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Thin spray-on liners: a historical overview and their future potential as support in underground coal mines

Claire Morton
University of Queensland

Zhongwei Chen
University of Queensland

Mehmet Siddik Kizil
University of Queensland

THIN SPRAY-ON LINERS: A HISTORICAL OVERVIEW AND THEIR FUTURE POTENTIAL AS SUPPORT IN UNDERGROUND COAL MINES

Claire Morton[1], Zhongwei Chen[2] and Mehmet Siddik Kizil[3]

ABSTRACT: Thin Spray-on Liner (TSL) is a fast setting, multi-component, polymeric material that is designed to be spray applied to a rock surface and provide areal support. TSLs are widely used in hard rock mining and some civil applications; however, they are yet to become a preferred support element in coal mining operations. Understanding of how TSL products behave to provide support to a coal rock mass and how they can be tested and monitored in-situ, is not well enough understood for them to be included as a routine support system. This presents a current challenge to the industry as how the assessment of a TSLs suitability or comparability to an existing support method can be done. This paper provides a broad overview of how TSLs have been used and tested to date and offers some insights into the future direction for establishing their use in underground coal mines.

BACKGROUND

To date, the application and design of TSLs in underground coal mines has been based on experience, field observations, engineering judgement and assumptions. It presents a current challenge to the industry as to how the assessment of a TSL's suitability or comparability to an existing support method can be done. In order to accurately quantify the parameters that are critical to a TSL to adequately support a rock mass under the effects of fracturing, induced stresses and rock mass instability, the mechanisms by which the liner actually supports the rock need to be reviewed, understood and incorporated into an engineering support design (Saydam, *et al.,* 2003).

TSL properties have been estimated and measured in the laboratory with testing methods continually being adapted and refined. In some material property testing, TSLs have proven to outperform other spray liners such as shotcrete (Yilmaz, 2011). However, coal specific laboratory and coal mine site testing and observations are underrepresented in practice and in literature. Thus, there is little use of TSLs as a support mechanism in underground coal mines, where mesh, both steel and cuttable, is used as the primary areal support for both roof and ribs. Using TSLs as part of the support method can potentially improve the advancing speed of development faces, in addition to offering a reduction in manual labour and reduced exposure to ground conditions for personnel, if it can be demonstrated that its technical performance is as good, or better, than current systems.

The onsite geotechnical engineer has the challenge of ensuring that any type of support that is introduced or used in a support design in lieu of an existing support type, meets or exceeds the performance specifications for the existing methods. The use of TSL as a support product has previously presented a challenge to this requirement as the behaviour and performance is quite different to any other support types in use.

While TSLs have been in use successfully in various types of tunnelling and mining environments (Yilmaz, 2011), their use in coal mines has not progressed as quickly. This may be in part because of the actual mechanical properties of coal and its ability to maintain structural integrity in laboratory testing. Pan *et al.* (2013) describe how the mechanical properties and behaviour of coal is different to rocks and governed by the rank of the coal and its microstructure. Furthermore, they found that the ability of coal to resist deformation is dependent upon the orientation of forces applied relative to the cleat alignment and the coal's microstructure. The direction of mining relative to cleat and fracture orientation cannot always be planned to provide the most favourable outcomes for adhesive support systems. Localised variation within coal measures means cleat and fracture orientation may vary over

[1] *Claire Morton, School of Mechanical and Mining Engineering. The University of Queensland. Email:* c.morton@uq.edu.au
[2] *Dr Zhongwei Chen, Senior Lecturer, School of Mechanical and Mining Engineering. The University of Queensland. Email:* zhongwei.chen@uq.edu.au
[3] *Assoc. Professor Mehmet Kizil, Mining Program Leader, School of Mechanical and Mining Engineering. The University of Queensland. Email:* m.kizil@uq.edu.au

short distances. Perhaps this adds additional complexity when trying to determine the effectiveness of a spray-on liner whose effectiveness relies on its ability to penetrate open spaces with the coal rock.

