Experimental study for reducing gas inflow by use of thin spray-on liners in underground coal mines

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This paper presents an investigation of the potential use of thin spray-on liners (TSLs) in underground coal mines as a gas management tool. The coal samples used were taken from a coal mine in Australia. Three different TSLs were examined. The experiments include single phase gas flow tests through intact and treated dry coal samples. Experimental observations indicate that TSLs can reduce gas permeability of coal by up to three orders of magnitude. However, the degree of the impact depends strongly on the type of TSLs. Further, the initial permeability of coal and TSL thickness also affect the efficiency of the process. There is a linear relation between the efficiency of the TSLs in controlling gas flow and their adhesion strength to the coal sample.

Keywords: Thin spray-on liners, Gas management, Gas flow in coal, Coal permeability, Underground coal mining

Introduction

Mining is one of the key drivers of the Australian economy as Australia is the world's largest exporter of coal. While longwall mining accounts for approximately only 18% of total coal production, this proportion is likely to increase as surface open cut operations reach their economically viable limits (Cram, 2006). As a precursor to extraction of coal using the longwall coal mining system, which is key to the high productivity system of underground coal mining currently used in Australia, large areas of coal of some 250 m wide by 2000 m long need to be initially blocked out. These areas are delineated by development tunnels or roadways driven within the coal using rock cutting machinery. The roadways are cut into the near horizontal coal seam forming a rectangular profile. Weak to moderate strength sedimentary rock layers are present in the roof and floor of the roadway. Over the years, various means have been employed to ensure the stability of these roadways and other underground excavations as the surrounding rock mass is subjected to high levels of stress (Craig *et al.*, 2009, 2010; Gilbert *et al.*, 2010).

In coal mines, the major gases of concern are methane (CH_4) and carbon dioxide (CO_2). The degree of coalification ranges from peat to the highest rank anthracite. During this process, water, CO_2 and CH_4 are formed from the original composition of hydrocarbons and oxygen present. CO_2 is formed in lower rank coals from excess oxygen but is then normally flushed out, to a greater or lesser extent, by CH_4 formed at a later bituminous or anthracitic stage. In general, higher rank cooking coals contain more methane and lower rank steaming coals a higher proportion of CO_2.

In a coal seam, CH_4 is physically adsorbed to the solid coal surface of the fractured matrix. The methane does not become a free gas and migrate to the drives/roadways until the pressure in the fractures (cleats) is reduced below the Langmuir pressure (Gilman and Beckie, 2000). Mining the coal seam is an obvious factor that disturbs the initial stress state of the seam. Consequently, the methane becomes free in the disturbed zones, which then migrates towards the mined excavations. The velocity of this migration depends on the coal permeability, which is almost entirely contributed by regularly shaped parallel fractures (Gilman and Beckie, 2000). Strict limits on methane concentrations in coal mine workings typically result in return concentrations $<1\cdot25\%$ (power off) (Thomas, 2002) or at worst $<2\cdot0\%$ (withdrawal of workers). Therefore, every mine has to develop effective gas control strategies to capture and control the gas, ensuring that gas concentration in the roadways is maintained below the 1·25% to prevent any explosion.

Sourcing and using methane gas from coal seams are of growing interest to the gas industry. In some circumstances, the gas can be safely drained to the surface through boreholes drilled into the unmined seams from the surface (Packham *et al.*, 2011). Gas drained in this way is called coalbed methane. In the majority of underground coal mines, however, it is not possible to drain the gas before mining takes place, and gas emission into the mine still stays as a serious hazard. Gas emissions sometimes limit the rate of coal production of a mine as peaks in gas emissions necessitate temporary shutdown. This represents a loss of revenue for the mine.

Use of thin spray-on liners (TSLs)

Over the past 20 years, the technology of TSLs has emerged as a promising alternative to the use of

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shotcrete and mesh as a ground support tool in underground mines. A TSL is defined as a thin chemical based coating or layer that is applied to mining excavations at a thickness of 3–5 mm (Saydam and Docrat, 2007; Lau *et al.*, 2008). They are generally applied by mixing and spraying a combination of liquid/liquid or liquid/powder components onto the rock face as quickly as possible, where a TSL sets quickly and develops a strong bond with the rock.

