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Effect of rock and liner properties, and environmental conditions on thin spray-on liner shear bond

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Article

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Shear-bond
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Curing period
Oil

Abstract

Thin spray-on liners (TSLs) are a promising rock support method due to their ease of application and versatility. However, their effectiveness relies on experience and lacks a complete scientific understanding. To bridge some of the knowledge gaps existing in support mechanisms, this study investigated the effect of different parameters on the shear-bond strength of TSLs as a surface support in underground excavations. The parameters included liner thickness, curing period, material type and surface cleanliness. A polymer based cementitious TSL was utilized while the material type included quartz and sandstone rocks and 30 MPa concrete. Liner thicknesses included 16.2 mm, 20.2 mm, 24.2 mm, 28.2 mm, and 32.2 mm while curing periods were 7 days, 14 days, and 28 days. It was observed that the TSL shear-bond strength varied with different materials. Quartz with the lowest porosity had the lowermost shear-bond strength at all liner thicknesses and curing periods. The shear-bond strength improved with liner thickness up to 24.2 mm and then decreased up to 32.2 mm due to the optimum thickness effect. It also increased with curing period. Oil reduced the shear-bond strength for all the material types at all liner thicknesses and curing periods.

1. Introduction

The increasing health and safety measures in the mining industry has added to the worldwide market pressure to improve profits' margins. According to Webber-Youngman & van Wyk (2009), fall of ground (FOG) fatalities represented 39% of total number of fatalities in underground mines in South Africa between August 2006 and March 2009. These statistics are similar to those of other mines worldwide where FOG fatalities account for about 30-40% of all mining fatalities. In 2021, there were an estimated 2,933 FOG fatalities in the mining industry, of which 2,478 were in underground mines. According to the Mine Safety and Health Administration (MSHA), fall of ground (FOG) was the leading cause of fatalities in U.S. coal mines from 2010 to 2020, accounting for 39% of all fatalities (Imam et al., 2023). In China, fall of ground (FOG) fatalities accounted for 31.7% of all mining fatalities in 2021 a significant decrease from 40.5% in 2020 as stated by China Coal Industry Association (Kong et al., 2022).

A rockfall study by Potvin & Nedin (2003) conducted in 26 Australian underground metal mines showed that over 90% of rockfall injuries involved rocks smaller than 1 ton within a few meters of the active face. Therefore, lack of surface support coverage can be singled out as the most obvious cause of rock falls in mining excavations (Daehnke et al., 1998; Klokow, 1999; Daenke et al., 1999). Rock tendons or props overall provide inadequate support for fragmented rock even in the case of grouting, and therefore blocks of rock from the excavation boundary can easily detach due to gravity, seismic activity, or blasting-induced vibrations. Additionally, support coverage can reduce weathering and unraveling of exposed rock surface (Ortlepp, 1983; Wojno et al., 1986; Applegate, 1987; Zhao et al., 2022).

Rock surface support is widely used to combat rockfalls and the resulting injuries and fatalities within the vicinity of active faces (Adams & Baker, 2002; Potvin, 2002; Lacerda & Rispin, 2002; du Plessis, 2021). The conventional (traditional) surface support systems in underground rock support include passive methods such as mesh and lacing, and active methods such as shotcrete (Kolapo et al., 2021; du Plessis, 2021; Zhao et al., 2022). However, statistical rockfalls associated with these methods over the years seem to suggest a steady increase in rockfall fatalities. They also negatively impact the mining operations with regards to costs, logistics and mine cycle times due to large material volumes (Tannant, 2001; Ozturk & Tannant, 2010; Ferreira, 2012; Roache et al., 2023). Therefore, there is a need for more enhanced systems and

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methods to improve safety standards in the mining industry (Li et al., 2017; Roache et al., 2023).

As a solution, since the 1990s, diverse kinds of Thin Spray-on Liners (TSLs) were developed with the aim of providing alternatives to the conventional methods (Stacey, 2001; Tannant, 2001; Yilmaz, 2011; Jjuuko & Kalumba, 2016; Dondapati et al., 2022). TSLs have various advantages over traditional methods as stated by various researchers including being lightweight, easy to install, flexible, durable, and cost-effective (Adams & Baker, 2002; Tannant, 2001; Hermanus, 2007; Yilmaz, 2011; Kolapo et al., 2021; Wang et al., 2024). TSLs have also been shown to be effective in preventing rockfalls and other ground instability problems. However, their application in the mining industry is still in its early stages. Therefore, their design as surface support systems is still based on experience, assumptions, field observations and cost considerations because the mechanisms by which TSLs act to provide support are not fully understood (Tannant, 2001; Leach, 2002; Saydam et al., 2003; du Plessis & Malan, 2021; Liang et al., 2021).

According to Tannant (2001), Jjuuko and Kalumba (2015) and Ozturk & Tannant (2010), the ability of a liner to resist displacements and fractures, to a greater extent, depends on a combination of shear-bond, tensile-bond and adhesive-bond between the liner and the rock. Though a lot of research has been done on the tensile and adhesive bond of TSLs to the rock substrate (Mason & Stacey, 2008; Ozturk & Tannant, 2010, 2011; Ozturk, 2012a, b; Yilmaz, 2013; Jjuuko & Kalumba, 2014, 2018), limited research has been done on the shear-bond strength of TSLs because early research suggested that shear-bond had negligible consequences on their performance (Espley-Boudreau et al., 1999; Espley-Boudreau, 1999; Liang et al., 2021). However, Stacey & Yu (2004), demonstrated that liner penetration into joints and fractures, where shear-bond is effective in resisting failure, results in a significant support mechanism of block interlock (Stacey, 2001). Therefore, quantification of shear-bond strength is essential in the formulation of design standards and requirements for TSLs.

In this study, the variation of TSL shear-bond strength with liner thickness, substrate type and surface cleanliness, and curing period was investigated. This is in line with previous studies, which have shown that the bond strength of liner materials is affected by several factors, including substrate surface roughness, substrate material, curing time of liner materials, liner thickness, and environmental conditions (Chen et al., 2020; Shan, 2017). The liner was a polymer based cementitious TSL and substrates were rock and concrete. The aim of the study was to provide valuable insights into the factors that affect the shear-bond strength of TSLs. The information can be used to improve the design and application of TSLs to ensure that they provide effective rock support in underground mines.

2. Materials and methods

2.1 Experimental plan

The laboratory investigation involved three substrates of quartzite and sandstone rocks and concrete, and a cementitious TSL. The TSL thickness and curing period were varied as shown in Table 1. The study also involved dipping the substrates in oil before the preparation of test specimens to examine the effect of oil on TSL shear-bond strength. A total of five specimens were prepared for each testing point. Henceforth, a total of 1125 specimens were prepared for each substrate type. This gave 2250 specimens prepared for the whole study resulting in 2250 experimentation results obtained for shear-bond strength analysis.

