http://dx.doi.org/10.17159/2411-9717/2016/v116n12a1

Potential use of thin spray-on liners for gas management in underground coal mines

by Z. Li*, S. Saydam*, R. Mitra*, and D. Chalmers*

Synopsis

Coal seam gas problems can adversely affect the safety and productivity of underground coal mines, leading to fatalities and financial losses. Conventional gas management technologies using ventilation and gas drainage are unable to deal with the high and irregular gas emissions associated with high-production longwall mining. New technologies need to be developed to supplement the traditional gas management techniques to minimize the hazard of coal seam gas. Thin spray-on liners (TSLs) have gained some success for rock surface support since their introduction to the mining industry. Due to their relatively low permeability and appropriate mechanical properties, TSLs also show potential to be used as a gas management tool in underground coal mines.

In this paper we review the current gas management challenges and discuss the potential use of TSLs as a gas management tool in underground coal mines. This may involve reducing gas migration into the excavations/roadways, enhancing in-seam gas drainage, and preventing spontaneous combustion. Some potential areas for future research work are identified.

Keywords

thin spray-on liner (TSL), gas management, underground coal mining.

Introduction

When a coal seam is influenced by mining activities, gas stored inside is liberated into the underground ventilation system. Gas emissions have created serious difficulties for the coal mining industry around the world. Therefore, coal mines have to develop effective strategies to control the gas concentration below the threshold value to meet statutory requirements. Ventilation has been the first solution in gas management for underground coal mining. When the emitted gas cannot be effectively diluted by ventilated air, gas drainage using pre- and/or post-drainage has to be introduced. However, even with ventilation and gas drainage, irregular gas emissions usually increase the gas concentration in roadways and slow down the development rate, thus causing significant economic loss to the coal mining industry (Thakur, 2006). Therefore, new technologies need to be developed to address this issue and mitigate the explosion risk.

A thin spray-on liner (TSL) is a thin chemical-based coating or layer that is applied onto mining excavations with a thickness of 3 to 5 mm (Lau *et al.*, 2008; Richardson *et al.*, 2009; Saydam and Docrat, 2007). Due to the operational benefits regarding both safety and logistics, TSLs have achieved some success as a ground support tool for some specialized applications, such as repairing shotcrete (Lacerda and Rispin, 2002), supporting the hangingwall in gold mines (Carstens and Oosthuizen, 2004) and supporting the longwall T-junction sections in coal mines (Thyrock *et al.*, 2010).

Besides ground support, due to their relatively low permeability TSLs also show potential to be used as a gas management tool in underground coal mines. For gas emission control purpose, TSLs may serve as a sealing skin to prevent irregular gas emissions from the ribs and keep the gas concentration in the roadway below the statutory requirements and guarantee the development rate. For gas drainage enhancement purpose, TSLs can prevent the ventilation air from migrating into the gas drainage boreholes and increase the gas drainage efficiency. For spontaneous combustion control, TSLs have the potential to slow down the oxidation process or even stop it due to the lack of oxygen migration through the coal seam.

Overview of thin spray-on liners

Background

TSLs are multicomponent polymer materials that can be applied to a rock mass surface at a thickness of 3–5 mm as a sealant or as surface support (Saydam and Docrat, 2007). There are many TSL products on the market. They differ by mix type such as liquid/liquid or liquid/powder and by polymer-based type (Northcroft, 2006). The polymer-based TSLs

* *School of Mining Engineering, UNSW Australia, Sydney, Australia.*

 ISSN 2225-6253. Paper received Nov. 2014; revised paper received Nov. 2015.

can be classified into six groups: acrylics, liquid latex where latex is any known polymer, polyurethane, polyurea, methacrylate, and hybrid (Kaiser and Suorineni, 2006).

Depending on the curing mechanism and liner formation, TSLs are categorized into two different types: reactive and nonreactive (Rispin and Garshol, 2003). Reactive TSLs cure quickly, but are sensitive to water and barely stick to wet surfaces; furthermore, they can only be applied with strict safety precautions. On the other hand, nonreactive TSLs cure slower but bond well to wet and dry surfaces and can be applied with normal safety precautions (Kaiser and Suorineni, 2006; Northcroft, 2006). For safety reasons, the majority of current products on the market are nonreactive, with modifications to reduce the curing time.

TSLs are more flexible than shotcrete, which has a typical thickness of 25–100 mm depending on the need. Effective polymer support is created by a continuous membrane, which adheres firmly to the rock. An 'ideal' TSL should have appropriate mechanical properties and comply with a number of operational, environmental, and economic standards. A list of desirable characteristics of an ideal TSL is shown in Table I. The manufacture of a number of TSL products has been stopped, since they do not possess adequate physical or chemical properties. However, newer products are continuously developed and introduced (Yilmaz, 2007).