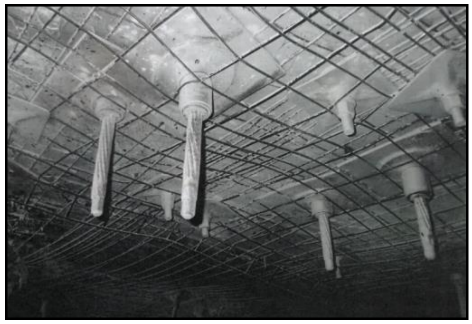

Figure 1: Photo of roof support in an underground coal mine showing mesh, bolts and cable support

The Australian mining industry developed a keen interest in the potential use of TSLs in both hard rock and coal mines due to the knowledge of their successful use abroad (Potvin and Nedin, 2003). A surge in interest initially resulted in the development of many TSL variations by various product manufacturers. However, many of the products were deemed unsuitable due to the inadequate mechanical or chemical properties. Since then, many of these products have been redesigned or new ones developed, but in the literature still no TSL system has achieved success to act as a standard mode of support in underground coal operations (Guner and Ozturk, 2018).

WHAT IS TSL

TSLs have generated interest since the early 1900's when the first cement gun was used to spray an early type of shotcrete. The ease and speed of application of this type has widespread appeal for many industries, and TSLs are widely used in hard rock and civil applications throughout the world. Common TSLs, also referred to as skins or membranes, are reactive or non-reactive polymer or water-based materials formed from a combination of a multi-component, polymeric material, cement and sand, or cement only, that are sprayed onto the rock surface at a thickness between 3 mm and 5 mm, and form part of a surface support system (Yilmaz, 2011). TSLs are applied close to the mining face to contain spall and unravelling of rock. The use of flexible support membranes prevents rock degradation and structural failure of excavations by mobilizing and conserving the inherent strength of the rock mass immediately about the excavation surface (Tannant, 2001). By applying a liner to a freshly exposed rock face, fractures can be prevented from dilating and any potential blocks secured in place. Early restriction of movement of this type could offer improved strength of the rock mass and overall increasing the stability of the excavation. Research has also been conducted into the ability of TSLs to mitigate the impact of rockburst in controlled environments. This work has produced positive results, indicating that TSL may have application in mines that are prone to outburst type conditions (Archibald and Dirige, 2006).

Kanda and Stacey, 2019 investigated the performance of TSL in various hard rock mines in South Africa and collated their findings to present varied uses of TSLs at different operations. They reported that various TSLs had been used for reasons such as preventing falls of ground, reduce scaling of pillars, mitigate the need for barring down and as a secondary support element. Pending the performance of TSL in underground coal, if proven to be a successful support material this indicates that the potential uses of TSL are wide spread, depending on the properties of the individual product.

HOW TSL WORKS

A quality liner will adhere strongly to the surface on which it is sprayed and provide containment to the rib side. As with all reinforcing support schemes, a supporting TSL is designed to develop forces in response to ground movements to minimise deformation and displacement. To be effective in this, the liner must have sufficient integrity to limit the movements of individual blocks of rock. Coal is inherently a heavily jointed rock mass, which tends to unravel easily once spalling has begun. If a liner can act to prevent the initial spalling and subsequent unravelling of blocks of coal in the rib or roof, then the coal blocks are forced to interact with each other essentially creating a stable beam. This is a critical point of differentiation between mesh and a TSL, where mesh is designed to allow deformation and spall to occur behind it, a TSL is designed to prevent it from occurring as shown in Figure 2. The greatest benefit of this type of support action is best realised prior to the rock undergoing significant displacements (Tannant, 1999), once significant spall or movement has occurred, the use of other restraining methods such as mesh may be more appropriate support options to employ.

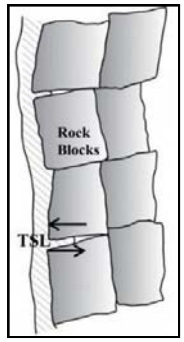

Figure 2: Penetrating of open joints and fractures between TSL and rocks (Saydam et al, 2003).

The following table (Table 1) presents the support mechanisms relevant to TSLs acting as a support mechanism, from Tannant (2001) and identifies their importance in relation to underground coal mining environments. Understanding the relative importance of the properties tabled, and their criticality in determining the performance of a TSL as a support method is still an opportunity for the coal mining industry to examine.

