The intent of the testing program was to determine how the material properties of TSLs interact and could be related to large scale and in-situ performance. Three sets of tests were conducted:
1. Laboratory testing to establish the material properties of the TSLs considered,
2. Large scale behavioural and support resistance testing in a surface mock-up,
3. Underground in-situ testing.

2.1. Laboratory testing
Four different TSL products were selected for laboratory testing. The selection was guided by the specification contained in the instruction from the mining regulator and application trials being conducted by the major platinum mines as a result of the instruction. Although only one manufacturer listed biaxial flexural strength as a performance characteristic, the independent lab results indicated that all 4 products met the minimum biaxial flexural strength and deformation specified by the mining regulator. The 4 products tested are denoted as products A-D. All four products were 2-part polymer based non-reactive cementitious spray on liners.

Based on the outcome of a PhD study conducted [9], the following TSL material properties are generally tested for the South African market; tensile strength, tensile-adhesion strength (bond), shear bond strength and material shear strength.

The average results of the tests conducted are summarised in Table 1. The performance ranges for the various parameters tested can also be classified in terms of weak, medium, strong and very strong [9]. This does however not relate to the overall performance of a product when applied in-situ as the product is reliant on all the parameters to interact to offer a support function. These performance ranges are not included in the paper for the products or parameters tested.

2.2. Large scale surface tests
The intent of a liner application is to assist the rockmass in supporting itself [11]. Once a deadweight of rock has been mobilized, it is difficult if not impossible for a liner, which has limited load capacity to resist such movements. Also, if conditions allow the rockmass to loosen excessively, then the liner's function should be to retain the loose rocks in place between rock bolts [11].

Almost no research has been directed to simulate the performance or failure mechanism of TSLs on a large scale. Findings from a large scale plate pull test [12] and a large scale baggage capacity test conducted [13] identified tension and adhesion strength properties to contribute to the loose-rock-supporting capacity of the test set-up and concluded that the interaction between loose blocks is enhanced when coated with a TSL.

The intent of the large-scale tests conducted by the author was to establish how the properties of a TSL could interact and provide stability to a jointed mass spanning between installed support units.
Large scale surface tests were conducted with a 1.5 m (w) x 1.8 m (l) test jig loaded with an external mass across a 1.5 m x 1.5 m support spacing [14]. Repeatable, comparative testing was conducted to establish the performance characteristics of the applied TSL on a larger scale. On a larger scale all of the properties of the product would have to interact to offer support resistance at small displacements. Also, the behaviour of the applied product could be observed when the sprayed mass was loaded to failure. For all the tests conducted an 8 mm thick layer of TSL was applied.

Panels sprayed with products A, B and C were tested up to 14 days of curing, but continued to prematurely fail in the absence of any external loading. Only product D yielded results. A total of 26 tests were conducted which included 23 TSL and 3 shotcrete panels. The average performance per curing interval of the externally loaded sprayed mass for product D was: 1 day (305 kg), 3 day (325 kg), 7 day (375 kg) and 28 day (450 kg). At failure, the liner would shear along the joint interfaces running through approximately the centre of the sprayed panel. For comparative purposes, panels covered with 50 mm quick setting oxifibre shotcrete was also tested. A panel cured for 24 hours was able to carry a load in excess of 1100 kg.

From the large-scale tests conducted, it could be observed that only once the sprayed surface was significantly loaded, the material would fail predominantly in observed shear. Loading of the mass resulted in flex of approximately 1 mm across the span between the supports. This induced direct tension (stretch) in the liner resulting in the snap through failure along the joint plane running through, approximately the centre of the panel.

| Test parameter | Curing interval (Days) | A    | B    | C    | D    |
|----------------|------------------------|------|------|------|------|
| Tensile strength | 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 | 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 | 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 | 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|
| Biaxial flexural strength | 1                      | 1.52 | 3.51 | 1.32 | 10.31|
|                 | 3                      | 7.69 | 5.99 | 5.76 | 13.83|
|                 | 7                      | 9.19 | 7.09 | 9.40 | 15.01|
|                 | 28                     | 9.84 | 5.29 | 7.66 | 13.06|

