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INVESTIGATION ON ADHESION STRENGTH OF THIN SPRAY-ON LINERS IN AN UNDERGROUND COAL MINE

Zecheng Li, Serkan Saydam, Rudrajit Mitra and Duncan Chalmers

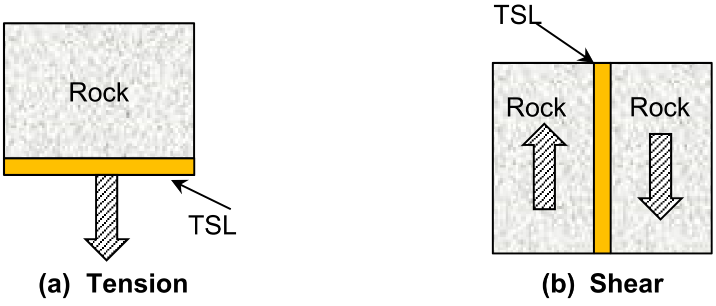
ABSTRACT: A Thin Spray-on Liner (TSL) is defined as a chemically based layer or coating (3-5 mm) that is sprayed onto the rock surface to support mining excavations (Saydam and Docrat, 2007). Since the introduction, TSLs have received success in some applications in hard rock mines; however, their use has been slow in coal mining. The adhesion strength between a TSL and a rock surface is an important parameter controlling the design and performance of liner support systems. The i*n situ* adhesion tests have been conducted to study the bonding between a TSL material and the coal substrate in an underground coal mine in NSW. A direct pull-off adhesion tester was adopted to conduct adhesion tests on the ribs of the roadway. In this paper, the *in situ* adhesion test results on coal substrate are analysed and presented.

INTRODUCTION

A Thin Spray-on Liner (TSL) is defined as a thin chemically based coating or layer that is applied onto mining excavations with a thickness of 3 to 5 mm (Saydam and Docrat, 2007). The adhesion strength between a liner and rock is one of the most important parameters in terms of support resisting capacity (Li *et al*., 2014). When liners are used for area support, there is an intimate contact between the liner and rock surface. Where adequate adhesion bonds exists, TSLs can carry or transfer the load created by gravity falls or loose rock onto stable or unfractured rock surface (Archibald, 2001).

The adhesion strength of a TSL can be defined as its ability to adhere to a particular surface (Swan and Henderson, 2001). Over the years, many adhesion test procedures have been proposed by researchers to assess the adhesion strength of TSLs. These adhesion test procedures can be divided into core adhesion test, embedded dolly test and glued dolly test. The glued dolly test method is the most widely used procedure by researchers due to its ease of application and accuracy of results (Mercer, 1992; Espley-Boudreau, 1999; Tannant *et al.,* 1999; Archibald, 2001; Spearing, 2001; Kuijpers *et al.,* 2004; Saydam and Docrat, 2007; Li *et al.,* 2014).

Kuijpers (2004) reported that two types of bond strength have to be considered: tensile and shear, as shown in Figure 1. Tensile bond strength is a measure of the ability of TSL to remain in contact with the rock when a tensile stress is applied normal to the rock-TSL interface. Shear bond strength is concerned with the ability to resist stresses that act parallel to the rock-TSL interface. In practice, there is usually some combination of these stresses acting on the interface (Saydam and Docrat, 2007).



(a) Tension **(b) Shear**

Figure 1: De-bonding mechanisms of TSLs (modified from Kuijpers *et al.,* 2004)

The use of TSL as a gas management tool in underground coal mines is currently being investigated by the School of Mining Engineering, UNSW Australia at an underground coal mine in NSW, Australia. A polymer based TSL was applied to the ribs of the coal mine. As part of the investigation, *in situ* adhesion tests were conducted to study the bonding between TSL and coal substrate. The test method adopted

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School of Mining Engineering, UNSW Australia, Sydney, NSW 2052, Australia, E-mail: zecheng.li@student.unsw.edu.au, Tel: 02 9385 6118 was a direct pull adhesion test which was adapted from ASTM D4541 standard. Due to the agreements with the mine and the TSL manufacturer, the mine name and the product name will not be disclosed in this paper.

In this paper, the in-situ adhesion test results on coal substrate are analysed and presented.

TEST PREPARATION AND EXECUTION

Test area description

A polymer based TSL was sprayed onto the ribs of the roadway. Figure 2 shows the adhesion test area before and after the TSL application. Due to the excavation disturbance and the stress concentration, the coal in the top part is more fractured, while the coal in the bottom part is relatively intact. Adhesion strength tests were conducted on both these regions to evaluate the influence of substrate integrity on the adhesion strength results.