Table 1: Support mechanisms of TSL with their relevance to underground coal (from Tannant, 2001)

MECHANICAL PROPERTIES	SUPPORT MECHANISM	DESCRIPTION	IMPORTANCE FOR COAL
Shear adhesion Tensile adhesion Shear strength Tensile strength	Interlocking of coal blocks	For a TSL to offer interlock between discrete blocks of coal, it must be well bonded to the surface and have sufficient tensile strength to withstand block movement, which is demonstrated in Figure 2. In this instance, it has been shown that shear movement between the coal (or shown on laboratory manufactured substrate materials) can be prevented and the movement of blocks constrained.	This is a critical mechanism to consider when applying TSL to an underground coal environment. Coal is made up of many discrete blocks, bounded by joints and natural cleats.
Shear adhesion Tensile adhesion	Gluing Action	Often working in conjunction with the restriction of block dilation, the action of spraying the TSL achieves penetration of the sprayed material into discontinuities or jointing which can be prevalent in coal as illustrated in Figure 1. By penetrating these openings and bonding to the surfaces, movement and rotation of blocks can further be restricted by this gluing action.	Coal is inherently jointed and cleated, providing opportunity for movement along these planes.
Shear strength Tensile strength Ductility/ flexural strength	Containment/ Basket Mechanism	In instances where rock has failed behind a sprayed TSL, and the liner has sufficient tensile strength, a basket may form which acts to contain failed rock. This type of mechanism can occur when using mesh, shotcrete or TSL; however the amount of rock that is able to fail behind a tenaciously adhering TSL or shotcrete may be minimised when compared to movement behind mesh.	Buckling, bulging, fretting are all common failure modes in coal that could be constrained by this mechanism.
Tensile strength	Skin/ membrane Action in conjunction with washers and bolt plates	Bolt plates are an important part of the support system and act to distribute the applied load from a bolt (or cable) to the surrounding strata. A sprayed liner can extend the area of influence of the face plate.	Increased face coverage can result in lower rate soft coal drop out, buckling and spall in coal ribs.

All the aforementioned support mechanisms may act independently or in combination with each other.

In addition to the supporting mechanisms of TSLs, if sprayed to provide full coverage on rib or roof and rib, liners will potentially prevent the ingress of air and water into the coal and reduce deterioration associated with the weathering. While limiting ingress, the liner also acts to reduce egress of gas and water out of the coal, thus may provide other operational benefits to an operation by reducing gas emission or water make into workings.

POTENTIAL BENEFITS IN UNDERGROUND COAL MINES

With the potential to offer considerable operational benefits with their fast application rates and much reduced product per square metre compared to shotcrete, interest in TSLs and their development exists throughout the coal mining industry. TSLs' advantages are extensively detailed throughout the literature and summarised by Yilmaz (2011):

- fast application rates,
- rapid curing times ranging from seconds to hours,
- reduced materials handling compared to shotcrete,
- high tensile strength with high areal coverage,
- high adhesion which enables early reaction against ground movement, and
- ability to penetrate joints.

Stacey and Yu (2004) suggest that these advantages have the potential to lead to improved cycle times, increased mechanization, and improved safety. If it can be implemented, the advantages of applying a thin spray-on liner at the coal face include, but not limited to, (i) better control over coal ribs close to the development face, (ii) reduced exposure for mine site personnel, and (iii) less manual handling operations – particularly if the system can be incorporated into existing surface to seam delivery infrastructure. The benefits of using these products from original product developers and listed by Li et al. (2016) are:

1. confine ground movement as soon as possible
2. unravelling of rocks is reduced compared to mesh – provide stability
3. provide immediate support to personnel compared to conventional support methods, i.e., bolt and mesh
4. active support method by constraining rock movement
5. reduce rib displacement and improve roadway serviceability
6. can achieve significant area coverage
7. surface to seam delivery can remove manual handling and assist in achieving Zero Harm
8. no rust / corrosion
9. fast set – obtain properties quickly
10. potentially improved cycle times for bolting constrained operations
11. progression towards automated system with rock support without personnel intervention.

Full coverage support

Bolting density and placement are critical considerations for any support regime. Strata failures or unravelling of coal, can occur in between support elements, and therefore the idea of a full coverage support that can be applied at the face and contain and control rock movement has widespread appeal. In addition to these benefits and specific to the support of coal mine roadways, a full coverage areal support that can be applied directly at the coal face could drastically improve the condition of roadway rib conditions.