The use of TSLs has been common in the civil engineering field for many years (Yilmaz *et al.*, 2003; Gilbert *et al.*, 2010). They are predominantly used in the hardrock mining industry (mostly gold, nickel, platinum and diamond mining in South Africa and North America) and their use has been slow to be adopted into coal mining. However, they are starting to have success in coal mining, especially in Australia and Europe, where they are being applied as an anti-weathering coating (as a sealant) or as a barrier layer for polyurethane injection (Kothe *et al.*, 2010).

A TSL application may not replace a conventional ground support such as rock bolts. It should be considered as a temporary or combined support with other ground support tools. However, TSLs have performed well when combined with other type supports such as rockbolts+TSL+shotcrete and rockbolts+TSL+mesh+shotcrete. Thin spray-on liners may prohibit the initiation and propagation of fractures and key blocks and hence improve the rock strength and excavation stability (Stacey, 2001). The following are the most common usages of TSLs (Potvin *et al.*, 2004):

- (i) support between rock anchors
- (ii) supporting areas with limited access and/or logistics constraints
- (iii) mesh replacement
- (iv) as primary support immediately after blasting
- (v) temporary support (before shotcrete)
- (vi) temporary support in TBM tunnels (poor ground conditions)
- (vii) reduce rockburst damage
- (viii) pillar reinforcement
- (ix) face support
- (x) large machine borehole lining and stabilisation
- (xi) stabilisation of return air tunnel
- (xii) ore pass lining
- (xiii) prevention of rock falls
- (xiv) rigid ventilation seals
- (xv) ground degradation (weathering fretting, swelling and slaking)
- (xvi) ground alteration (moisture, heat, humidity and chemical contamination).

A report conducted by an European experts group (EFNARC, 2008) also identified the following possible advantages of using TSLs compared with shotcrete: thinner applied thickness; increased toughness, durability, resilience, stronger permanent bond to the substrate; reduced dusting; much greater tolerance to ground movement and resistance to cracking. The report also clearly mentioned the advantage of using TSLs as a barrier against gas and moisture movement.

An Australian Coal Association Research Program research project was conducted on TSLs by Ostle *et al.* (1998). This study shows the potential of use of TSLs in underground coal mines. They conducted a series of tests and trials in different underground coal mines using a TSL product and as part of the application procedure, stone dust was first washed out from the surface to provide better adhesion to the coal surface (Laurence, 2004).

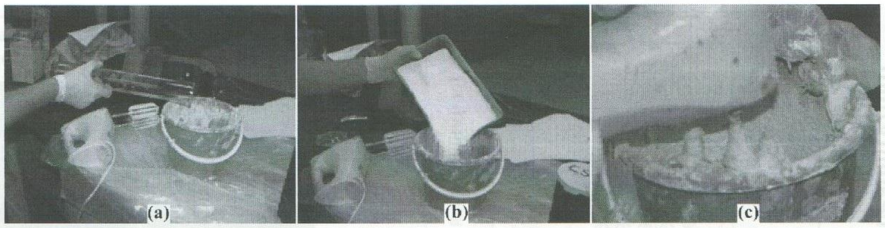
Gerard (2007) and Gilbert *et al.* (2010) also identified TSLs' further usage as applications in the maingate area to improve safety and productivity considering that these areas are one of the most highly trafficked areas in the longwall section by its crew and are also located in a region which is undergoing the fastest rate of rib deterioration in underground coal mines.

Coates (1970) suggested that if the applied surface support is airtight, entry of air will be prevented or limited and dilation will be restricted. Stacey (2001) mentioned that for a rockmass to fail, dilation must take place, with opening occurring on joints and fractures. If such dilation can be prevented, failure will be inhibited. Stacey (2001) also indicated that 'although this is unlikely in a static loading environment, in dynamic loading situations, in which rapid entry of air into the rockmass will be restricted, it is possible that an air tight TSL might promote stability'. Goaf seals may be considered as airtight and watertight. However, leaks in goaf seals can create potentially dangerous environments leading to significant safety and economic problems. Leakage can occur through cracks and fractures created in the seal after it has been installed. This may lead to displacement of ribs, roof and floor due to the increased stresses (Gerard, 2007).