2.2 Thin spray-on liner (TSL)

A polymer-based cementitious thin spray-on liner, Capcem KT Fast 2C was obtained. It was based on conventional cement and solvent free water-based polymer, supplied as separate cement and polymer components Table 2 shows further specifications of the TSL.

2.3 TSL mixing

A kitchen food mixer was used to mix the cement and polymer in the measured portions. It was the preferred method since it was easy and found to produce superior quality of TSL mixture. The material was mixed well, to avoid unmixed lobes, for five minutes at medium speed (speed 4/18000rpm). Small portions were consumed since small specimens were prepared. It was impractical to use a whole bag of cement. 1 L of polymer liquid was mixed with 3.5 kg of cement powder as suggested by the manufacturers and no water was added.

Table 1. Experimental plan.

Factors	Level	Code	Description
Substrate Type	3	Q	Quartzite
		S	Sandstone
		C	Concrete
Curing Time	3	T1, T2, T3	7 days, 14 days and 28 days
Liner Thickness	5	L1, L2, L3, L4, L5	16.2 mm, 20.2 mm, 24.2 mm, 28.2 mm and 32.2 mm.
Surface cleanliness	2	O1, O2	Clean and soaked in oil

An electrical weighing scale was used to weigh the TSL cement while a marked plastic tube was used to measure the polymer in the specified ratios. Manual pouring was used to apply the required TSL onto the specimens. Figure 1 presents the materials that were used in the study.

2.4 Rocks

A variety of different rock types that are or equivalent to mining field material were obtained from diverse sources as shown in Figure 2. These included, sandstone from Table Mountain slopes, Figure 2a; quartzite from Table Mountain slopes, Figure 2b, and equivalent to Wits gold rocks; sandstone, Figure 2c, d, f, and shale, Figure 2e, from Exarro Leeuwpan Colliery, Delmas, Mpumalanga. Leeuwpan is located 80 km south-east of Pretoria near the town of Delmas, Mpumalanga province. The Delmas coalfield is situated to the west of Witbank coalfield. The stones weighed around 40 kg and were roughly 400 x 400 mm^2 in size. The water content, dry density, porosity and UCS of the rocks was determined according to the "The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006", the results are presented in Table 3.

From the initial tests, it was discovered that weaker rocks could not be utilized in the study. This was since their compressive strength was weaker than their shear-bond strength to the TSL. Therefore, they crushed before attaining failure between the rock and TSL interface. The rocks in this category included shale and reddish weathered sandstone. Stronger rocks of quartz and sandstone were consequently employed in the study to investigate the effect of rock type on the TSL shear-bond strength.

Table 2. Specifications for Capcem KT Fast 2C (OMSSA Technical Data Sheet).

Properties (all components at 25 °C)	
Pump Life	40 Minutes
Fresh Wet Density	1777 kg/m^3
Strength Development (25 °C) – Typical	
Tensile Adhesive (28 day)	2.5 MPa
Tensile Adhesive (56 day)	5.4 MPa
Mixing	
Cement Powder (supplied in kit) (kg)	Polymer Liquid (supplied in kit) (litres)
19	5

2.5 Rock core preparation

The cores were prepared by diamond saw cutting using a portable power-driven rock coring machine. Diamond saw cutting process was highly recommended since it was found to result in comparable surface finishes. After cutting, the specimens were cleaned with water and checked for any faults. Those found with faults like cracks were discarded as they would cause deviations in the substrate roughness. The good specimens were air surface-dried and marked, Figure 3a, for cutting into smaller cores for TSL shear-bond testing using a circular diamond blade on a cutting machine. The specimens were cut flat, top and bottom. They were then air-dried for about four days under constant temperature (24-26 °C) and humidity (50-70%). This was to ensure all samples from the same rock type had the same moisture content before bonding with TSL. It was believed that moisture content would influence the bond between the TSL and substrate.

2.6 Concrete core preparation

Occasionally underground excavations are lined with concrete rings as a means of support on which liners are then sprayed. Table 4 gives details of the percentages of the different

Table 3. Determined rock properties.

Parameter	Rocks	
	Quartzite	Sandstone
Water content (%)	0.011	0.027
Dry density (kg/m^3)	1829.9	2229.9
Porosity (%)	5.6	14.2
UCS (MPa)	163	72

Figure 1. (a) Packaged cement, (b) Packaged polymer, and (c) Grey-brown cement in a bowl.