*Anomalous values for tensile adhesive strength for products A and B are highlighted in the table.*
2.3. In-situ testing

Two types in-situ tests were conducted:

1. Tensile adhesion tests,
2. Plate pull tests.

The intent was to determine and potentially relate the in-situ product performance characteristic of a TSL to the results obtained in the large-scale jig tests and laboratory tests. As product D was the only successful product tested in the large scale tests, the product was used to conduct all of the underground tests.

In platinum mines, the application surfaces will vary between Pyroxenite, Chromitite and Norite or Anorthosite. As these rock types are morphologically significantly different, some rock types are more prone to absorb and contain water in the rock structure. Tests were therefore conducted on all 3 rock types. The application and test surfaces were also varied to determine the impact on the performance of the product, namely:

- Dusty surface (rock surface is not washed and material was applied on the exposed rock surface),
- Wet surface (rock surface was washed and the TSL is applied while the surface was still wet),
- Clean and dry surface (rock surface was washed and allowed to dry prior to the TSL being applied).

Three tests were conducted for every variation. Tests were repeated for curing intervals 1, 3, 7 and 28 days. Thirty-six of each test type would therefore be performed per rock type for the range of curing intervals and three different prepared surfaces (108 tests per test type – either tensile adhesion or plate pull tests). Note that both of these methods are very time consuming and difficult to conduct regularly underground should it be considered as a method to determine an acceptable application quality control.

2.3.1. Tensile adhesion tests. Once the TSL was applied to the respective rock surface, a portion of TSL was overcored to create an isolated disk of TSL bonded to the rock surface. A dolly was glued to the TSL surface. Both mechanical (drill) versus hand cutting methods were attempted to create the bonded disk of TSL to best preserve the Rock-TSL bond interface. At each respective curing interval, the dolly was pulled with a pull test ram mounted on a tripod. The failure mode observed and load achieved was recorded to derive the tensile adhesive (bond) strength (MPa). The intent was to relate the in-situ bondage capability of the TSL to the laboratory performance.

With all of the tensile-adhesion tests conducted, the TSL failed either within the material or along the glued Dolly–TSL interface rather than detaching from the rock surface. This indicated that the bond strength between the TSL and rock surface was greater than the material shear or glue’s adhesive properties. Very few successful tests could be performed. The results obtained from the tensile-adhesion tests ranged between 0.25 – 0.5 MPa and 0.5 – 1 MPa for the 24 hour and 7 day tests respectively. In all cases the Rock–TSL adhesion strength was greater than the measured strengths. It was however not measurable. The lab result may therefore be justified and absolute.

In most cases, this test method only determines an indirect quantity of either shear strength of the material, the tensile strength of the glue or the state of the application surface depending where the samples fails; i.e. Glue – Dolly interface, within the TSL or along the applied surface. Consultation with TSL manufacturers [15][16] who have attempted the same testing method at various platinum and chrome mines confirmed similar behaviour and results. The measured underground performance and observed behaviour is therefore not anomalous. The tensile-adhesion tests conducted was of little value. It did confirm that the method of testing was not well suited as a routine in-situ quality control tool or to relate in-situ to laboratory product performance.

Previous tests conducted at various gold mine sites concluded that the underground adhesion strengths were much lower than the laboratory results, predominantly due to poor surface preparation. The results of the 88 in-situ tensile-adhesive tests conducted showed a variation between test sites and...
a variation between individual tests at any particular site [17]. Tensile adhesion tests conducted at another gold mine site indicated the underground strength result obtained was less than half the manufacturer’s specification derived from laboratory testing [18]. *In-situ* tensile adhesion tests are therefore not advocated to derive a TSL performance characteristic.