Besides ground support, TSLs also have a great potential to stop gas migration into underground coal mines, thereby improving seam gas management. Archibald *et al.* (1999) measured the radon gas blocking capacity and gas permeability of different TSL materials. They emphasised the potential use of liners in reducing gas inflow and decreasing air flow frictional resistance. They also mentioned that the TSLs have the capability to restrict hazardous gas inflows and optimise flow capacities of ventilation networks that will provide additional benefit for health and safety while reducing mine power costs. It is important to note that the hazardous gases, easily diffusing from rock pores into the working area, cannot be effectively blocked by shotcrete (Tannant *et al.*, 1999). However, TSLs can penetrate into cracks and joints and increase the frictional strength of the partings (Stacey, 2001; Saydam *et al.*, 2004).

Saghafi and Roberts (2001) reported measurements of the permeability of a common TSL product for methane, carbon dioxide and carbon monoxide. Their results indicate permeability of TSLs in the range of nanodarcies. They reported that the permeabilities to CH_4 and CO_2 are very similar whereas the permeability to CO is a few times higher.

Gerard (2007) identified the benefits of using TSLs in coal mines and suggested spraying TSLs on the ventilation intake side to prevent any further oxygen from entering the leakage path if a spontaneous combustion event is exposed in a chain pillar. Furthermore, the study added, if detected early enough, the oxidation process may slow down and ultimately stop due to the absence of oxygen. However, they both argued that, if a TSL is sprayed to the ribs whether for support or gas management (as sealant), the oxidation could be avoided completely.



a water is first poured into a container; *b* powder component is then added in stages; *c* liner is mixed by an electric mixer

1 Mixing procedure for TSL-2

In this paper, the application procedures of liners in underground coal operations have not been discussed and the focus of this study is the TSLs' potential for applications for gas management in underground coal mines through laboratory tests of gas flow on coal samples. To the best of our knowledge, none of the previous tests on gas management has investigated the interaction between TSLs and coal samples.

Experimental

Thin spray-on liners materials

There are many different types of TSL product in the market. They differ by polymer base and mixture types based on their chemical compositions. According to Potvin *et al.* (2004) and Northcroft (2006), polymer based TSLs can be divided into six distinct groups: acrylics, liquid latex, polyurethanes, polyureas, methacrylates and hybrids (polyuria/polyurethane, cement/acrylic and cement/polyurethane).

Three different TSL products, each from two different companies were tested in this study. Owing to confidentiality agreement, the product names are not disclosed here, instead they are named as TSL-1, TSL-2 and TSL-3. TSL-1 is a mixture of water and powder. The powder of TSL-1 comprises limestone, calcium oxide, cement, alumina, kaolin, boron calcium oxide, pentahydrate, anyhydrite and crystalline silica. TSL-2 is also a water/powder mixture, in which the powder is the Portland cement. TSL-3 is comprised of liquid/powder mixtures where the liquid is polymer acrylic emulsion and the powder is binder and calcium sulphate. According to this classification, all three TSLs can be considered as the cementious acrylic based products.

The adhesion strength of these TSLs to the coal surface was tested and reported by Gilbert *et al.* (2010). They found that TSL-1 had the lowest adhesion strength (0·4 MPa) and TSL-3 had the highest adhesion strength (0·77 MPa) of the products tested on the coal samples. TSL-2 had a strength of 0·53 MPa.

The mixing procedure for the TSLs is dependent upon the components of the products. The ratios of the TSL components for each product were mixed in accordance with the manufacturer's guidelines. It is crucial to follow these guidelines in order to achieve the desired product. The laboratory mixing procedure for TSL-1, as an example, is shown in Fig. 1.