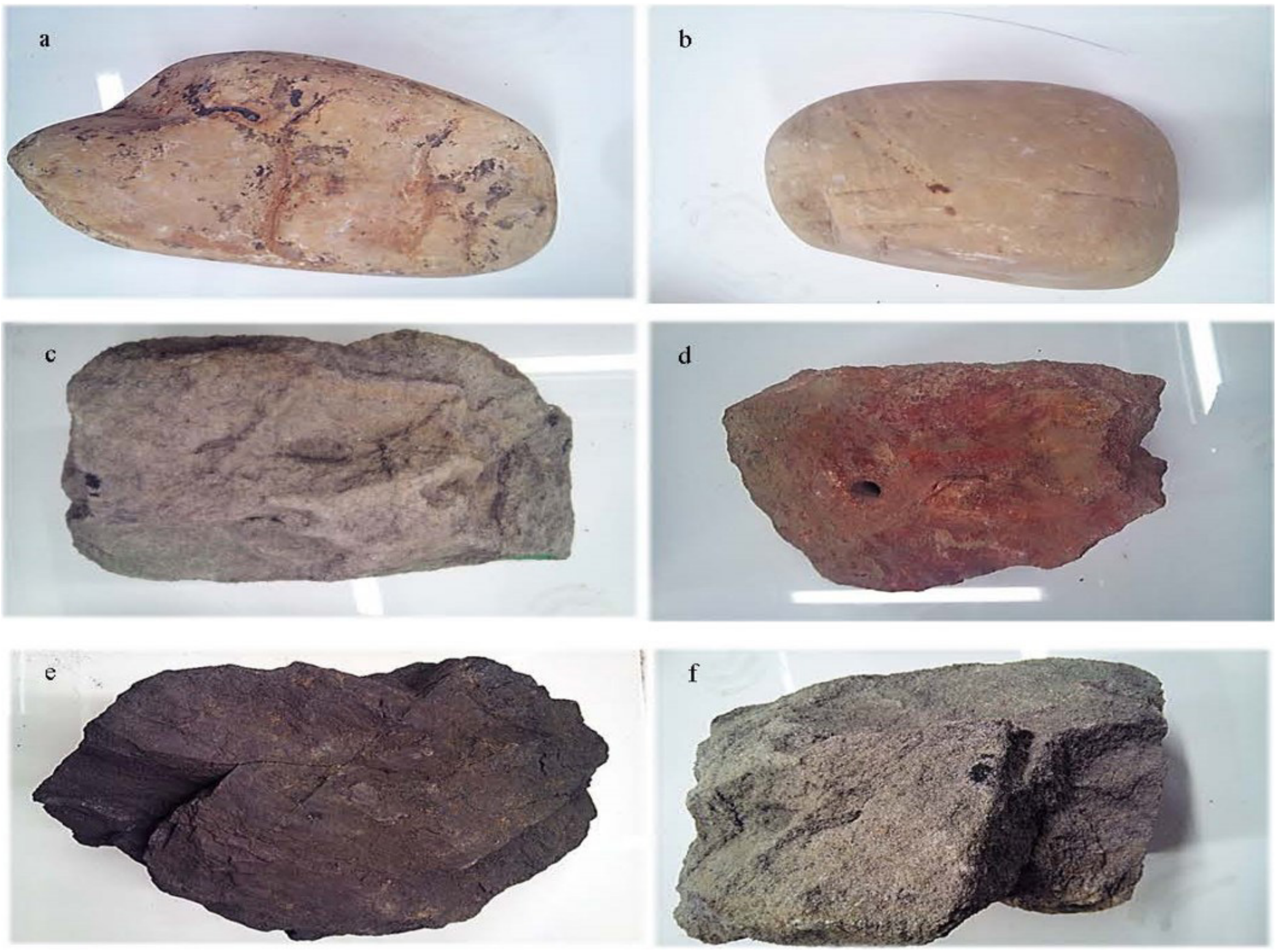

Figure 2. (a) Weak sandstone with faults from Table Mountain slopes, (b) Quartz from Table Mountain slopes, (c) Sandstone from Exarro, (d) Weak reddish weathered sandstone from Exarro, (e) Shale from Exarro, and (f) Sandstone from Exarro.

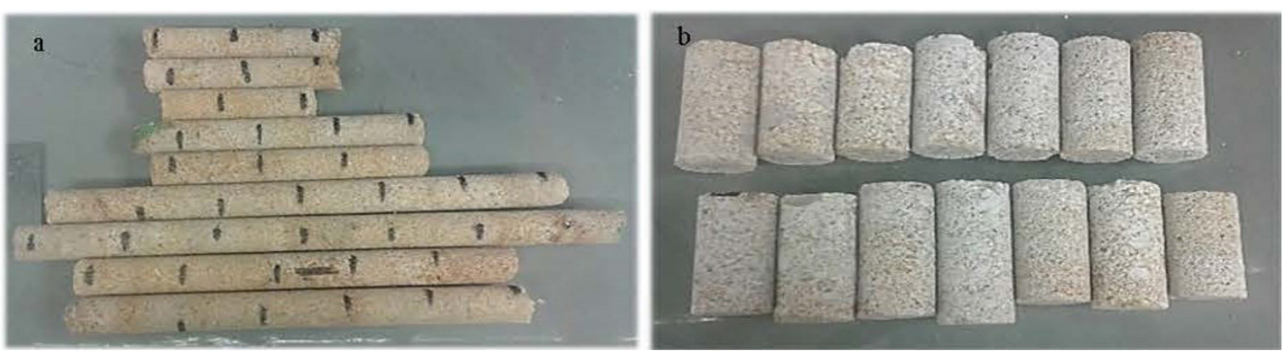

Figure 3. (a) Sandstone cores marked for cutting into specimens and (b) Sandstone core specimens.

Table 4. Details of 30 MPa concrete mix utilized.

W/B	0.7	Density (kg/m^3)	Mass (kg)	Batch Volume	40 L Batch
	%			Volume (m^3)	Mass (kg)
Water	7.7	1000	185.0	0.185	7.40
CEM 1 52.9	11.0	3140	264.0	0.084	10.56
Stone greywacke (19 .0 mm)	43.7	2700	1050.0	0.389	42.00
Dune Sand	37.7	2650	906.0	0.342	36.24

Table 5. Concrete cube strength results.

Date of Cast	Date Tested	Sample Number	Dimensions (mm)	Weight (kg)	Dry Density (kg/m^3)	Crushing Load (kN)	Ultimate Compressive Strength (N/mm^2)
		1		7,96	2358	652.5	29.0
29/04/2015	21/05/2015	2	150x150x150	7,70	2282	642.0	28.5
		3				675	30.0
		Average Compressive Strength (N/mm^2)					29.2

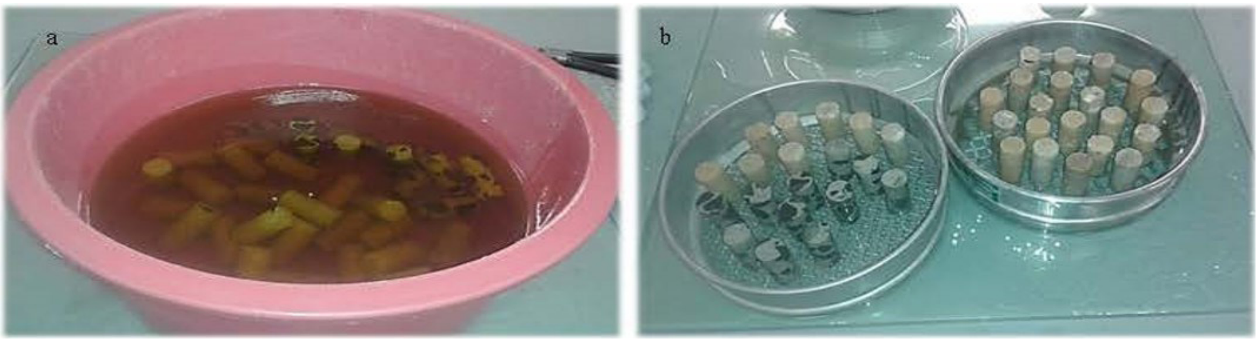

Figure 4. (a) Sandstone and concrete substrates submerged in oil for 24 hours, and (b) Air-drying the submerged substrates for 24 hours.

materials used in the mix for a 30 MPa concrete liner. 30 MPa was selected since it is one of the most used concrete strength in underground excavations. After the curing period of 28 days, out of the many prepared cubes, three were randomly selected and tested for the achieved UCS strength. Table 5 summarizes the test results. The remaining concrete cubes were then used in the preparation of cores for TSL shear-bond strength testing. The same procedure used for rock coring was again utilized here. Concrete cores used for TSL shear-bond testing had an average water content of 2.818%, average dry density of 2320 kg/m^3 and average porosity of 9.8%.

2.7 Oiled cores

In order to investigate the effect of surface cleanliness on the shear-bond strength of TSLs, some of the rock and concrete cores were submerged in oil for 24 hours, Figure 4a. After 24 hours, they were removed from the oil and air-dried for another period of 24 hours, Figure 4b. They were air-dried standing on top of wire meshes with holes wide enough to allow the dripping of oil away from the bottom of the specimens. After 24 hours of air-drying, the oiled core specimens were used in the preparation of specimens for TSL shear-bond strength testing. The main source of oil contagion in underground rock excavations is from machinery hence hydraulic oil was used in the study. The oil was of CALTEX (Havoline Formula SAE 20W-50).