Using conventional methods, full rib coverage with the use of rib bolts and mesh at the coal face is constrained heavily by the time it takes and the equipment in use. Minimum distances from the floor to the lowest rib bolt can be as much as 1.2m for some continuous miner operations. This gap of unbolted, unmeshed rib can fail or spall, and in most cases is rebolted or shotcreted as part of a remedial support process to minimise personnel exposure and improve roadway conditions, as shown in Figure 3. If this lower rib is unstable, this can also cause unravelling or destabilisation of the rib above as the lower rib frets away, eventually requiring additional support to a much larger portion of the rib than just the initially unsupported section. TSL also has the advantage of being able to be sprayed into areas that may be awkward or hard to reach with bolts and mesh due to spall, geological structure or cavities.

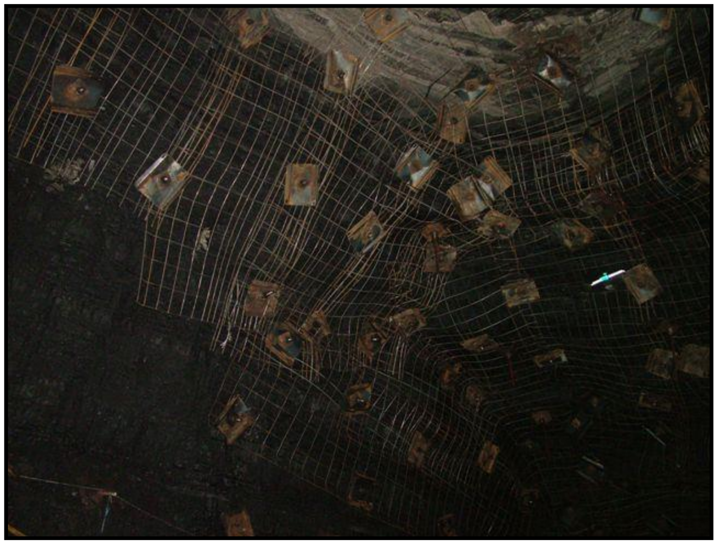

Figure 3: A rib with intersecting structures and roof cavity showing coverage provided by bolts and mesh.

TSL roof to floor has the potential to eliminate any lower rib exposure for personnel and deterioration of the roadways serviceability, thus reducing the requirement for remedial support. Developing a specific suite of material testing criteria so that a design method can be followed for the application of TSLs as a primary rib support, and with a potential for the future as a primary roof support, will be critical for the benefits of this product to be usable.

Automation of TSL application

Manual handling is one of the major impediments to achieving Zero Harm in the mining industry. The ability to automate the application of spray-on support is an enabler to full automation of development operations. The continued success of automated processes centre on having the ability to quickly and easily provide a way to support the rock face, without requiring people to do the task.

Success and advances in technology in recent years of surface to seam outfits, delivering products for strata support, ventilation control and general mine maintenance could further reduce the required handling of a spray lined. This type of delivery system could provide a unique opportunity to be able to deliver a spray support from the surface directly to a freshly cut coal face within minutes.

Ease of application

Other immediate benefits of a successful TSL delivery system at the coal face include TSL's potential to be sprayed in outbye areas, particularly difficult to access areas including belt roads, chambers and tailgate roadways. A surface delivery system that can provide spray on areal coverage support would offer solutions to many areas of mines that require remedial support in difficult to access areas. The erection, mobilisation, and access to scaffolding for the bolting re-support of these locations is often prohibitive. Figure 4 from Jjuuko and Kalumba, 2014 seeks to demonstrate the logistical differences between spraying TSL compared to the equipment required to psray shotcrete. Thicker linings such as shotcrete also have suitability issues in areas with minimal space such as alongside a belt road and still require significant room to manoeuvre their application equipment.

Investigations into the application time may also reveal productivity gains with the widespread use of TSLs compared to shotcrete or even meshing and bolting systems.

Figure 4: Photos of TSL application and shotcrete (Jjuuko and Kalumba, 2014)

BRIDGING THE GAP FOR MAKING TSL MORE USEABLE

The role of roadway support in an underground coal mine is to achieve an acceptable level of risk to coal mine workers while excavating roadways for mine access. Designing required support to maintain stability and ensure roadway serviceability and personnel safety is a multi-faceted process. Support design must be specific to an application, incorporate the full suite of available geotechnical information and local anecdotal evidence to-hand.