### 2.3.2. Plate pull tests.

An alternative method to better resemble both the tensile, material shear and adhesion properties of an applied TSL would be to conduct a plate pull test. The process requires a dolly to be placed on the bare rock surface. TSL would be applied over the dolly to the required thickness. The dolly would be pulled through the TSL to determine the failure load. From observation, the mode of failure (shear, debonding or a combination of both) can potentially be used to determine the characteristics of the applied TSL. Three different modes of failure were recorded (figure 1):

A. **Debond:** TSL material debonded from the surrounding rock surface. The combination of tensile and material shear strengths of the TSL are greater than the adhesion strength. The material predominantly fails in tension once the debonded surface significantly increased.

B. **Shear:** The TSL material fails by shearing immediately around the dolly or within an enlarged diameter within the TSL. The adhesion strength of the TSL is greater than the combination of both shear and tensile strength. The material displays high bond strength. Once the tensile strength is exceeded, the material will fail in shear without any debonding taking place.

C. **Combination of debonding and shear:** The TSL material partially debonds from the rock and shears through the TSL material, usually at an enlarged failure diameter. The material tensile and adhesion strengths are approximately equal. The material partially debonds. Once the tensile strength acting across the affected area is compromised, the material subsequently fails in shear over an extended area.

![Figure 1](image_url)

**Figure 1.** (a) Mode A failure, (b) mode B failure and (c) mode C failure. The arrows in the photographs indicate where the liner failed in tension across an effective width, \( w_e \). Note the position of the failure surface relative to the failure mode experienced (Rock–Liner interface versus top of liner or a combination).

The small scale *in-situ* plate pull tests conducted were valuable to observe the behaviour of the liner subjected to an axial load. It created a better understanding of the small-scale liner behaviour. This may not necessarily be relatable to an underground scenario where the liner will be loaded by large keyblocks between installed support or by a damaged rockmass.

108 Plate pull tests were conducted along 3 different rock types and 3 different rock preparation surfaces. A range of minimum / maximum performance could be defined. The tests were useful in establishing general behavioural trends from small scale repeatable performance testing.

From the *in-situ* tests conducted, a very thin failure surface could be observed around the perimeter of the liners failure zone (refer to figure 1). This failure surface was prevalent where the liner was subjected to the highest tensile forces and subsequently failed in tension resulting in the failure mode observed. The failed surface area was approximately 0.1 x the liner thickness (approximately 1 mm).
and is defined as an effective width, \( w_e \). Figure 1 shows this effective width and the position relative to the liner’s zone of failure for each respective failure mode observed (A - C).

Figure 2 shows examples of some of the comparative outputs expanded on below. The high level findings concluded from the test results were:

- Most samples did not show significant strength increase beyond 7 days of curing. After 1, 3 and 7 days of curing approximately 60%, 75% and 90% of the total performance was achieved respectively,
- 50% of the samples applied on a clean dry surface failed by a combination of bond and shear (mode C failure),
- Type C failure modes result in the best performance,
- A dry clean Norite surface yielded the best performance and defined the upper performance limit (figure 2a). The Norite samples displayed high early strength and maintained the strengths from approximately 3 days onward. The tested samples had an approximately 60/40 type B/type C failure mode ratio. Bonding improved over time resulting in improved performances at 28 days,
- Approximately 50% of the wet surfaces failed as a result of shear (mode B failure),
- A dusty UG2 surface yielded the worst performance and defined the lower performance limit (figure 2b). The UG2 samples generally tested along the bottom performance limit irrespective of the surface condition. Fifty-five percent of the UG2 samples failed by a combination of bond and shear (mode C failure). However after 7 days of curing it appeared as if the bond strength to the rock surface slightly improved resulting in more mode B failures,
- Wet Pyroxenite surfaces resulted in improved bonding. Pyroxenite typically absorbs water, which may result in improved curing conditions. The Pyroxenite samples typically bonded well to the rock surface. However, as the material cure and the material gains strength, the surface contact area may fail as a result of the large grains constituting the material.
- Dusty UG2 and Pyroxenite surfaces archive approximately 76% and 80% of the Norite samples performance (figure 2b),
- Clean and dry UG2 and Pyroxenite surfaces archive approximately 67% and 83% of the Norite samples performance (figure 2a).