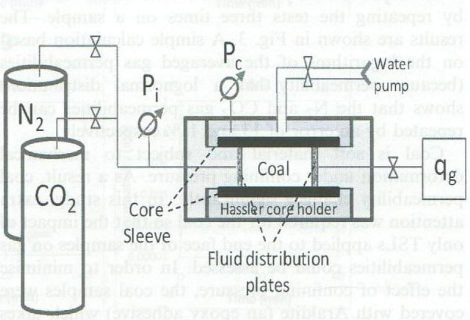
Gas flow tests

A Hassler type core holder was used to perform single phase gas flow tests on the coal samples. A schematic of the experimental set-up is shown in Fig. 2. Cylindrical coal samples of 45 mm in diameter and 107 mm in length were placed in a Viton sleeve attached to a core holder. Then a confining pressure of 1500 kPa was applied on the sleeve by means of a water pump in order to make sure that gas flow occurs within the coal sample. The confining pressure also simulated the overburden pressure on coal seams. A leakage test was carried out to ensure that there was no leakage from the confining part before injection of the gas. The outlet was open to the atmosphere and the flowrate of the gas at the outlet was measured as a function of time. The pressure and flowrate were initially stabilised for a steady state flow. After they were stabilised, the experiment was then terminated. Using the data of core dimensions, flowrate and injection pressure at the steady state, the gas permeability at the relevant differential pressure was calculated using the following Darcy equation modified for compressible gas flow

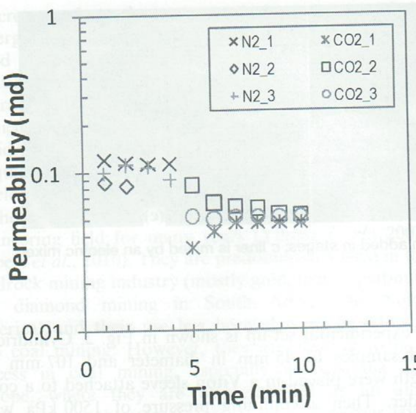
$$k = \frac{2\times 10^{-3} q_g \mu L P_a}{A \Delta P^2} \quad (1)$$

where k is the permeability (mD), q_g is the flowrate (cm^3 s^{-1}), μ is the viscosity (mPa s), L is the length (cm), P_a is the atmospheric pressure (bar), A is the cross-sectional area (cm^2) and ΔP^2 is the difference between injection and outlet pressures squared (bar^2). The Klinkenberg slippage correction to the permeability was not made. Instead, the pressure differential across the samples was kept constant for all experiments (1000 kPa) in order to make a reasonable comparison between the measurements.

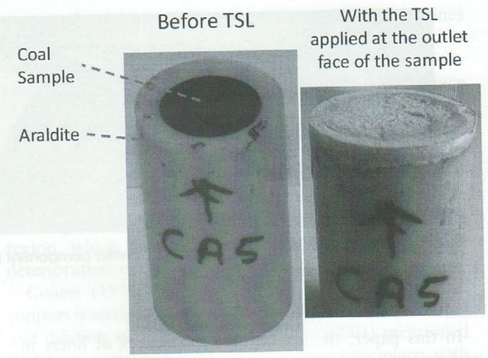
Carbon dioxide (CO_2) and nitrogen (N_2) were chosen as the gas phases in the experiments due to the fact that



2 Schematic view of experimental apparatus used for gas flow tests



3 Reproducibility gas flow tests on a coal sample treated with TSL-3



4 Coal sample preparation and TSL application

both gases have different interactions with the coal matrix. Past work suggests that CO_2 has much more tendency to adsorb on coal surface than N_2 and CH_4, while CH_4 has slightly higher affinity than N_2 (Pini *et al.*, 2009). As a consequence, when injected, CO_2 swells the coal, thereby reducing its permeability; whereas N_2 shrinks the coal through which it improves the permeability (King *et al.*, 1986). For example, there is field evidence that matrix swelling associated with CO_2 adsorption may cause two orders of magnitude reduction in coalbed permeability (Reeves *et al.*, 2003). Because CO_2 is more viscous and has larger molecular size compared with the other two gases, its desorption rate is relatively slower. The flow behaviour of CH_4 is expected to be in between CO_2 and N_2 flows, hence our choice of gases for the experiments should cover the expected physical phenomena.

A systematic procedure has been followed to examine the effect of TSLs on gas permeability. The coal samples were first tested without any TSL products. First N_2 flow test was made followed by a CO_2 flow test. Then, in order to assess the impact of TSLs on the gas control, the TSLs were applied on the outlet face of the cylindrical coal samples in a uniform thickness. The gas flow test at the same conditions was repeated to observe the change in gas permeabilities to N_2 and CO_2.