Use of thin spray-on liners

TSLs had been used in civil engineering as sealants for many years before being introduced to the mining industry (Kuijpers, 2004; Yilmaz *et al.*, 2003). TSL materials for the mining industry were initially designed as sealants to limit the weathering of rock, and later were intended to be used as a substitute for mesh or shotcrete (Spearing *et al.*, 2009; Yilmaz, 2007). The idea of using TSLs as surface support was initiated in the late 1980s in Canada and was originated by the thought that a liner as thin as 5 mm should perform the same as, or even better than, shotcrete (Archibald, 2004; Yilmaz, 2011). Since the 1990s, TSL support has become a focus of mining industry due to the considerable operational benefits, with the potential to reduce mining costs (Ozturk, 2012).

Table I

Ideal thin spray-on liner properties and characteristics (modified from Espley-Boudreau, 1999)

Property or characteristic	Recommended range
Non-combustible	Flame spread ratingmax < 200
Tensile strength	> 5 MPa
Adhesion strength	> 1 MPa (hard rock), > 3–4 MPa (weatherable ground)
Shear strength	> 2 MPa
Curing time	< 1 h
Temperature tolerant	0–50°C
Application rate	> 1 m^2/min
Pot life	> 1 h
Cost	< \$20 per m^2
Application	Minimal or no surface preparation
Rebound	< 5%

TSLs have undergone research and development for over 20 years, with numerous trials conducted in underground mines. Belfield (2006) reported that over 50 mines around the world have used TSLs for rock support. Potvin *et al.* (2004) listed the most common usages of TSLs, and these applications were usually at locations with exceptionally unfavourable ground conditions or ground control problems (Yilmaz, 2011).

- Support between rock anchors
- Supporting areas with limited access and/or logistics constrains
- Mesh replacement
- As primary support immediately after blasting
- Temporary support (can be covered by shotcrete at later stage if necessary)
- Temporary support in TBM tunnels (permanent support can be installed behind the equipment)
- Reducing rockburst damage
- Pillar reinforcement
- Face support
- Large machine borehole lining and stabilization
- Stabilization of return air tunnel
- Orepass lining
- Prevention of rockfalls caused by unravelling, slabbing, or loosening of small blocks of rocks
- Rigid ventilation seals
- Prevent ground degradation from weathering fretting and swelling.

In spite of the adverse ground conditions, most of the TSL trials have proved to be successful for their planned application in specific areas (Potvin *et al.*, 2004). For some TSL application cases, poor bonding, falling of large slabs, peeling, tearing, and damage due to blasting and moving machinery were observed (Nagel and Joughin, 2002; Tannant, 2001). In these applications, TSLs were used mainly for temporary support for strata control and ground stabilization. However, the use of TSLs is still limited to special applications rather than to general application as a systematic surface support, as are mesh and shotcrete. Their use has not become widespread in underground mines.

The advantages of TSLs are fast application rates, rapid curing time, reduced material handling compared to shotcrete, high tensile strength with high areal coverage, high adhesion which enables early reaction against ground movement, and ability to penetrate into joints (Kuijpers *et al.*, 2004; Pappas *et al.*, 2003). These properties ease logistics, improve on cycle times, increase mechanization, and improve safety for underground support (Stacey, 2001). In spite of these benefits, the original aim of using TSLs as an alternative to mesh and shotcrete has not yet been achieved. Most of the products on the market are still undergoing study and field trials, and no reports yet exist about TSLs being systematically applied as surface support in mines (Darling, 2011). Several reasons may contribute to this. Firstly, the support that a TSL can provide is not fully understood (Tannant, 2001) although many efforts have been made to study the support mechanism using analytical (Fowkes *et al.*, 2008; Mason and Abelman, 2009; Mason and Stacey, 2008) and numerical (Dirige and Archibald, 2009; Tannant and Wang, 2002; Wang and Tannant, 2004) methods. Secondly, the design of TSLs as surface support systems is currently based on experience, assumptions and field observations, and cost considerations (Jjuuko and Kalumba, 2014), and application guidelines are needed for using TSLs as a surface support for different ground conditions. Thirdly, there is still a lack of standard laboratory test methods to determine the mechanical properties of TSLs, with only tensile and tensile-bond strength tests having met with general acceptance from TSL stakeholders to date (Archibald, 2001); this makes it very difficult to compare and select among different TSL products.

TSL technology is not yet mature and still under development. It should be noted that a TSL application may not replace traditional ground support such as rockbolts. However, TSLs have performed well when combined with other types of support, such as rockbolts plus TSL plus shotcrete and rockbolts plus TSL plus mesh plus shotcrete (Hussain *et al.*, 2012).