2.8 Moulds

The study utilized the circumferential shear-bond strength testing method developed by Yilmaz (2011). The moulds

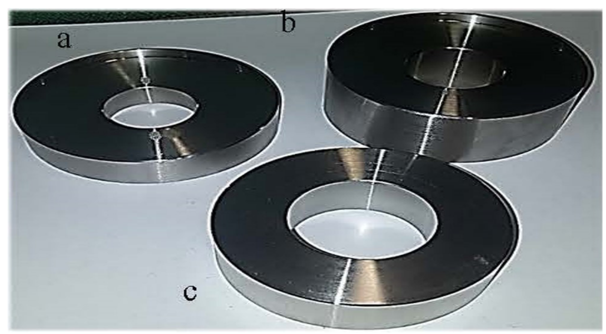

Figure 5. (a) Steel rock centering ring, (b) Steel support ring, and (c) One of the steel rings.

included a steel ring, steel rock centering ring and a steel support ring, Figure 5, Figure 6 and Figure 7. Steel was preferred for the moulds due to its high strength, low cost and high corrosion resistance. In case of rusting, there is a possibility of interference with the bonding properties.

2.9 Specimen preparation

The steps followed during specimen preparation are demonstrated in Figure 8. Firstly, the steel centering ring was placed on a flat glass surface, Figure 8a. This was to ensure that the specimen does not move when TSL is poured. The top surface of the centering ring was then slightly oiled to prevent the TSL from bonding to it during setting. The steel ring was then placed on top of the centering ring, Figure 8b. The core was centrally positioned in the inner hole of the centering ring, Figure 8c. This way

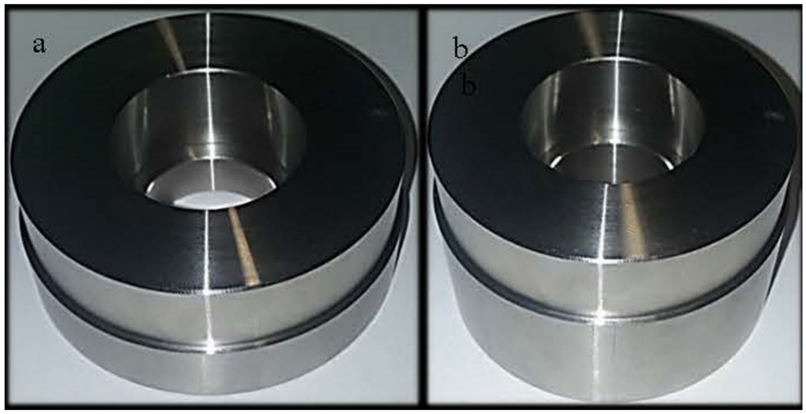

Figure 6. (a) Steel ring in steel rock centering ring and (b) steel ring in steel support ring.

it was also centrally located in the steel ring. Afterwards, the TSL components consisting of cement and polymer were mixed according to the manufacturer's specifications of 19 kg to 5 L respectively. The cement was measured using an electronic scale, Figure 8d, while the polymer was measured using a plastic measuring tube, Figure 8e. TSL was then poured into the space between the core and the ring, Figure 8f. A putty knife was used to assist in the settling of the TSL in position and avoid air being trapped within the TSL. Flattening of TSL's exposed top surface to ensure uniform TSL thickness was done by tamping a sheet of plastic against the surface. Masking tape was used to prevent the TSL from coming into contact with the core surfaces where bonding was not wanted.

2.10 Test set-up and execution

The prepared specimen, after curing for the required time, was carefully placed on top of the steel support ring, Figure 9a, and then positioned in the Zwick loading machine (Material prufung – 1474), Figure 10. A spherical seat was used on the top surface of the substrate in order to ensure that the load was uniformly distributed. The machine platen, with springs again for uniform distribution of load, was attached to the spherical seat. The specimen was then made to just make contact with the machine platen. Compression loading was done in displacement control mode. The specimen was initially loaded up to 5 N at 0,001 mm/s for alignment and setting, and then at 0,002 mm/s up to failure. Load and machine displacements were recorded automatically by the Zwick machine. The load at failure was noted for each tested specimen.

After each test, the Zwick machine was used to drive out the rock core by means of a smaller diameter steel rod, Figure 9b. The TSL was also pushed out of the steel ring in the same way by using another steel rod that was a few mm smaller than the inside diameter of the steel ring, Figure 9b. The height of the pushed-out TSL, Figure 9c, was measured evenly at three positions in order to calculate the de-bond area. The average of the measured height was calculated.

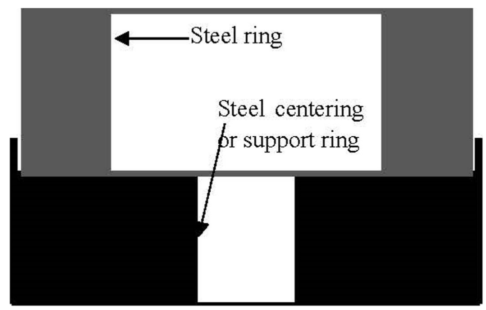

Figure 7. Schematic diagram showing the steel ring seated in either the steel centering or support ring.

2.11 Calculations

The boundary conditions on the specimen assembly are shown in Figure 11. The load is applied on the top surface of the core. The reaction takes place on the fixed support base indicated by red lines. The green lines are stress free surfaces. The bonding of core and TSL, and eventual shearing takes place at the yellow lines. For rocks where the core strength is not reached, full failure takes place at the TSL-core contact surface. Shear movement on the TSL-core boundary develops shear stress (τ_b) calculated as presented in Equation 1, proposed by Yilmaz (2011).

$$\tau_b = \frac{F}{\pi D t}(Pa) \quad (1)$$

where:
F = Maximum applied force;
D = Core diameter;
t = Depth or steel ring height.

3. Analysis and results

3.1 Statistical analysis of results

For statistical validity and comparison of test results, specimen preparation and testing should be repeatable.