![Shear-Tensile strength test (various rock surfaces) - dry clean surface](image1)

![Shear-Tensile strength test (various rock surfaces) - dust](image2)

**Figure 2.** Plate pull test results for TSL applied on a dry-clean (a) versus a dusty surface (b) for various rock types. Failure mode A (debond), B (shear) and C (combination of both bond and shear failure) are indicated on the figures.
3. Interpretation of results

The following observations could be related when comparing the underground plate pull test results to the laboratory results (Table 1). Note that these observations could only be considered for similar sample conditions; that is laboratory, clean and dry Norite samples versus underground clean and dry Norite samples:

- Laboratory measured tensile adhesive strength significantly increased from 1 – 3 days of curing,
- After 3 days of curing, the underground plate pull test result were approximately double the laboratory tensile adhesion test result (7 MPa vs 4 MPa) for product D,
- Underground, failure was as a result of high tensile strength displayed by the sample. The adhesion strength had to exceed the tensile strength for the material to fail in shear (within itself) – mode B,
- Of significance was that product D had higher laboratory measured material shear strengths up to 3 days of curing. Thereafter the strength parameter was lower, compared to the other 3 products tested. Early material strength may therefore have a significant impact in the overall performance of a product.
- The interaction of material properties on one another are most likely underestimated.
- Of significance is that product D had significantly higher laboratory measured tensile and tensile adhesion strengths.
- The product also measured the highest biaxial flexural strength. This suggests that the interaction of critical material parameters contribute to material behaviour allowing beam / material flexing with increased tensile loading capabilities. This is potentially the characteristic which controlled the behaviour of the large-scale tests.
- From the underground and large scale tests observations, it could be noted that, once the tensile strength is exceeded for a bonded area, the material fails in shear.

The plate pull tests gave insight to the liners performance when applied on different rock types and different application surfaces conditions. From the results achieved it was very clear that TSLs are less effective in certain environments. It is also very clear that laboratory results cannot be replicated underground. The tests were insightful in understanding the small scale liner behaviour which may impact on large scale performance.

The extensive in-situ and large-scale testing conducted brought along new insight and understanding with regard to stiff type TSL behaviour which needed to be considered and further expanded on.

The applied liner uses a combination of shear, adhesive and tensile strength to resist minor shear displacements. If the liner does not debond, direct shear or diagonal tensile shear failure will occur with negligible keyblock displacement. From the plate pull tests results, it could be observed that irrespective of the liner thickness, failure as a result of induced tension occurred along a very small surface area which resulted in the complete failure of the liner. This surface area is located at the position where the tensile stress, \(\sigma_t\) would have been the greatest and is dependent on the failure mode (A, B, C). The support ability of the liner is therefore a function of the tensile stress acting across this effective width, \(w_e\) along the perimeter length of the failure zone. Tensile failure transpires in the observed shear rupture across the liner thickness.

The estimated height of a block that can be supported by a liner is given by equation (1). The equation is derived from the applied axial force required to destabilize a keyblock, inducing a tensile force \(T\) acting across an effective width, \(w_e\) along the failed perimeter length, \(L\) of the debonded zone.

\[
h = \frac{L \cdot \sigma_t \cdot w_e}{\rho \cdot g} \quad \text{(per m)}
\]  

(1)