Permeability characteristics of thin spray-on liners

Besides ground support, a report by European experts also mentioned the advantage of using TSLs as a barrier against gas movement because of their relatively low permeability (EFNARC, 2008). During the past few years, much research has been carried out to study the permeability characteristics of different TSLs.

The first permeability test of a TSL reported in the literature was by Archibald and de Souza (1993), who investigated the potential of a polyurethane-based TSL for blocking radon gas entry. They carried out radon gas permeability tests with different TSL thicknesses. Their results showed that with a thickness of 0.37 mm, the TSL product tested could effectively reduce the radon flux by as much as 94%, and such potential promised to improve significantly with increasing TSL thickness. Archibald and de Souza (1993) emphasized the potential use of TSLs in restricting hazardous gas inflows. It is important to note that the hazardous gases, easily diffusing from rock pores into the working area, cannot be effectively blocked by shotcrete due to its high permeability (Tannant, 2001).

Similar tests were conducted by Saghafi and Roberts (2001). They measured the permeability of a cement latex-based TSL product for methane, carbon dioxide, and carbon monoxide. Their results indicate that the permeability of the tested TSL is in the range of nanodarcies. They reported that the permeabilities for methane and carbon dioxide are very similar, whereas the permeability for carbon monoxide is a few times higher. However, both the tests conducted by Archibald anddDe Souza (1993) and Saghafi and Roberts (2001) considered only the TSL material itself, without considering the substrate it was applied to; the substrate will determine the adhesion strength for a particular TSL material. Previous test results show that there is a linear relationship between the efficiency of the TSLs in controlling gas flow and their adhesion strength to the substrate (Hussain *et al.*, 2012).

Considering the interaction between TSLs and the substrate applied, Mass and Renken (1997) conducted radon gas permeability tests on concrete coated by different cementitious-based TSLs with the test apparatus shown in Figure 1. Their results showed that the coatings tested all exhibited excellent permeability coefficients; two to three orders of magnitude smaller than the average concrete permeability coefficient. Mass and Renken (1997) further stated that any sealants placed on a highly permeable concrete would greatly reduce the permeability.

In order to investigate the potential of TSLs as a gas management tool in underground coal mines, Hussain *et al.* (2012) carried out permeability tests on coal samples coated with three different TSL materials (two polymer/cementitious-based TSLs and one cement/latex TSL) of varying thicknesses. The tested gases include carbon dioxide and nitrogen. A 'Hassler' type core holder was used for this test, as shown in Figure 2. The experimental results indicate that the TSLs tested could reduce the gas permeability of coal by up to three orders of magnitude. This was the first test to investigate the potential use of TSLs for coal mine gas management, and the results showed favourable potential. However, the permeability tests were conducted only with nitrogen and carbon dioxide; methane, the gas of main concern in underground coal mining, was not tested. The influence of gas adsorption on permeability was not considered in the test either, which influenced the accuracy of the results, as coal permeability is pressure-dependent due to different degrees of gas adsorption (Zhou *et al.*, 2013a, 2013b).

Permeability results from TSLs of different mix base chemistries were compared based on the literature available, and the following order of permeability obtained: polymer/cementitious-based TSL < polyurethane-based TSL < cementitious-based TSL. Specifically, the permeability of polyurethane-based TSL is about one order of magnitude lower than that of the cementitious-based TSL; while the permeability of polymer/cementitious-based TSL is about four to five times lower than that of cementitious-based TSL. The polymer modifications can significantly reduce the permeability of TSLs, and this finding also conforms with previous research results (Golsby, 2015).

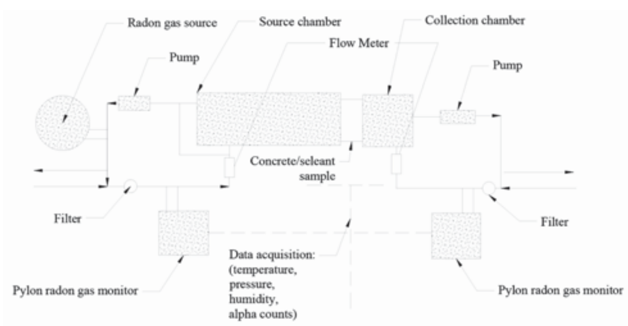


Figure 1—Schematic of permeability test apparatus for concrete and TSLs (Mass and Renken, 1997)

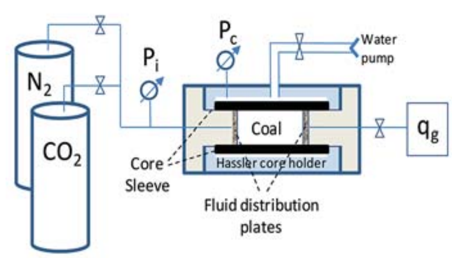


Figure 2—Schematic of experimental apparatus for permeability test (Hussain *et al.*, 2012)

Gas emission and control in underground coal mines

Gas emission into mine workings

The quantities of gas contained in coal seams are a function of the degree of coalification and permeability of the overburden (Noack, 1998). When influenced by mining excavations, the gas is emitted into the ventilation system. Inadequate air quantities in the ventilation system may cause gas to accumulate to dangerous levels, and may result in gas explosions under certain circumstances and conditions (Lunarzewski, 1998). Table II shows some of the major mine explosions since 2000 (Karacan *et al.*, 2011; State Administration of Coal Mine Safety, 2014; United Nations, 2010). Due to the explosion risk, gases have always been regarded as a threat in underground coal mining. Every coal mine has to institute effective gas control strategies to maintain the gas concentration in the working areas below the statutory requirements.