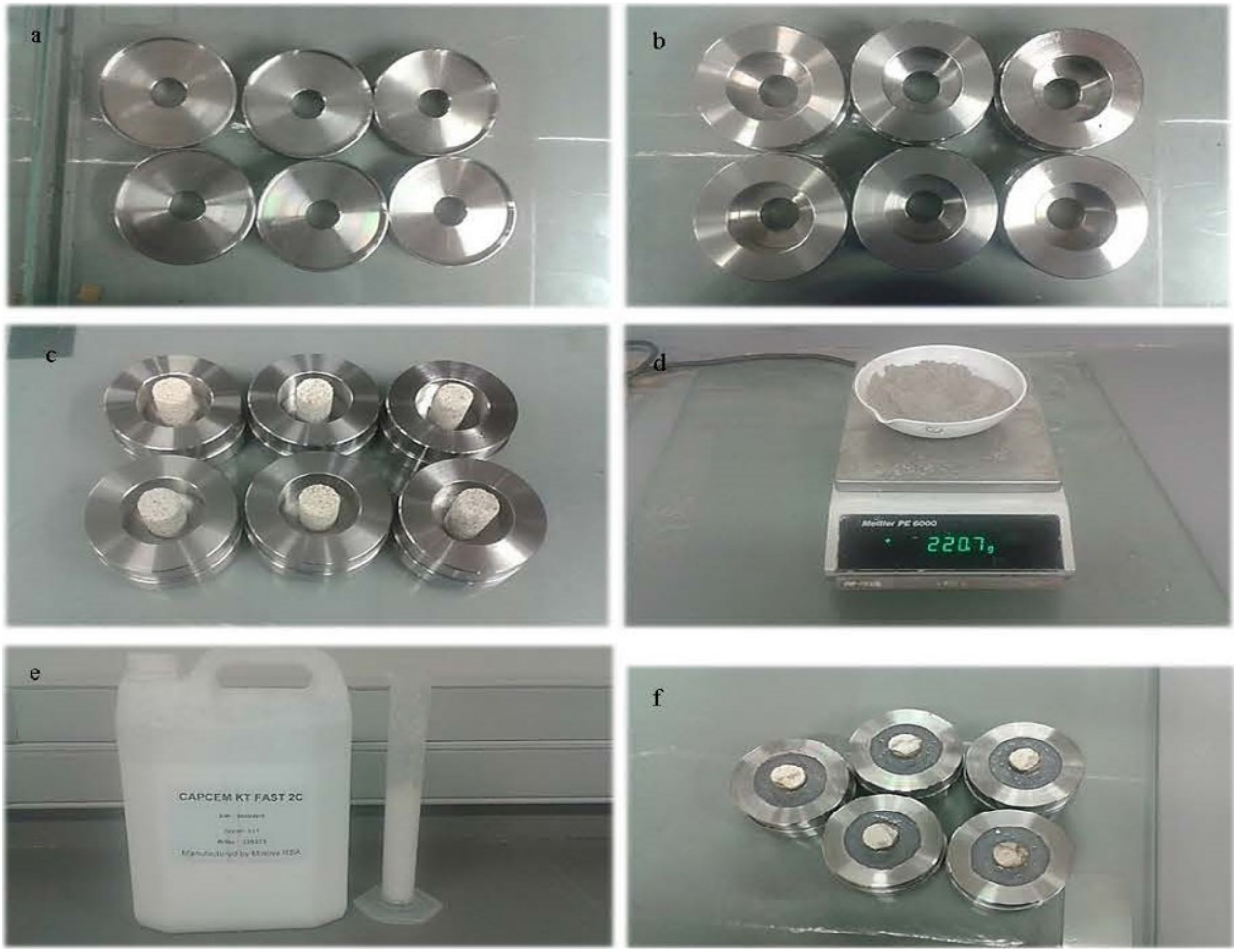

Figure 8. (a) Centering ring placed on flat glass, (b) Steel ring seating on centering ring, (c) Sandstone substrate seated in the steel ring and centering ring, (d) Measuring the required amount of cement, (e) Measuring the required amount of polymer, and (f) Prepared specimens.

Figure 9. (a) Specimen on steel support ring ready for testing, (b) Steel rods for driving out the substrate and liner, and (c) Liner driven out of the steel ring after testing.

The repeatability of the test results was investigated with calculation of repeatability standard deviation and coefficient of variation. The standard deviation (SD) ranged between 0.1 and 2.1. The oiled substrates had all their SD values either equal or under 0.6, hence demonstrating high consistency. The Coefficient of Variation (CV) varied between 3.0% and 25.4%. It should be noted that CV is a better parameter to quantify the dispersion of shear-bond strength values. There was no definite trend in the spread of SD and CV over liner thickness, curing period and substrate. A maximum CV of 25.4% is a good sign of uniformity of the test results obtained. The smaller the calculated values of SD and CV, the more repeatable the testing methodology. The statistical analysis of the laboratory results showed that they were uniform and consistent. Hence, they could be employed in the analysis and conclusion of the variation of shear–bond strength with investigated parameters.

3.2 Variation of shear-bond with liner thickness

Liner thicknesses affect the interpretation of TSL test results. Shear bond strength is the ability of a thin spray-on liner (TSL) to resist shearing forces when it is bonded to a rock substrate. Liner thickness is the distance between the top and bottom surfaces of the TSL. There is a relationship between shear bond strength and liner thickness. Previous studies have shown that, generally, shear bond strength increases with increasing liner thickness. This is because thicker liners have more surface area to bond to the rock substrate. Several studies have been conducted to investigate the bond strength of TSLs (Ozturk & Tannant, 2010; Chen et al., 2020; Yilmaz, 2011). The results of these studies show that the bond strength of TSLs can vary widely. Yilmaz (2011), demonstrated that the shear bond strength increased from 1.5 MPa to 4.5 MPa as the liner thickness increased from 2 mm to 5 mm. Chen et al. (2020) reported adhesive strength from pull-off tests varying between 0.97 MPa and 2.86 MPa for liner thicknesses of 8 mm and 1 mm respectively.

Figure 10. Zwick machine.

In this study, liner thicknesses of 16.2 mm, 20.2 mm, 24.2 mm, 28.2 mm, and 32.2 mm were utilized to investigate the effect of varying liner thickness on TSL shear-bond strength. Figure 12 illustrates the variation of shear-bond strength with liner thickness for the substrate of Quartzite, Sandstone and Concrete respectively. Five tests were carried out for each liner thickness at a specific curing period. The averages of the respective shear-bond strengths were used to come up with the curves of variation as shown on the graphs.