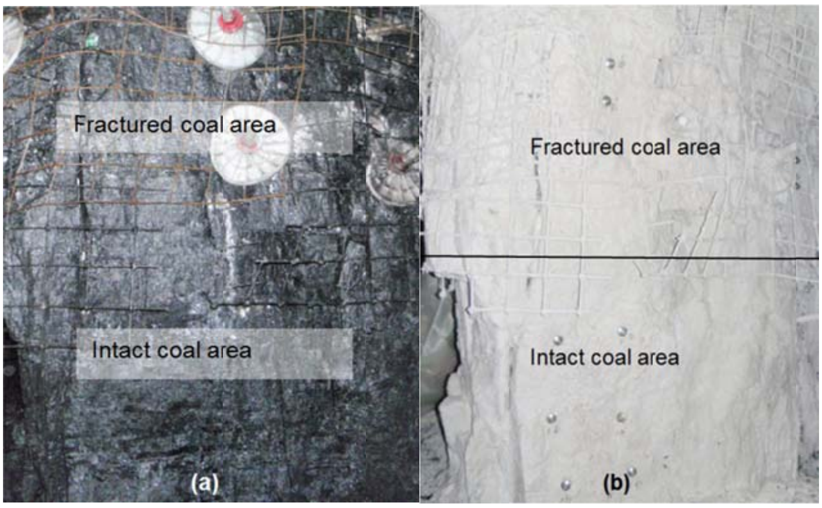

Figure 2: ***In situ*** **adhesion test area (a) before TSL application, (b) after TSL application**

Test apparatus and procedure

The PAT GM01-Elcometer testing apparatus was used in this test. The test apparatus works on a distributed force pull off system, which can apply a maximum force of 6.3 kN. The steel test dollies are 28.2 mm in diameter which is the standard size supplied with the equipment. The range of the test pressure is 0-10 MPa for the size of the dollies used.

The test dollies were glued to the surface with araldite epoxy. The test area was over-cored by using a coring bit to make sure the pull force will only be applied on the test dolly area. Then a pull force was applied normal to the coal surface until de-bonding occurred. The liner was allowed to cure for 1 day, 7days, 14 days, 21 days and 42 days before testing. At least 5 tests were conducted for each condition. Figure 3 shows an in-situ test execution on the rib of the roadway.

Figure 3: ***In situ*** **adhesion strength test (a) overcoring, (b) dolly under test**

TEST RESULTS AND ANALYSIS

Adhesion strength test results

In total, 58 adhesion strength tests were conducted at the mine on both intact and fractured coal areas. Table 1 provides the average adhesion test results and image processing results with different curing times of 1 day, 7 days, 14 days, 21 days and 42 days.

Table 1: Adhesion strength test results

Test area	Curing time days	Adhesion strength MPa	Standard deviation MPa	Percentage of coal on failure surface %	Standard deviation %
Intact coal area	1	0.23	0.03	47.41	18.26
	7	0.59	0.05	75.63	12.19
	14	0.91	0.23	81.00	7.17
	21	0.91	0.13	84.32	4.18
	42	0.95	0.17	87.61	1.97
Fractured coal area	1	0.12	0.03	43.20	20.03
	7	0.53	0.10	84.33	7.47
	14	0.52	0.21	83.38	8.72
	21	0.57	0.26	85.18	4.03
	42	0.58	0.25	84.86	4.55

Effect of curing time

As curing time increases, the adhesion strength increases and then stops for both intact coal and fractured coal, as shown in Figure 4. For intact coal, the adhesion strength increases from 0.23 MPa to 0.59 MPa from 1 day to 7 days, and then reaches the final value at 14 days. After 14 days, the adhesion strength is almost the same. While for fractured coal, the adhesion strength reaches the final value at 7 days, and there is no significant change to the adhesion strength after 7 days.

For each curing time, the adhesion strength for intact coal is much higher than that on fractured coal, with final adhesion strength of about 0.9 MPa, and 0.55 MPa for intact coal and fractured coal respectively, as shown in Figure 4. The results revealed that the integrity of the substrate has a great influence on the adhesion strength.

It is also interesting to compare the standard deviation of adhesion strength for both intact coal and fractured coal. As shown in Figure 5, the standard deviation for fractured coal is much higher than that for intact coal. For 21 days testing, the standard deviation of adhesion strength result on fractured coal almost doubled compared that on intact coal. It can be concluded that the adhesion strength results on fractured coal varies considerably compared to those on intact coal. This may be due to variability of the friability of the coal at each dolly site.