The amount of gas emitted into mine workings depends on a number of factors. The most important of these are the productivity of the coal mine, the gas content of the coal seam, presence of other coal seams in the vicinity of the seam being worked, operational variables, and geological conditions (Karacan *et al.*, 2011).

Gas emissions in underground coal mines can be classified into emissions from development ribs and from longwall panels. Although many methods have been developed for estimating gas emission for both development and longwall panel production stages (Karacan *et al.*, 2011; Lunarzewski, 1998; Noack, 1998), these methods often lack accuracy due the numerous defining parameters and assumptions involved. Besides, irregular gas emission makes the estimation more difficult.

Gas emission in development excavations

As headings advance into the virgin coal seam, free and adsorbed gas from the immediate ribs of a development heading are released. Typically, the rib emission rate is a function of the age of the rib. Initially, the emission rate is relatively high, followed by a rapid decay from this peak to a residual level. This process can be described by Equation [1] and Figure 3 (Moreby, 2005):

$$E_g = E_0 \cdot e^{-\lambda t} + E_r \qquad [1]$$

where, E_g is the rib emission rate in L/s/100 m; E_0 is the initial gas emission rate ($t = 0$) in L/s/100 m; λ is the rate of decay; and E_r is the residual emission ($t = \infty$) in L/s/100 m.

For development headings, the total amount of gas liberated from coal at the face over a period is dependent upon the gas content of the coal and the mining rate. However, gas emission at the face is not regular but fluctuates over very wide limits, depending upon the mean mining rate and method of mining (Vutukuri and Lama, 1986). Strategies must be adopted to control this irregular gas emission to establish workable conditions in the development headings.

Gas emission at longwall faces

In longwall mining, gas is emitted from the seam being mined as well as from the surrounding medium, which may contain very large amounts of gas, particularly in the surrounding seams. Saghafi *et al.* (1998) demonstrated that the amount of mine gas emissions exceeded the gas content of coal by a

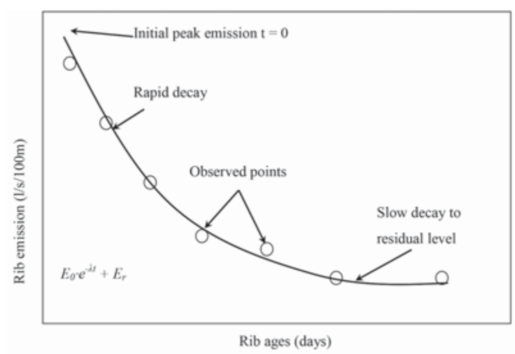


Figure 3—Characteristics of gas emission decay (modified from Moreby, 2005)

Table II

Major coal mine explosion incidents since 2000 (modified from Karacan *et al.*, 2011; State Administration of Coal Mine Safety, 2014; United Nations, 2010)

Country	Date	Coal mine	Fatalities
China	14 February 2005	Sunjlawan, Haizhou shaft, Fuxin	214
USA	2 June 2006	Sago, West Virginia	12
Kazakhstan	20 September 2006	Lenina, Karaganda	43
Russia	19 March 2007	Ulyanovskaya, Kemerovo	108
Ukraine	19 November 2007	Zasyadko, Donetzk	80
USA	5 April 2010	Upper Big Branch, West Virginia	29
Turkey	17 May 2010	Karadon, Zonguldak	30
New Zealand	19 November 2010	Pike River Mine	29
China	29 March 2013 1 April 2013	Babao, Baishan, Jilin	36 17
China	12 May 2013	Taozigou, Luxian, Sichuan	28
China	13 December 2013,	Baiyanggou, Hutubi, Xinjiang	21
China	21 April 2014	Hongtutian, Yunnan	14

factor of four, due to the emissions from the overlying and underlying strata, as shown in Figure 4. Therefore, gas emissions during longwall mining are very difficult to predict and may depend on many factors besides the gas content of the mined coal.