It was believed that another set of liner thicknesses may show the same variation, as obtained in the graphs, with a peak point at a different liner thickness depending on the contact shear area at the start of the test. To overcome this constraint, an aspect ratio was calculated as presented in Equation 2.

$$Aspect\ ratio = \frac{Liner\ thickness\,(m)}{Shear\ area\,(m^2)}(m^{-1}) \tag{2}$$

Aspect ratios of 13.0, 16.2, 19.4, 22.7, and 25.9 were utilized in this study. Graphs of shear-bond strength against

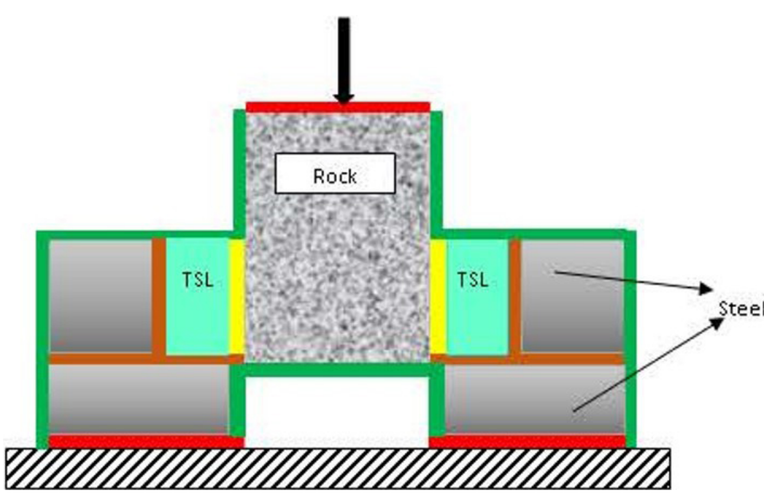

Figure 11. Boundary conditions in shear-bond strength testing.

aspect ratio were then plotted. The shear-bond strength generally increased with increase in aspect ratio up to 19.4 m^{-1} and then decreased. Initially, there was a small increment in shear-bond strength with the curve concave upwards followed by a sharp increment of a concave downward curve up to the peak value. After the highest value, there was a sharp decrement in shear-bond strength and then a slight decrement.

The variation of shear-bond strength with liner thickness is due to the optimum thickness effect. The bond strength between the liner and the substrate is affected by the surface area of the interface (Zhang et al., 2022). When the liner thickness is very thin, the surface area of the interface is small, which limits the bond strength. As the liner thickness increases, the surface area of the interface increases, which leads to an increase in the bond strength. However, when the liner thickness becomes too thick, the bond strength starts to decrease again. This is because the thicker liner becomes more difficult to apply evenly, which can lead to voids and other defects in the bond (Chen et al., 2020). In this study, the optimum thickness was 24.2 mm.

3.3 Variation of shear-bond strength with substrate

In laboratory TSL shear-bond testing, rocks associated with higher UCS values are desired. Their surfaces are competent, and their structure is more resistant to any type of loading. Weaker rocks have the risk of rock failure before shear failure between the substrate and TSL. This is in addition to rocks with cracks or any other structural weakness. The selection of substrates utilized in the investigation represented the main rock types encountered in the mining industry; quartzite for gold mines, sandstone for platinum mines and concrete cubes representing concrete ring covers. This was to contribute to the knowledge of TSLs in mining applications as one of the aims of this investigation.

The variation of shear-bond strength with substrate type at the respective curing days was plotted against the aspect ratio in Figure 13. It was noted that Quartzite had the lowest shear-bond strength at all liner thicknesses and curing periods while sandstone had the highest values.

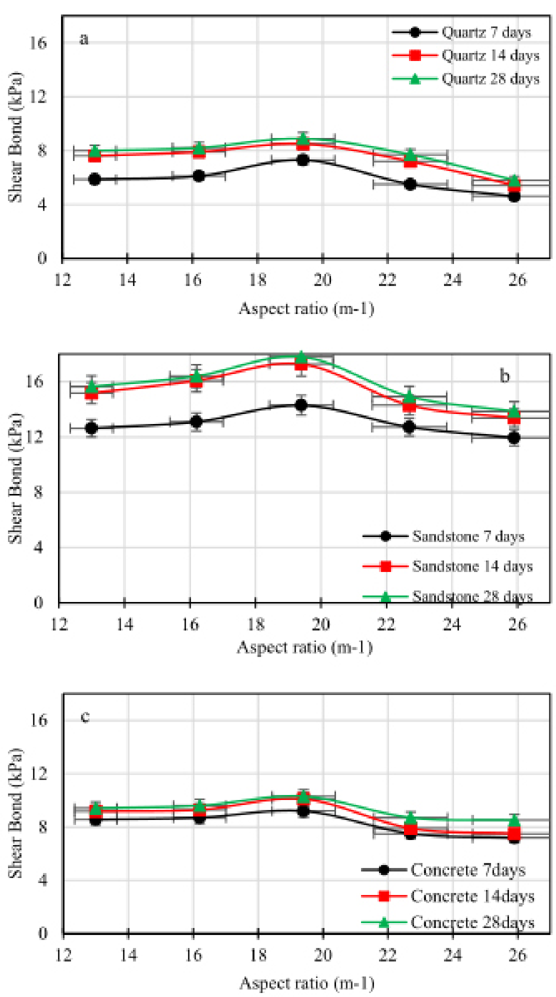

Figure 12. Variation of shear-bond strength with aspect ratio for (a) Quartz, (b) Sandstone and (c) Concrete.

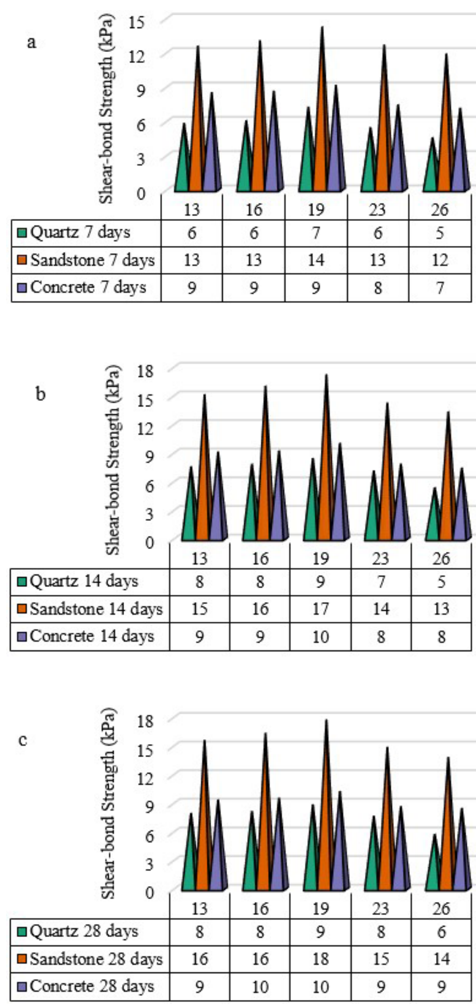

Figure 13. Variation of shear-bond strength with substrate type at (a) 7, (b) 14 and (c) 28 days of curing.

The shear-bond strength values of concrete substrate were close to those of quartzite substrate. At all liner thicknesses, the shear-bond strength of sandstone was more than 50% higher than that of quartz for all the curing periods. Concrete shear-bond strength values were higher than those of quartz by values ranging between 36.1% and 11.5% for all liner thickness and curing times.

Previous studies have shown that the shear-bond strength of TSLs is higher with concrete substrates than with rock substrates (Saydam et al., 2011; Chen et al., 2020). This is because concrete is more uniform and has a smoother surface than rock, which makes it easier to apply the liner evenly. Additionally, the surface roughness of the substrate can also affect the shear-bond strength. A rough surface provides more mechanical interlocking between the liner and the substrate, which can improve the bond strength. This is because the rough surface creates a larger surface area for the bond to form, and it also helps to prevent voids from forming between the liner and the substrate.