Support elements or hardware undergoes a rigorous testing and quality analysis process before being included into accepted design principles at each mine site. Each type of hardware, such as roof or rib bolts, bolt plates, cable bolts and plates, standing support elements or mesh type are included in the design process and must meet minimum technical requirements. Quality Assurance (QA) and Quality Control (QC) processes are employed by OEMs and mine operators to ensure that all support equipment being used performs to these requirements or the minimum specifications as stated by the OEM. For TSLs to be accepted as a trusted part of the support regime, further work needs to be done on understanding and measuring the support it will provide to an underground coal excavation. Yilmaz (2011), used the testing results of hundreds of samples of TSL and proposed a function for categorising the strength of a TSL based on its measured tensile strength. This is shown in Figure 5. Developments such as these are steps forward in establishing the usability or suitability of a TSL for various applications.

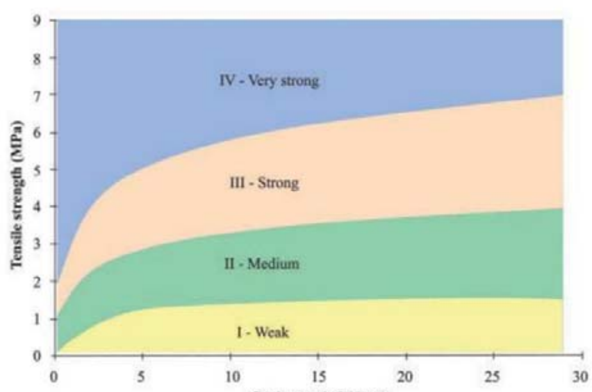

Figure 5: Tensile strength categories (Yilmaz, 2010)

Different support types play individual roles within the system to provide roadway stability. Bolts and cables provide active support which can clamp together rock to form beams for stability. Cables can also be installed to provide suspension type support. Mesh is installed as a skin control and provides a restraining force upon a rock face once the rock face mobilises or delaminates (i.e., passive support).

The mesh will offer a restraining force up to its strength limit and provide reduced rock dilation once the rock has mobilised to rest against the mesh and therefore reduce the area to allow further movement. Mesh also offers certain advantages such as supporting crushed, damaged or weak coal; however it cannot offer active resistance to movement until its strength is initiated by rock movement onto it. When considering the use of TSLs as part of the support system to replace mesh, the understanding of how mesh works, and further understanding of how TSLs work to provide support is critical. The two support types differ markedly in several key technical areas, which could form the fundamental basis for support choice and design in any given application.

In addition to the mechanical and technical properties of a support method (mesh or TSL), it is most probable that the way in which the support can be applied or installed will ultimately determine suitability for most operations. This is a critical aspect for consideration when designing a testing or monitoring program for TSLs. Certain 'mix and pump' products which are generally water-based polymer mixed with specialised cementitious powder are not practical to apply at the coal face. In this case certain variables such as rate of gain or curing time become less important to the application when compared to a product that meets the criteria to be able to be safely sprayed off the miner and used as a support element for advance mining. For example, the properties of shotcrete make it a suitable support product to be sprayed in outbye areas and assist with long term roadways stability. However due to the large logistical effort and machinery required to be utilised to spray shotcrete, its rate of curing and its slumping properties, shotcrete is not a support type that could be considered for spraying at the coal face and provide improved safety and production, whereas TSL should be considered.

The routine use of TSLs as part of a mine support strategy will need to be complimented by the overall operational strategy of the mine or mining company dedicated to the development of automation. Spray-on support that can be applied as part of a cutting cycle, such as bolts and mesh, represents a significant change to current work practices in Australian coal mines. The downstream benefits of a change like this can only be truly realised where the vision of an operation is aligned with research and development towards automated processes. The commitment to the development, research, and actual implementation of making a spray on support available at the coal face is large, but potentially yields considerable downstream economic and social benefits.

CONCLUSIONS

Determining an appropriate methodology for designing and measuring the performance of TSLs as a support to underground coal mine roadways is not an easy task. The effectiveness of the support mechanisms that can influence how effective a liner will be, as well as the relative involvement of each of these parameters in varying conditions requires further testing and analysis. Developments, in hard rock mining and civil applications, over the past 30 years in understanding and modelling of TSL behaviour and performance have improved the situation. However, the gaps in real world field testing and the development of a reputable and reliable design process remains an opportunity to be investigated and presented to underground coal operations as a valid support method.

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