Control of gas emissions

As the coal mining environment becomes deeper and gassier, problems associated with gas management becomes more significant (Karacan *et al.*, 2011). A well-designed ventilation system can deal with low to medium gas emission problems. When it is not economic or not operationally practicable to manage gas emission by ventilation alone, gas drainage using pre-drainage and/or post-drainage is required to reduce the gas emissions in the working areas.

Diluting gas with ventilation

Ventilation has been the first recourse for controlling gas emissions (Karacan, 2008; Karacan *et al.*, 2007; Noack, 1998). The supply of sufficient fresh air to dilute the gas to safe limits and render it relatively harmless is essential for the safety of longwall mining (Schatzel *et al.*, 2008). This method is applicable only in mines where gas emission is low to medium. The system will fail when high gas emission is encountered because of high costs and unacceptable air velocities at the working places. Thakur (2006) indicated that with a well-designed ventilation system, it is economically feasible to handle specific gas emissions up to 28.3 m^3 per ton of coal mined.

Gas drainage

Mine operators often try to supply maximum ventilation air based on the capacity of the system to dilute the gas concentration. Nevertheless, as time passes and the roadways become longer, ventilation capacity may decline because of leakage (Schatzel *et al.*, 2008). Furthermore, gas emissions that flow into the ventilation system may increase as mines progress into deeper and gassier coal seams, and as longwall operation parameters change (*e.g.* increased advance rates) (Karacan *et al.*, 2011). Consequently, it has become increasingly difficult to control the gas concentration below statutory requirements by ventilation alone, as this will require impractically large quantities of air (Gillies and Wu, 2013).

When it is impractical to control gas concentration by ventilation alone, gas drainage using pre-drainage and/or post-drainage techniques has to be introduced to reduce the gas contents and emissions (Brunner *et al.*, 1997).

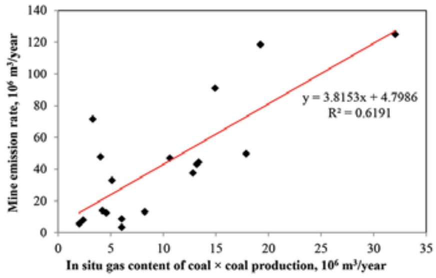


Figure 4—Mine emissions *versus* gas content of mined coal (modified from Saghafi *et al.*, 1998)

Pre-drainage methods aim to reduce the gas content of the coal seam before mining for the purpose of reducing gas emissions during development and longwall production. Post-drainage methods (also known as goaf or gob drainage) aim to capture gas during longwall phases to reduce the amount of gas managed by ventilation.

When coal seams have a sufficiently high natural permeability, gas drainage has been a positive and reliable method for controlling high gas emissions in mines. DuBois *et al.* (2006) investigated the use of in-seam boreholes for shielding the entries from gas flow. Their results showed that after gas drainage for 6 to 24 months prior to any mining, the gas emissions into the entries reduced by between 30% and 35%. However, gas drainage has met with limited success in low-permeability coal. Almost 50% of the underground in-seam gas drainage programmes delivered little to no benefits to gas content reduction (Black and Aziz, 2008). Besides low permeability, many other factors also restrict the efficiency of in-seam gas drainage (Black and Aziz, 2009):

- Insufficient drainage time prior to intersection by development gateroads
- Insufficient monitoring and management of borehole performance, resulting in low to no flow due to accumulation of water and/or coal fines within the borehole
- Insufficient monitoring and management of the gas reticulation pipe network, with blockages or significantly restricted flow capacity due to accumulation of water and/or fines in sections of the range
- Poor standard of sealing holes following intersection by development, resulting in air in the pipe range and reduced suction pressure
- Insufficient standpipe length and sealing (grouting) standard, resulting in air dilution in the pipe range and reduced suction pressure
- Boreholes drilled down-dip and not in the optimum orientation for maximum drainage performance
- Absence of in-hole dewatering where boreholes have been drilled down-dip, resulting in water accumulation restricting gas desorption.

A method that can offer a substantial increase in drainage time is surface-to-inseam drilling (Black and Aziz, 2009). This method allows drainage to take place for several years prior to mining (Thakur, 2006). However, with very low permeability strata this method has limited success in reducing the gas content (Packham *et al.*, 2011).

A promising technique referred to as 'enhanced gas recovery' was firstly described by Puri and Yee (1990). This technique involves injecting a gas, which is different to the seam gas, into the coal seam to stimulate methane (or other gas) production (Packham *et al.*, 2011). This technique may help to increase the production of gas from coal seams and improve the recovery rate from low-permeability coal. Although promising, this technique is still under development, and the mechanism for the stimulation is not yet fully understood.

As the seams worked become deeper and gassier, gas drainage has been progressively adopted to reduce the *in situ* gas content and gas emission. However, gas drainage is effective only for coal seams with high permeability; besides, gas drainage needs time to become effective and it cannot solve the irregular gas emission problem in underground coal mines timeously, which may cause the stoppage of work in development headings and longwall faces.