The reproducibility of gas flow tests was investigated by repeating the tests three times on a sample. The results are shown in Fig. 3. A simple calculation based on the logarithms of the averaged gas permeabilities (because permeability has a lognormal distribution) shows that the N_2 and CO_2 gas permeabilities can be repeated by an error of 13 and 11% respectively.

Coal is soft material and subject to mechanical deformation under confining pressure. As a result, coal permeability changes significantly. In this study, extra attention was required for the coal so that the impact of only TSLs applied to the end face of the samples on gas permeabilities could be assessed. In order to minimise the effect of confining pressure, the coal samples were covered with Araldite (an epoxy adhesive) which takes over the confining pressure. Figure 4 shows coal sample CA-5 treated with Araldite and TSL-2 material.

Thin spray-on liners with various thicknesses were applied in order to examine the role of TSL thickness on gas flow. The flow direction in the coal samples was kept the same for all experiments. Consequently, the difference between the measured permeability data was then attributed to the effect of the TSL application at the outlet face of the coal sample. The dimensions of the coal samples and TSL types and thicknesses are summarised in Table 1.

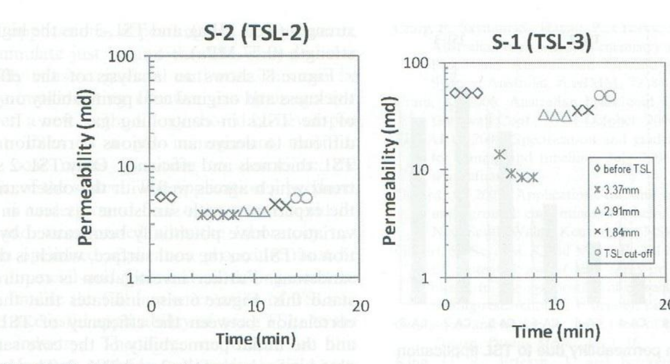
Results

With the purpose to form a benchmark for the coal experiments as well as understand any effect of confining pressure on gas flow through coal, the same procedure was first applied on outcrop sandstone samples. Sandstone is a brittle rock and its flow properties are not expected to be affected by a small confining pressure of 1500 kPa. The results are shown in Fig. 5. After a gas permeability test, the first sample was subjected to TSL-3 application with a thickness of 3·37 mm and a gas flow test was carried out. The permeability decreased by almost one order of magnitude. Then, the TSL-3 was cut off gradually and the permeability increased as a result. Finally, when the liner was removed completely, the permeability reached its original value. In another experiment, a low permeability sample was used with TSL-2 and a similar trend in permeability change but with a lower degree of change was observed, which can be attributed to the type of the liner and original permeabilities of the samples.

The results of the gas flow tests with the coal samples are shown in Fig. 6. They include two N_2 and two CO_2 gas

Table 1 Data for cylindrical coal samples of diameter of 25·2 mm

Samples		Length/ mm	TSL type	TSL thickness/ mm
Coal	CA-1	63·5	TSL-3	1·77
	CA-2	62·8	TSL-3	1·80
	CA-3	63·0	TSL-3	3·18
	CA-4	59·6	TSL-2	1·24
	CA-5	64·8	TSL-2	3·18
	CA-6	61·6	TSL-2	2·68
	CA-7	66·6	TSL-1	2·16
	CA-8	66·6	TSL-1	2·16
	CA-9	54·8	TSL-1	5·62
Sandstone	S-1	52·8	TSL-3	Variable
	S-2	54·6	TSL-2	Variable