A study by Saydam et al. (2011) investigated the shear bond strength of TSLs with different types of rock substrates. The study found that the shear bond strength was higher for sandstone than for limestone. The study also found that the shear bond strength was higher for unweathered rock than for weathered rock. Chen et al. (2020) investigated the effects of substrate materials and liner thickness on the adhesive strength of a novel thin spray-on liner (TSL). The TSL was made from a water-based cementitious material and was applied to three different substrate materials: concrete, sandstone, and granite. The liner thickness varied from 2 to 32 mm. The results showed that the adhesive strength of the TSL was affected by both the substrate material and the liner thickness. The TSL had the strongest bond with concrete, followed by sandstone and then granite. Li et al. (2017) reported that the adhesion strength of TSLs increases with rock strength. This is because stronger rocks are more resistant to shear forces, which can help to prevent the TSL from delaminating from the rock surface. In the same study, the adhesion strength of TSLs also increased with surface roughness. This is because a rough surface provides more mechanical interlocking between the TSL and the rock surface, which can improve the bond strength. The optimum surface roughness for TSLs is typically in the range of 20-30 µm. This is because a surface that is too smooth will not provide enough mechanical interlocking, while a surface that is too rough can create voids and other defects that can weaken the bond.

3.4 Variation of shear-bond strength with curing time

Summary graphs of shear-bond strength against curing periods for each substrate and related aspect ratio are shown in Figure 14. The averages of the respective shear-bond strengths are indicated on the graphs as markers. The best fit curve was found to be logarithmic, and it was applied for

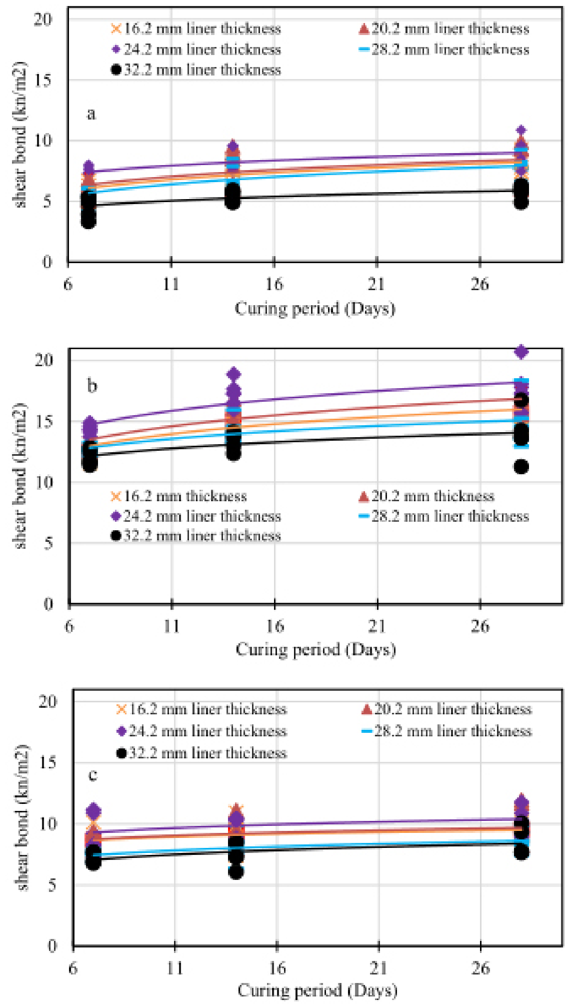

Figure 14. Variation of shear-bond strength with curing period for substrate of (a) quartz, (b) sandstone and (c) concrete.

all the data points on a graph. Additionally, equations and correlation coefficients (R^2) of the best-fit curves are shown. The logarithmic function was chosen because it gave higher coefficients.

Generally, the shear-bond strength increased with increase in curing period for all the substrates. The increase in shear-bond strength from up to 14 days was very steep. However, the increase from 14 days to 28 days was generally moderate. The chemical reaction between the polymer and the cementitious TSL is continuous and this leads to the eventual setting and hardening. The rate of reaction and hence the rate of hardening is faster in the first 14 days thus the steep increase in shear-bond strength. However, the reaction rate reduces after the 14 days, therefore the moderate increase in shear-bond strength.

The shear-bond strength equations and correlation coefficients (R^2) are listed in Table 6 for all the substrates and aspect ratios. The Strength equations and R^2 were obtained by setting the trend lines to best fit the relative test results in an excel spread sheet program. Generally, there was a good

Table 6. Shear-bond strength equation and correlation coefficients (R^2).

Parameters		Substrate					
		Quartzite		Sandstone		Concrete	
		Strength Equation (MPa)	R^2	Strength Equation (MPa)	R^2	Strength Equation (MPa)	R^2
Aspect ratio (m^{-1})	13.0	1.15Inx + 5.19	0.92	1.38Inx + 9.43	0.92	0.61Inx + 7.45	0.94
	16.2	0.85Inx + 3.02	0.96	2.17Inx + 8.76	0.86	0.65Inx + 7.48	0.97
	19.4	1.59Inx + 2.61	0.91	2.38Inx + 8.91	0.82	0.79Inx + 7.77	0.88
	22.7	1.51Inx + 3.42	0.86	2.52Inx + 9.79	0.86	0.87Inx + 5.75	0.96
	25.8	1.54Inx + 3.10	0.88	1.59Inx + 9.79	0.94	0.96Inx + 5.22	0.91

number of high R^2 values. Therefore, the test results could be relied on. Concrete substrate had the highest R^2 values while Sandstone had the lowest values. Concrete, being a material produced under a controlled system, was expected to have the highest values. Quartzite and sandstone are natural materials. They are therefore expected to vary a lot from specimen to specimen.

The shear-bond strength of thin spray-on liners (TSLs) typically increases with curing time. This is because the curing time allows the TSL material to harden and develop its full strength. The longer the curing time, the stronger the bond will be. The optimum curing time for TSLs will vary depending on the specific material and application. Li et al. (2017) investigated the effects of curing time on the shear-bond strength of TSLs. The TSL was made from a cementitious material and was cured for different periods of time. The curing times were 24 hours, 7 days, and 28 days. The results showed that the shear-bond strength of the TSL increased with curing time. The TSL had the strongest bond after 28 days of curing. Chen et al. (2020) investigated the effects of curing time on the shear-bond strength of TSLs. The TSL was made from a water-based cementitious material and was cured for different periods of time. The curing times were 7 days, 14 days, and 21 days. The results showed that the shear-bond strength of the TSL increased with curing time. The TSL had the strongest bond after 21 days of curing. The adhesive strength increased with curing time up to 28 days, after which it plateaued. This suggests that a curing time of 28 days is sufficient to achieve the maximum adhesive strength of the TSL.