The limitations of both ventilation and gas drainage require new techniques to be developed to deal with irregular gas emission problems, enabling development and production activities to continue uninterrupted.

Potential uses of TSLs for gas management

Gas emission control with TSLs

During longwall development, headings are driven into gassy coal and gas is released as the seam is depressurized, at a rate that is a function of gas content, pressure, and permeability (Noack, 1998). When ventilation and gas drainage are not sufficient to control the gas emissions, the development headings have to be stopped for safety reasons, which is not acceptable for mining companies. A technology is urgently needed for reducing the gas emissions rate in this situation, allowing the headings to advance.

Due to their relatively low permeability, TSLs may have the potential to deal with irregular gas emissions. Their operational benefits, such as rapid application, rapid curing, and low volume required allow the timely sealing of the irregular gas emission area. Their appropriate mechanical properties, such as high tensile strength and elongation, can also deal with deformable ground conditions. It is worth pointing out that these benefits cannot be provided by other sealing techniques such as shotcrete. A schematic of TSL applied in an irregular gas emission area is shown in Figure 5. The application of TSL may reduce the gas emission rate in the development heading and allow the advance of the heading. Besides the gas management benefits, application of a TSL may also help to maintain the stability of the fresh excavations.

Based on the permeability test results of Saghafi and Roberts (2001), Gerard (2007) conducted a theoretical analysis of the effectiveness of TSLs in reducing rib emissions. He stated that a sharp drop in rib emissions would occur once TSL spraying begins, and this process is illustrated in Figure 6. Although the study showed the potential for reducing rib emissions with TSLs, there was no field trial or data to support these assumptions. However, these theoretical results did show the potential of TSLs for reducing rib emissions and field trials are recommended to prove these assumptions. At the same time, problems associated with the application of TSLs can be addressed.

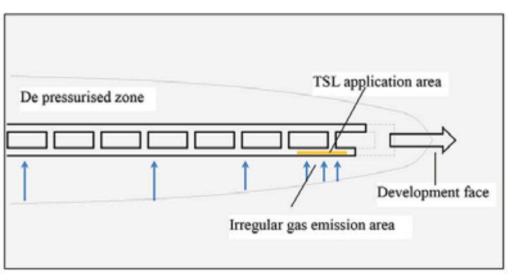


Figure 5—Areal TSL support for gas emission control during longwall development

Enhancing in-seam pre-drainage with TSLs

Because of the influence of the excavation, stress-induced rock fracture near the roadway will increase the permeability of the coal mass near the roadway (Zhou and Lin, 1998), as shown in Figure 7. This will cause serious air leakage around a drainage borehole due to the high suction pressure created by gas drainage (Xia *et al.*, 2014a), as shown in Figure 8a. This air leakage may not only result in a low gas drainage concentration, but also lead to many other hazards, such as spontaneous combustion of coal, gas combustion, and gas explosion (Xia *et al.*, 2014b). Apart from the risks, Palchik (2002) stated that if the migration air can be reduced by one-half to one-third, the drained gas flow rate can increase 1.5–2 times. Therefore, there is an urgent need to develop an effective method to deal with ventilation air migration into the drainage boreholes.

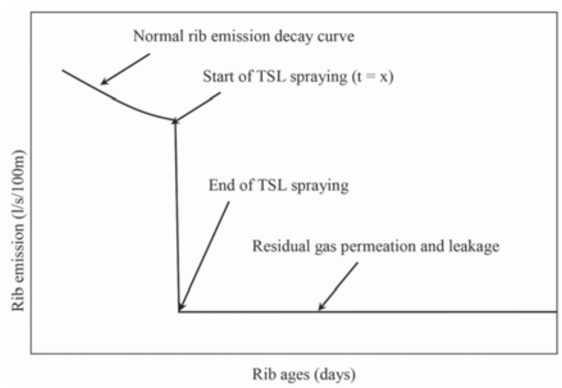


Figure 6—Theoretical rib emission curve with TSL applied at *t=x* (modified from Gerard, 2007)

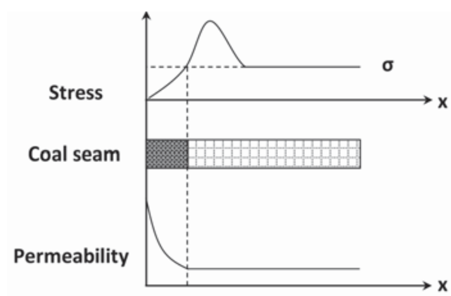
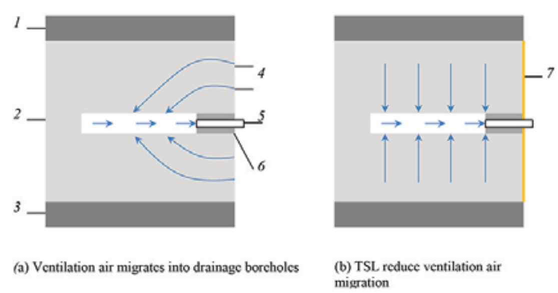