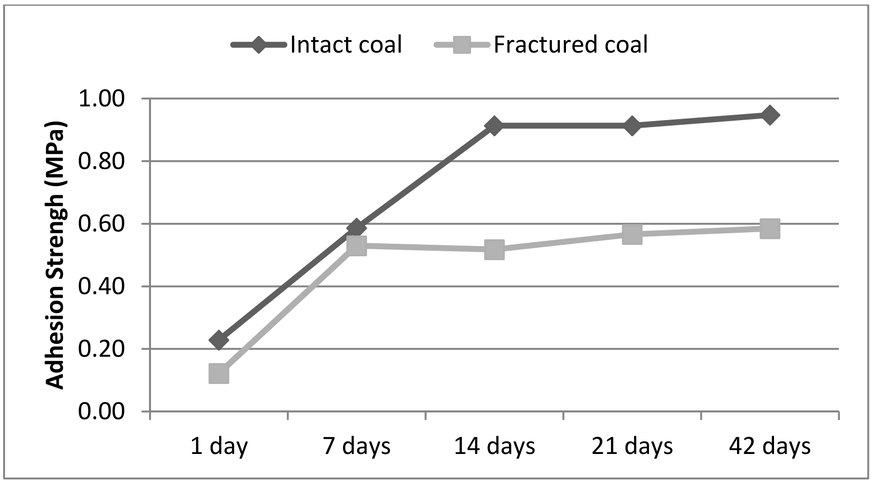

Figure 4: Adhesion strength with different curing time

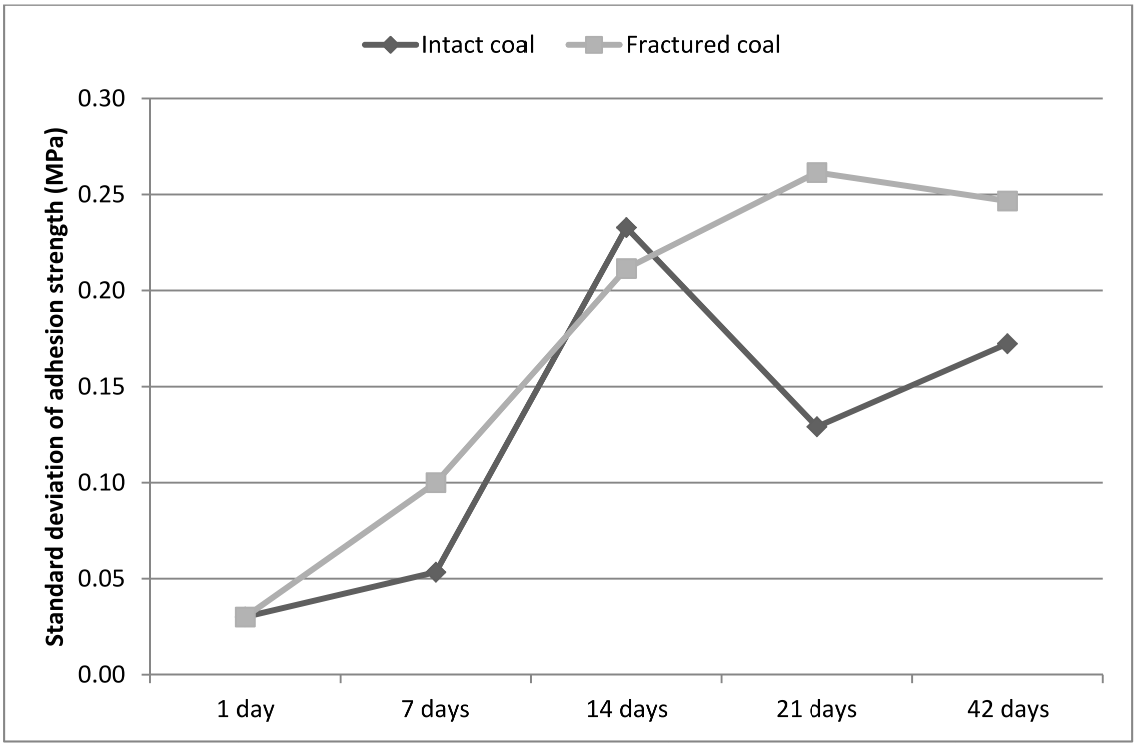

Figure 5: Standard deviation of adhesion strength with different curing time

Failure mode analysis

Failure of the adhesion test can occur in several ways. These include failure between the liner and the host rock (which is coal in this case), internal failure of the host rock, de-bonding of the adhesive material between either the liner or the steel dollies (Saydam and Docrat, 2007; Gilbert *et al.,* 2010). A new methodology was adopted for analysing the failure mode of the adhesion test. This involved using an image processing software to calculate the percentage of coal and liner on the failure surface. This procedure is outlined in Figure 6. Figure 6 (a) is the original photo of the failure mode and the chosen area for analysing is shown in Figure (b). Then the chosen area is converted into an 8-bit image which only contains black and white colour. As shown in Figure 6 (c), the black area represent the coal and the the white area represent the liner. The proporation of coal and liner on the failure surface can be obtained by calculating the percentage of black and white area.

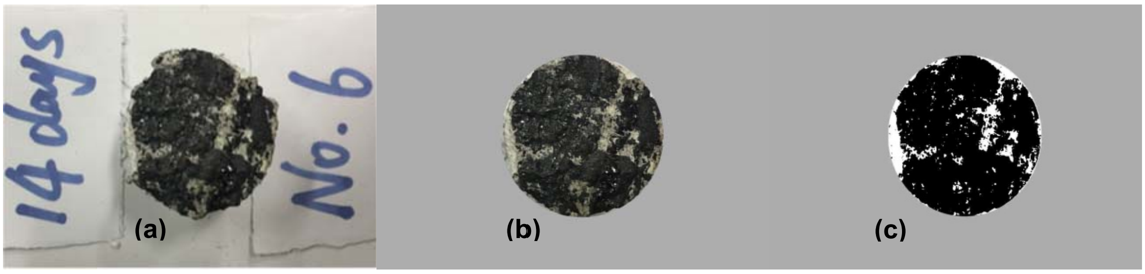

Figure 6: Image software processing