3.4.1 Effect of surface cleanliness on shear-bond

Various environmental factors have negative effects on the shear-bond strength of TSLs (Yilmaz, 2011; du Plessis, 2021; Ozturk & Tannant, 2011; Qiao et al., 2015). Among these factors is the contamination of rock surfaces. Rock surfaces may be unclean due to airborne mineral dust particles and salts and minerals present in moisture or free water. The most damaging chemical conditions are those with high contents of sulphides and salts (Ozturk & Tannant, 2011). Bonding and composition of TSLs is affected by the interaction of such materials with TSL. The main surface contaminants are oil (grease) and dust. In this study, only the effect of oil contamination on rock surfaces was investigated.

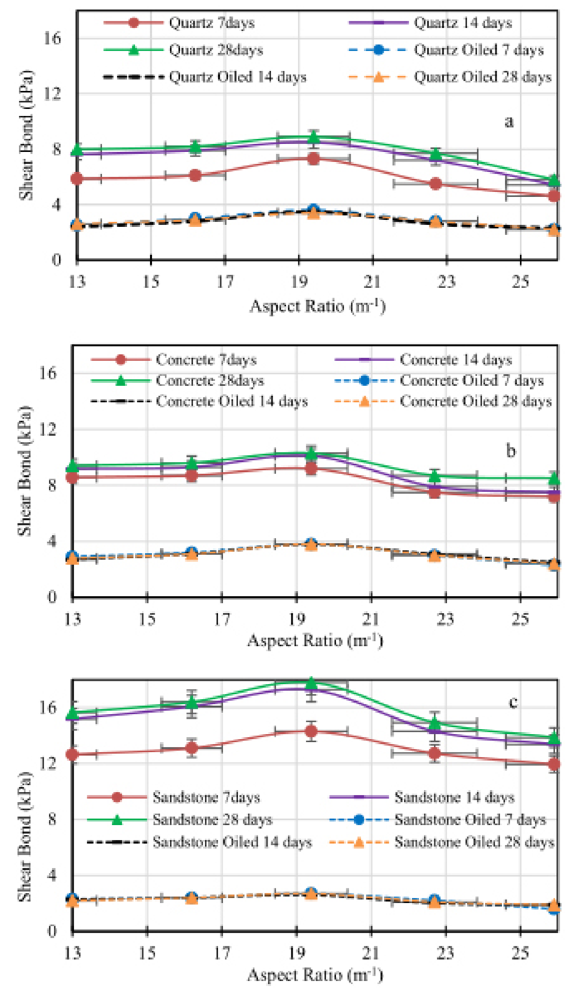

Figure 15. Shear-bond for substrates of: (a) Quartz and oiled Quartz, (b) Concrete and oiled Concrete and Sandstone and oiled Sandstone.

Figure 15 shows the effect of oiling the substrates on the shear-bond strength values. Each data point on the graph represents the average of respective five shear-bond strengths. Generally, oiling the substrates greatly reduced the achieved shear-bond. The greatest reduction was observed with the oiled sandstone substrates. This was attributed to the fact that oil filled the pores which would have been filled by the TSL and act as a grip against shear failure. The contribution of grip effect to shear-bond resistance was more with sandstone substrates with higher porosity. No significant variation of shear-bond strength values with curing period was observed for all the oiled substrates. At 28 days of curing and liner thickness of 24.2 mm, the shear-bond values reduced by 61.8%, 63.1% and 84.8% for Quartz, Concrete and Sandstone substrates.

A clean and dry surface provides a better mechanical bond between the TSL and the substrate. This is because the TSL can interlock with the surface features of the substrate, which can help to prevent the TSL from delaminating from the substrate. du Plessis (2021) showed that the surface cleanliness of the rock face has a significant impact on the bond strength between the TSL and the rock. TSLs applied to clean rock faces had significantly higher bond strengths than those applied to dirty rock faces. This is because the dirt and debris on the rock face can interfere with the adhesion of the TSL. Qiao et al. (2015) investigated the effect of surface cleanliness on the shear bond strength of TSLs. The results showed that the shear bond strength was significantly higher for specimens with clean surfaces than for specimens with dirty surfaces. This is because a clean surface provides a better mechanical interlock between the TSL and the rock substrate.

4. Conclusion

TSLs are increasingly being used for structural support of rock excavations as surface support materials though, to-date, no acceptable standard tests or testing regimes have been defined. There is a need to develop tests and testing regimes, and reliable sets of data. A total of 2,250 tests were conducted to investigate the variation of TSL shear-bond strength with liner thickness, substrate type and surface cleanliness, and curing period. The liner was a polymer based cementitious TSL and substrates were quartzite and sandstone rocks, and concrete.

The material types in this study included quartz and sandstone rocks and 30 MPa concrete. Liner thicknesses included 16.2 mm, 20.2 mm, 24.2 mm, 28.2 mm, and 32.2 mm while curing periods were 7 days, 14 days, and 28 days. It was observed that the TSL shear-bond strength varied with different materials. Quartz with the lowest porosity had the lowermost shear-bond strength at all liner thicknesses and curing periods.

The shear-bond strength improved with liner thickness up to 24.2 mm and then decreased up to 32.2 mm. Therefore, a liner thickness of 24.2 mm is recommended for applications in underground excavations although smaller thicknesses may be utilized for smaller loads.

It also increased with curing period. The increase in shear-bond strength up to 14 days was very rapid while from 14 days to 28 days it was generally moderate. The rate of reaction and hence the rate of hardening is faster in the first 14 days thus the steep increase in shear-bond strength. The reaction rate reduces after the 14 days, which explains the moderate increase in shear-bond strength.

Oil reduced the shear-bond strength for all the material types at all liner thicknesses and curing periods. The contribution of grip effect to shear-bond resistance was more with sandstone substrates with higher porosity. No significant variation of shear-bond strength values with curing period was observed for all the oiled substrates. Oil is one of the main surface contaminants in underground excavations of the mining industry through leaks from machines utilized in the excavations.

Further research is warranted to investigate the shear-bond strength of various TSL products, such as water-based and polyurethane TSLs, with different substrates and liner thicknesses. Additionally, it is essential to develop or modify testing methods for weaker rocks, such as shale, that cannot be tested with existing methods. These efforts should be complemented by field trials to validate the results of laboratory testing.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Samuel Jjuuko: conceptualization, investigation, methodology, project administration, resources, software, data curation, visualization, writing - original draft preparation. Denis Kalumba: conceptualization, supervision, validation, writing - reviewing and editing, funding acquisition.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

t	Depth or steel ring height
CV	Coefficient of variation
D	Core diameter

F Maximum applied force
SD Standard deviation
TSL Thin Spray-on Liner
UCS Unconfined compressive strength

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