Figure 7—Change in coal seam permeability due to excavations (modified from Zhou and Lin, 1998)



1 – Roadway roof, 2 – coal seam, 3 – roadway floor, 4 – ventilation air migrates into drainage borehole, 5 – drainage borehole, 6 – drainage borehole seal, 7 – TSL material

Figure 8—Use of TSLs in reducing air migration into drainage boreholes

Measures need to be taken to deal with this air leakage around gas drainage boreholes. In gas drainage practice, a sealing material such as polyurethane is used to seal the borehole; however, it can seal only the borehole itself, and the internal cracks of the coal seam are not blocked off (Lu *et al.*, 2014). A TSL may be used to reduce the migration of ventilation air into the drainage boreholes. After spraying, the TSL material will bond firmly to the coal ribs and form a liner with low permeability. The liner can seal the cracks around the drainage holes and prevent the migration of ventilation air into the drainage holes, as shown in Figure 8b. The performance of the drainage hole is enhanced: on the one hand, the purity of the drained gas is increased as the path between the ventilation air and the drainage holes is sealed; on the other hand, the suction pressure can help desorption of gas from the coal and increase the gas production. Furthermore, the TSL can also reduce the rib emission rate to the ventilation system, which enhances gas management in underground coal mines.

A field trial of using TSL for enhancing the gas drainage efficiency was carried out by Tenney *et al.* (2015). The trial involved spraying a polymer/cementitious-based TSL on the area surrounding gas drainage boreholes, whereby the TSL acts as a thin membrane decreasing the permeability of the coal. The results showed that the methane purity was increased by 9.14% and air contamination reduced by 7.93% after the application of the TSL. However, problems are also associated with the trials, such as the variability of the methane flow rate, the interpretation of the results, and the area for spraying the TSL material, which need to be investigated in future tests. The advantages and disadvantages of gas emission control techniques are compared in Table III.

Spontaneous combustion control with TSLs

Spontaneous combustion of coal has been a serious problem for coal producers and users for many years. As a result of spontaneous combustion, the coal producers may suffer (Ham, 2005; Simion *et al.*, 2005):

- Fatalities caused by hazardous gases
- Loss of equipment
- Loss of a large amount of coal reserves.

It is important for the mine ventilation engineer to be conscious of the zones in which spontaneous combustion is most likely to occur. Typical areas where spontaneous combustion can occur are along ventilation leakage paths. Leakage can occur in rib fractures around ventilation stoppings, through faults or cracks passing through a pillar, or along the bed separation in any remaining coal left in the roof (Ham, 2005; McPherson, 1993). Oxygen may accumulate in these areas where insufficient ventilation exists, resulting in the inadequate dispersion of heat from oxidation (Cliff, 2009).

TSLs have the potential for controlling spontaneous combustion. If a spontaneous combustion event was discovered in a chain pillar, then a TSL could be sprayed on the ventilation intake side to prevent any further oxygen from entering the leakage path. If detected early enough, the oxidation process may slow down and eventually be stopped due to the oxygen deficiency. In fact, if a TSL has already been sprayed onto the ribs (whether for support or other gas management reasons), spontaneous combustion may have been avoided already, as shown in Figure 9.

Ventilation benefits provided by TSLs

Ventilation power costs have a direct relationship with frictional head losses in mine airways. A reduction in the airway friction factor would result in a corresponding reduction in power costs. TSLs have a very low ventilation

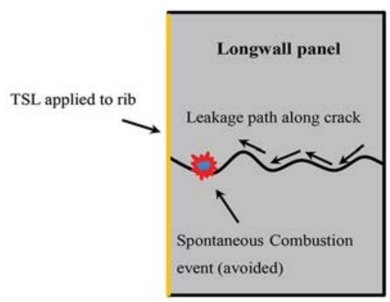


Figure 9—Example of TSL possibly preventing spontaneous combustion

Table III

Advantages and disadvantages of different gas emission control techniques

Technique	Advantages	Disadvantages
Ventilation	• Most common method of dealing with gas emission • Applicable in mines with low to medium gas emission	• Not effective with high gas emission, because of high costs and unacceptable air velocities • Ventilation capacity may decline due to leakage
Gas drainage	• Reliable method for controlling high gas emission in mines • Reduces the gas content of the coal seam and shields the development entry • Can capture gas for power generation	• Needs long drainage time prior to intersection by development road • Limited success in low-permeability coal • Fractures around the drainage pipe, resulting in air dilution and reduced suction pressure • Cannot deal with irregular gas emissions
TSL	• Very low permeability • Can deal with irregular gas emissions • Many operational benefits such as rapid application, rapid curing, low volume required • Can bring other benefits such as ground support, spontaneous combustion control, and reducing the ventilation friction factor	• TSL cannot be applied alone to control gas emission; it has to be applied to supplement other techniques

friction factor, which gives them potential to improve mine ventilation capabilities (Archibald and de Souza, 1993; de Souza and Archibald, 2002).