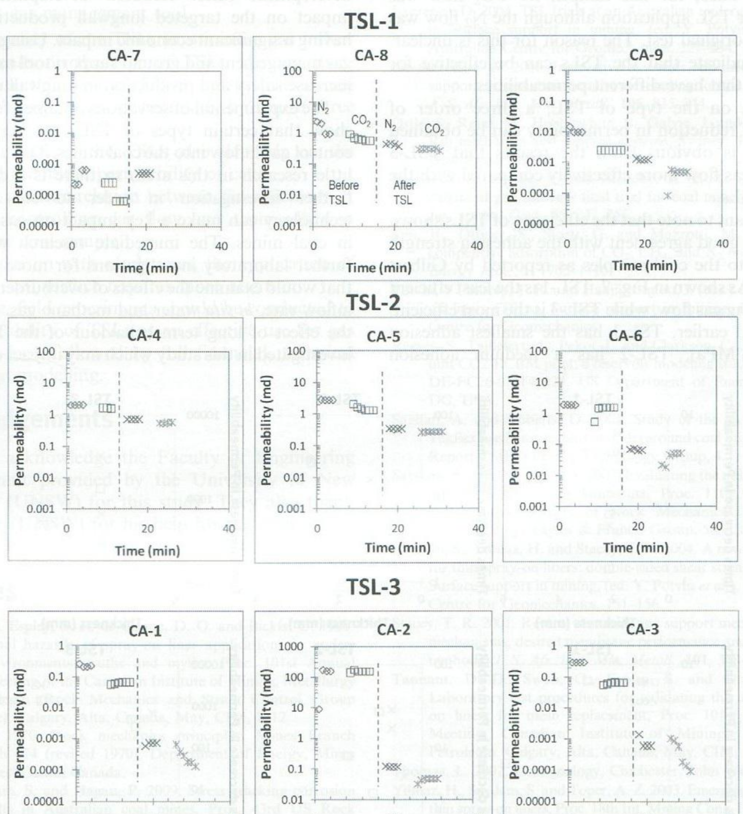


5 **Effect of TSLs on N_2 flow in sandstone**

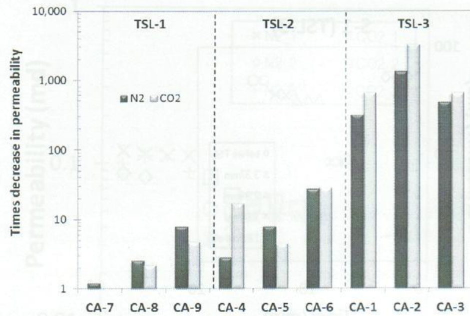
flow tests, before and after TSLs were applied. The results show a remarkable effect of the TSL on gas flow through the coal samples. However, the effect depends on the coal sample and the type of TSL. Generally all samples except for CA-7 gave the following similar response:

(i) the pre-TSL N_2 injection gave highest permeability
(ii) the pre-TSL CO_2 injection reduced permeability
(iii) the post-TSL N_2 injection reduced permeability further
(iv) the post-TSL CO_2 injection reduced permeability.

This response is in good agreement with the knowledge cited in the literature where CO_2 has more adsorption capacity to coal compared with N_2 and this causes coal swelling and permeability reduction (see the section on



6 **Gas permeabilities to N_2 and CO_2, measured before and after TSL application at outlet of coal samples**



7 Degree of decrease in permeability due to TSL application

'Gas flow tests'). The permeability of coal samples treated by TSL-1 and TSL-2 decreased approximately by one order of magnitude, whereas the permeability of coal samples treated by TSL-3 decreased by three orders of magnitude. Figure 7 shows the degree of the decrease in permeability in response to the TSL application. Only sample CA-7 did not show any measurable decrease in permeability. Also, for this sample, no CO_2 flow was observed after TSL application although the N_2 flow was similar to its original test. The reason for this is unclear. The results indicate that the TSLs can be effective for various coals that have different permeabilities.

Depending on the type of TSL, a three order of magnitude of reduction in permeability can be obtained by TSLs. It is obvious from the results that TSL-3 reduced the gas flow more effectively compared with the other two TSLs.