Image processing results reveal that the failure mode for both intact coal and fractured coal is mainly attributed to the internal failure of the coal substrate besides 1 day testing. As shown in Figure 7, for 1 day testing, the failure mode is a combination of internal failure of the coal substrate and the liner, with a percentage of coal on the failure surface about 47.41% and 43.20% for intact coal and fractured coal respectively. This is due to the fact that the TSL material is still very weak after 1 day curing, and the material fails easily in tension. While for testing after 7 days of curing, the TSL material has developed a relatively strong tensile strength compared with the adhesion strength between coal substrate and the liner. The percentage of coal on the failure surface almost exceeds 80%, which indicates an internal failure of the coal substrate, as shown in Figure 7. Typical view of failure surface with different curing time is shown in Figure 8.

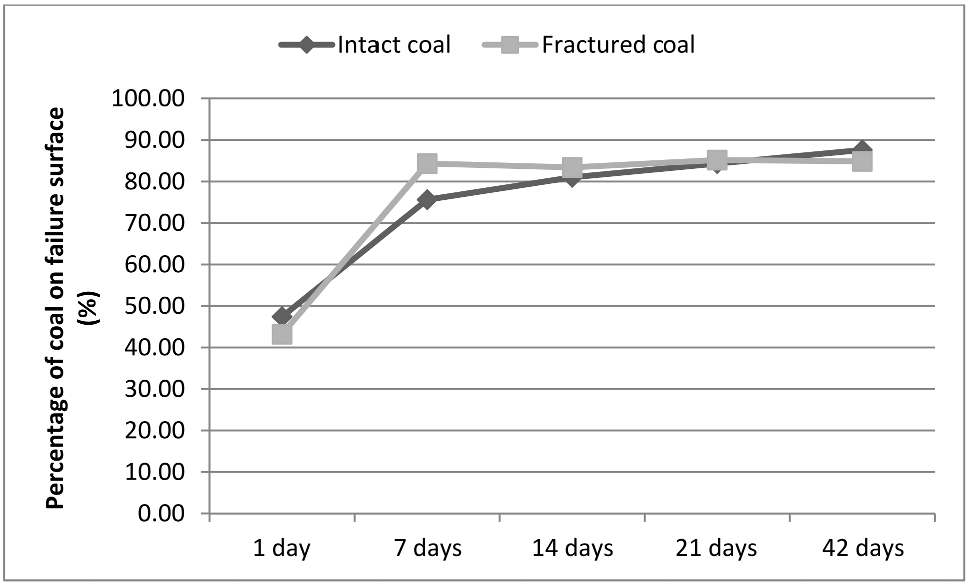

Figure 7: Percentage of coal on failure surface with different curing time

Figure 8: Typical view of failure surface with different curing time

Unlike the standard deviation for adhesion strength results, as the curing time increases, the standard deviation of percentage of coal on the failure surface tends to decrease and then reaches a steady value, as shwon in Figure 9.