Ozturk [19] defined a “work of adhesion” property as a function of the adhesion strength, \(\sigma_a\) acting across an effective bond width, \(w_b\). He derived the parameter by applying an energy balance approach.
using pull-out load displacement data and determining the work required to separate a unit area of TSL from a substrate. Ozturk considered the combined results of dogbone tests, tensile adhesion tests and a back-to-back pull tests using a 2-component cement based polymer liner. The product performance characteristics was similar to products (A-D) as defined in table 1. The findings from the study indicated that the product had a work of adhesion range between $777 - 973$ N/m. This also related to an average effective bond width, $w_b$ of 0.7 mm on different substrates. This was a significant finding and contradicted the belief of previous researchers that the adhesion strength acted across and effective bond width, $w_b$ equivalent to the liner’s thickness [11]. Ozturk noted that the defined design methodology took into account the adhesion strength behaviour of the liner. However, once deboning took place the tensile strength would control the failure of the liner. Ozturk did also only consider the properties of the liner based on small scale tests. He did not have the insight of additional large scale tests where induced liner flex would result in tensile failure and resulting shear irrespective of the bond condition.

Back calculations of the large scale and in-situ plate pull tests results indicated an effective bond width, $w_b$ ranging between 0.5 – 0.8 mm. The work of adhesion values for product D ranged between 2000 - 3000 N/m. Although additional test verification may be required, the results were relatable to Ozturk’s findings. From the test observations it was noted that the support ability of the liner was more dependent on the tensile stress acting across an effective width, $w_e$ along the perimeter length of the failure zone. The adhesion and tensile strengths for product D are approximately equivalent for the various curing intervals (table 1). It may therefore be assumed that the effective width, $w_e$ as observed in the plate pull tests is equivalent to the effective bond width, $w_b$ for the stiff type liners considered in the testing program. The test results verify the significant overestimation of a liners performance when assuming that the tensile or adhesion strengths act over an effective width equivalent to the liner thickness\[11\] as oppose to only a small portion (1/10) of the liner thickness. It clarifies the misconception and false information put to the greater industry by some manufacturers that, TSLs have support resistance (SR) capabilities > 10 000 kg/m². These numbers “quoted” were related from small scale testing where; e.g. TSL applied over an approximately 50 mm core insert drilled from a granite slab. The push force (≈ 430 kg) to break the 8 mm thick TSL over a 157 mm core perimeter length, $L$ was extrapolated to have a support capacity per square metre (4 m perimeter length) of 10950 kg/m² by assuming a linear size-strength relationship;

$$SR = \frac{P}{L} = \frac{430}{\left(\frac{157}{4}\right)} = 10950 kg/m^2$$

(2)

However, if the strength properties of this liner is considered ($\sigma_s = 1.86$ MPa; $\sigma_t = 3.54$ MPa), the support resistance per square metre (722 kg/m²) can be estimated from equation (1) for a perimeter length of 4 m, assuming $w_e = 0.5$ mm and $\rho = 3000$ kg/m³. Nevertheless, during the large-scale tests, this product could not support approximately 100 kg/m² after 14 days of curing.

The maximum size of a loose keyblock which an areal support system should be designed to resist, can be estimated by a prism with side angles of 60 degrees between installed support units [20]. A 1.5x1.5 m spacing similar to what was used in the large scale tests set-up (2.25 m²) equate to approximately 2500 tonnes or 29 kPa of support pressure. These capabilities cannot be met by TSL’s and care should be exercised when attempting to use TSL’s as a structural support to manage a fall of ground problem.

4. Conclusion
An extensive testing and research program was developed to establish how the material properties of a TSL as tested in a laboratory could relate to large scale in-situ performance characteristics. The in-situ and large scale tests conducted were very valuable in conducting repeatable comparative testing. It also identified the most critical parameters influencing the performance of a liner for the testing
methodology followed. Biaxial flexural strength properties were measured for each product. The validity was not further explored as it is not believed to contribute to the overall behaviour of a TSL.