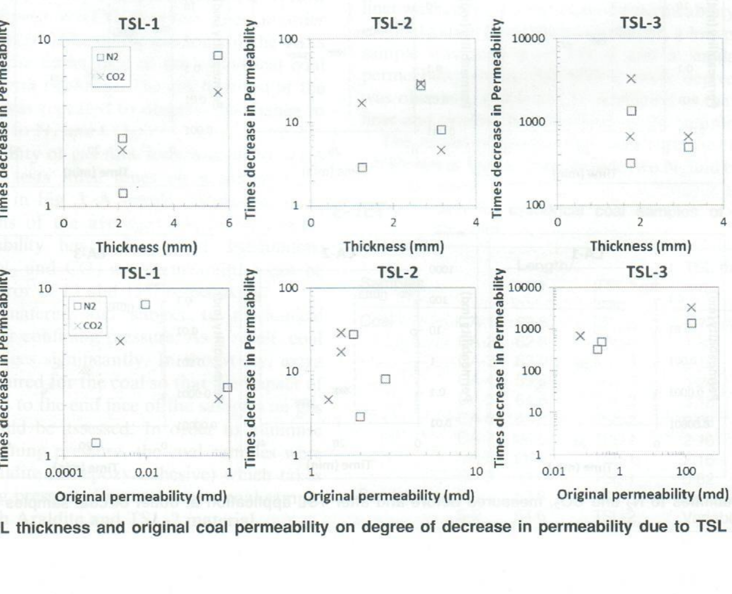
It is important to note that the efficiency of TSLs shown in Fig. 7 is in good agreement with the adhesion strength of the TSLs to the coal samples as reported by Gilbert *et al.* (2010). As shown in Fig. 7, TSL-1 is the least efficient liner preventing gas flow, while TSL-3 is the most efficient. As mentioned earlier, TSL-1 has the smallest adhesion strength (0·4 MPa), TSL-2 has a medium adhesion strength (0·53 MPa), and TSL-3 has the highest adhesion strength (0·77 MPa).

Figure 8 shows an analysis of the effects of TSL thickness and original coal permeability on the efficiency of the TSLs in controlling gas flow. It seems to be difficult to derive an obvious correlation between the TSL thickness and efficiency. Only TSL-2 shows a clear trend which agrees well with the observation made for the experiment with sandstone (as seen in Fig. 5). The variations have potentially been caused by the application of TSL on the coal surface, which is different from sandstone. Further investigation is required to understand this. Figure 6 also indicates that there is a clear correlation between the efficiency of TSL application and the initial permeability of the core sample. This is obvious for both TSL-2 and TSL-3. The data with TSL-1 showed a curve with a maximum at the middle permeability value.

Discussion

The Australian mining industry aims to achieve a higher production rate. To accomplish this in high gassy seams, rib emissions can be a major factor in determining development rates. Reduced development rates can impact on the targeted longwall production, therefore having a significant economic impact. Using TSLs as both gas management and ground support tool may potentially increase safety and production in longwall mining.

The experimental observations obtained from this study show that certain types of TSLs are very efficient to control gas inflow into the coal mines. There has been very little research in this area, so there is a clear need for further investigation in order to see whether this technology can make a key impact on gas management in coal mines. The immediate research would include further laboratory investigations for more realistic cases that would examine the effects of overburden pressure, gas inflow rate, *in situ* water and methane gas. Furthermore, the effect of long term behaviour of the TSLs was not investigated in this study which may impact the gas flow in



8 Effect of TSL thickness and original coal permeability on degree of decrease in permeability due to TSL application

coal. In field applications, depending on circumstances, gas may accumulate just behind the TSL skin and this may potentially cause a gas/coal outburst. This can be controlled by implementing effective gas drainage systems. However, a new methodology should be developed to implement TSLs as a gas management tool for underground coal mines in order to determine the potential value of the system. The application procedures of the liners in underground coal operations should be investigated and incorporated with the laboratory test results and an optimised application procedure must be generated. A financial and technical modelling must be conducted to finalise the full implementation of TSLs to determine the successful applicability of using TSLs to the coal mining industry. Therefore, in order for this technology to become a viable tool, multiple field tests under various conditions need to be conducted. Numerical modelling work should also be developed to simulate the laboratory tests. Further, the field tests should be verified with numerical modelling results.

Conclusions

1. The experimental observations of gas flow tests have indicated the potential benefit of using TSLs in coal mines as gas management tool.

2. The efficiency of the TSLs to minimise gas inflow strongly depends on the type of TSLs. Among three TSLs used in this study, TSL-3 showed a strong efficiency, reducing the gas permeability by almost three orders of magnitude.

3. The efficiency of the TSLs also depends on the thickness and the initial permeability of coal.

4. There is a linear relation between the efficiency of the TSLs in controlling gas flow and their adhesion strength to the coal sample.

5. In comparison with sandstones, the application of TSLs on the coal surface requires more attention.

6. In future, field experiments should be conducted to see the applicability of TSLs as an effective use for gas management tool, followed by full financial, technical and numerical modelling.

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