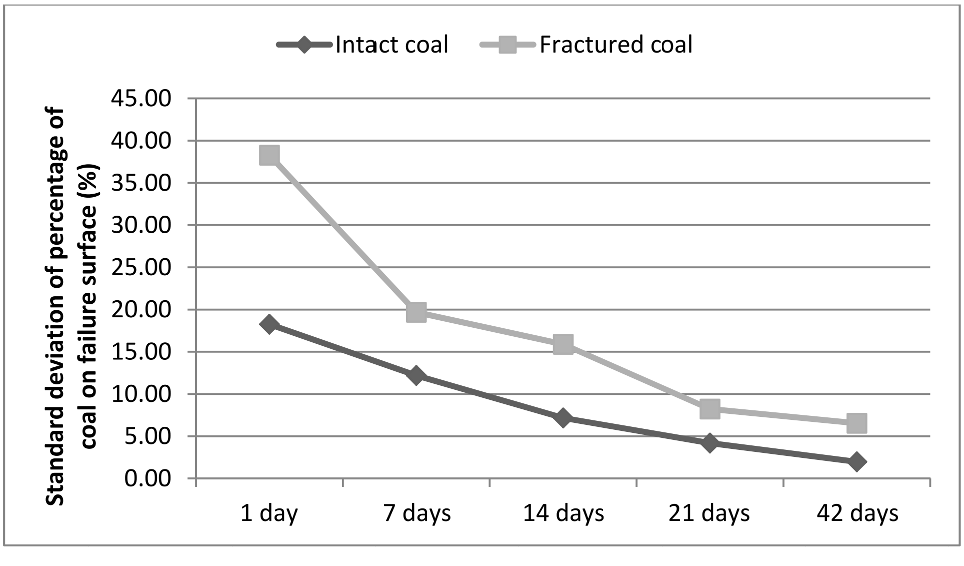

Figure 9: Standard deviation of percentage of coal on failure surface

DISCUSSION

The adhesion test is designed to determine the bond strength existing between a liner material and the substrate. The test results revealed that the TSL material chosen can bond firmly to the coal substrate *in situ*. However, the tests were only conducted with a maximum curing time of 42 days, and TSL's long-term performance should be investigated in the near future.

Previous laboratory research revealed that the coal bedding plane directions have a significant influence on the adhesion strength. Previous laboratory tests also indicated that the adhesion strength parallel to the bedding planes was much higher than that normal to bedding planes (Gilbert *et al.,* 2010; Li *et al.,* 2014). However, for the in-situ applications, the adhesion strength tests were only able to be conducted on the ribs of the roadway, so all the tests conducted were parallel to bedding planes. For adhesion strength normal to bedding planes, laboratory adhesion tests should be conducted as a replacement of the in-situ tests.

The adhesion strength tests are part of the project that investigates the potential use of TSLs as a gas management tool in underground coal mines. The adhesion strength results should also be combined with other test results to evaluate the performance of the TSL chosen.

CONCLUSIONS

In-situ adhesion tests were conducted to investigate the bond strength properties of a polymer based TSL on coal in an underground coal mine in NSW, Australia.

For comparison of the adhesion strength results, tests were conducted on both intact coal and fractured coal areas. With the increase of curing time, the adhesion strength increases for both intact coal and fractured coal, and the adhesion strength on the intact coal area is much higher than that on the fractured coal area.

The adhesion strength results on fractured coal are much more scattered with a higher standard deviation of adhesion strength compared with that on intact coal. The standard deviation tends to increase with the increase of curing time.

The adhesion strength results from this research indicate that the TSL material tested could be implemented for underground coal mining conditions. This is due to the main failure mode of the adhesion strength test observed being the internal failure of the coal substrate.

RECOMMENDATIONS

This is a pilot research to study the potential applications of TSLs in underground coal mines. However, in order for this technology to become a viable tool for undergrond coal mining, research emphasis should be put on multiple field trials of TSLs under various conditions.

Apart from the use of TSLs as a complementary ground support medium, the application of TSLs could also bring many other benefits, such as gas management and ventilation benefits. A systematically economic model should also be built to evaluate the cost and benefits of TSLs for underground coal mines.

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