Interpretations from small-scale lab tests on intact samples subjected to slow loading rates may also present fictitious results when extrapolated to a larger scale. In reality the liner will fail due to direct tension as a result of snap-through or surface tension observed as direct shear failure. The in-situ application of a liner must consider a massive jointed rockmass, which will be subjected to instantaneous axial loading (gravity), no clamping forces (hangingwall subjected to tensile forces) for an area of at least 1.5 – 2.25 m². From the tests conducted it could be concluded that liner elongation (stretch) and permittable displacement governs the liners ability to resist both shear failure and tensile rupture. The results may be conservative but is based on actual test data. Also, the findings substantiate the assumption that the tensile stress only acts over a small effective width, \( w_e \) prior to rupture. For stiff type liners, this effective width is approximately equal to the effective adhesive bond width, \( w_b \) defined by previous researchers. Without this insight, significant overestimation of a liners performance may result. It is believed that this parameter would control the liners ability to resist load. Liner flexing (deflection), stretch or loading result in induced tension. When the tensile stress of the liner acting across the effective width is exceeded, the liner fails in observed shear. It is therefore the tensile rather than adhesion strength that controlled the performance of the stiff type liners considered in this study. 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.

References
[1] Jager AJ and Ryder JA 1999. A handbook on rock engineering practice for tabular hard rock mines. SIMRAC; 1999.
[2] Malan DF and Napier JAL 2018. Rockburst support in shallow-dipping tabular stopes at great depth. Int J Rock Mech Min Sci. 2018;112:302-312.
[3] Pretorius, M 2018. The successful extraction and bennification of the UGS split reef. Proc. ARMS 10. Singapore
[4] 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.
[5] Stacey, T and Wesseloo, J 1998. In situ stresses in mining areas in South Africa. Journal- South African Institute of Mining and Metallurgy. 98. 365-368.
[6] Watson, BP 2010. Rock Behaviour of the Bushveld Merensky Reef and the Design of Crush Pillars. PhD thesis, School of Mining Engineering, University of the Witwatersrand, Johannesburg, South Africa.
[7] Stacey TR 2001. Review of membrane support mechanisms, loading mechanisms, desired membrane performance, ad appropriate test methods, J. S. Afr. Inst. Min. Metall. 2001;343-351.
[8] Borejszo, R and Bartlett, P 2002. Developments and the future of thin reactive liners since the previous conference in Australia. In. 2nd Int. Seminar on Surface Support Liners: Thin Sprayed Liners, Shotcrete, Mesh. S. Afr. Inst. Min. Metall., Section 13, pp.1-10. South Africa.
[9] Yilmaz H 2011. Development of testing methods for comparative assessment of thin spray-on liner (TSL) shear and tensile properties. PhD thesis, University of the Witwatersrand.
[10] Yilmaz, H 2019. Laboratory test results of thin spray liner strength parameters. Consultancy report, South Africa.
[11] Tannant, D 2001. 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] 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.

[13] Swan G, Henderson A. Water-based spray-on liner implementation at Falconbridge Limited. In: Proceedings CIM/AGM, Calgary; 1999.

[14] Du Plessis, M and Malan, DF 2021. Investigating the use of polymer-modified cementitious thin spray-on liners for stope face support. Int.J. Rock Mechanics and Mining Sciences.

[15] O'Connor, D 2019. Personal communication, Minova, South Africa.

[16] Van der Sandt, H 2019. Personal communication. Provest group, South Africa.

[17] Kuijpers JS, Sellers EJ, Toper AZ, Rangasamy T, Ward T, Van Rensburg AJ, Yilmaz H, Stacey TR 2004. Required technical specifications and standard testing methodology for Thin Sprayed Linings, SIMRAC Final Report, SIM 020206, 2004.

[18] Carstens, R and Oosthuizen, AO 2004. Application of thin sprayed liner (TSL) in VCR gullies behind advancing stope panels at Savuka Mine. SANIRE 2004, The Miner’s guide through the earth’s crust, South Africa. pp 89-94.

[19] Ozturk H 2012. Work of adhesion of thin spray-on liners. Rock Mechanics and Rock Engineering.

[20] Barrett SVL, McCreath DR. Shotcrete support design in blocky ground: towards a deterministic approach. Tunnels and Deep Space. 1995;10(1):79-89.