Archibald and de Souza (1993) carried out wind tunnel simulations of airways, made of plywood, to evaluate the friction factor (K) parameters associated with the installation of a polyurethane-based TSL. This work demonstrated that the TSL used had a ventilation friction factor about 0.00249 $N.s^2/m^4$, which is approximately two to four times lower than that of typical mine airway rock surfaces. The introduction of TSL material in mine airways could therefore serve to reduce system friction head losses while maintaining good environmental quality (dust reduction) and improving mechanical support performance.

A field determination of friction factor parameters was conducted by de Souza and Archibald (2002) in conjunction with a field application. As shown in Figure 10, the field application was carried in a 91 m long, stable fresh air drift at an underground mine. The airway resistance, friction factor, and roughness height were calculated from the data from three ventilation surveys. The results indicated that the liner, on average, decreased the airway resistance by 7.44%, the friction by 7.42%, and the roughness by 12.19%. However, only one TSL material was tested and the benefits of TSL for ground support were not investigated in this study.

Summary

This paper reviewed the current gas management challenges and presented the potential benefits of TSLs for gas management in underground coal mines. These may include reducing gas emissions into the ventilation system, enhancing the in-seam drainage performance, and controlling spontaneous combustion.

Since their introduction, TSLs have received increasing attention from the mining industry around the world due to the significant benefits they bring, such as low volume, rapid application, and rapid curing, with great potential to reduce mining costs. However, this technology is not yet mature and is still under development. Most of the products on the markets are still undergoing study and field trials.

For safety reasons, reactive TSLs such as polyurethane-, polyurea-, or methacrylate-based materials are not recommended for underground applications. Most of the products on the market are nonreactive TSLs with modifications to reduce the curing time.

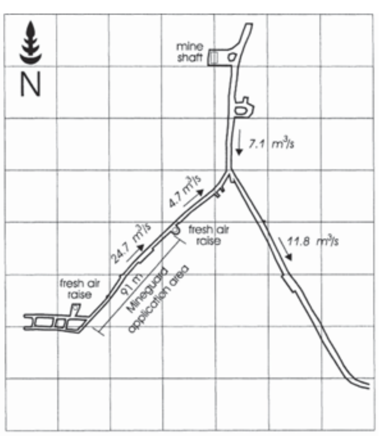


Figure 10—Mine level plan schematic (de Souza and Archibald, 2002)

Motivated by the potential for using TSLs as a barrier against gas movement, many tests have been conducted to investigate the permeability characteristics of different TSLs, either with or without considering the interaction with the substrate. Among all the TSL materials tested, the polymer/cementitious-based TSLs have the lowest permeability and are recommended for gas management in underground coal mines from a permeability perspective.

Gas emissions can adversely affect safety and production in underground coal mining. Appropriate approaches and equipment are needed for controlling gas emissions in order to provide safe working conditions. Ventilation and gas drainage are the most important techniques for this purpose. However, irregular gas emissions will usually increase the gas concentration in the roadways and slow down or even stop development. To address this issue, TSLs have the potential to be used as a 'cosmetic' support for sealing the fractured zone and decreasing the irregular gas emissions.

During underground in-seam drainage, the application of a TSL may prevent gas migration into the drainage holes through the fractures near the ribs, thus increasing the drained gas purity and gas production. Furthermore, the application of TSL can also help decrease the rib emissions to the ventilation environment.

TSLs have the potential for controlling spontaneous combustion by sealing the leakage path and thereby reducing the oxygen level in the spontaneous combustion locality. In fact, if applied early enough, TSLs could also prevent the occurrence of spontaneous combustion.

The application of TSLs could also potentially reduce the friction resistance of the ventilation airway, thereby reducing power and ventilation costs.

Recommendations

TSLs show potential to be used as a gas management tool in underground coal mines. However, there has been limited research into this topic. It is obvious that further investigation is needed in order to ascertain whether this technology can have a significant impact on gas management. Multiple laboratory and field tests under various conditions are recommended. The application procedures for TSLs in gas management in underground coal mines should also be studied and incorporated with the laboratory and field test results. Furthermore, an optimized application procedure of TSLs for gas management should be put forward.

Besides gas management, the application of TSLs can also bring many other benefits, such as in ground support and ventilation. A financial and technical model should be built to evaluate the cost-benefit of using TSLs in the coal mining industry.

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