CHAPTER 1

Introduction

1.1 Background

When excavations are made in rock masses, risks of instability occurring which might be hazardous or have negative consequences are possible. The instability of rock masses surrounding an underground opening can result from:

- failure of rock material or mass around the opening as a result of high stress to strength conditions (failures are induced from overstressing);
- movement and collapse of rock blocks as a result of the geological structure (structural instability). This is when the pre-existing blocks in the hangingwall and the sidewall are free to move because the excavation is made;
- a combination of the above (stress induced rock failure and structural instability);
- failure of “beams” as a special case of the above. This could be either footwall or hangingwall, or both, depending on the dip.

Rock surface supports in the underground excavations are mainly used to assist the rock mass to support itself by controlling and managing deformations that can result from failure, hence ensuring safety where there is human access. These supports are used in various ground conditions. “The conditions range from good rock masses, where surface support is required to control small scats that occur as a result of long term exposure, to highly stressed environments where the layer must attempt to improve the inherent rock mass strength by providing confinement at the boundary of the excavation”(Morton et al,2008).

Underground excavations are commonly dependent on shotcrete, wire mesh, shotcrete and wire mesh in combination, and shotcrete reinforced with various types of fibres, to mitigate falls of ground (Stacey, 2001b). Shotcrete has been around for almost a century and has been in use since the 1950’s in underground excavations (Spearing *et al*, 2001). Other support liners such as mesh were used before shotcrete was introduced, while thin spray-on liners (TSL) have been introduced in recent decades (Lacerda, 2004).

Sprayed liner support is not limited to mining, but is also used in civil engineering. In mining, service excavations must be stable for their required life span (short term) and in civil engineering, stability must be in proportion with the projected life span of an excavation (long term). Rock supports that are used in mining or civil engineering can either be active or passive according to their behaviour in relation to the rock mass. According to Brady and Brown (1993), active support exerts a predetermined load to the rock surface once installed, and passive support is a support that develops its load while the rock mass around the excavation dilates or deforms. Sprayed liner supports are referred to as containment support and fall into the category of passive support (Henderson and Louw, 2001). These are rock surface supports, functioning only when the surrounding rock dilates, causing the support to deform and hence induce a reaction force in the support.

A sprayed liner alone may not be adequate for surface support, hence they need to be applied in combination with other forms of support e.g., rock bolts. These systems depend on the ground conditions and preferred designs.

Shotcrete and thin spray-on liners as surface support systems have the potential to reduce the level of accidents, and to increase productivity. They can be applied on the face of the rock surface to maintain the integrity of the rock mass by keeping small key blocks in place, and to reduce the potential for gravity induced fallouts of small pieces of rock. The combination of thin spray-on liners coated on top of the shotcrete has not been referred in the literature, hence this system requires investigation.

Most thin spray-on liner products are polymer-based products, applied to the surface of the rock mass to provide surface support to excavations. Thin spray-on liners can be classified as either reactive or non-reactive, and this depends on their chemical formation or curing mechanisms (Spearing and Hague, 2003). The reactive system relies on cross linking of polymers (e.g methyl mechacrylate, epoxy, etc) while the non-reactive liner systems are cement or water polymer systems which are accompanied by the loss of water, and strength gain in hours. The non-reactive liner systems have longer curing times than the reactive liners systems. Spearing and Hague (2003) have shown that the thin spray-on liner thickness can be as low as 3 to 4mm.

Shotcrete is a mixture of cement, aggregate and water which is pumped pneumatically through a nozzle onto the wall of an excavation to form a bonded coherent layer (Jager and Ryder, 1999). The mixture may contain admixtures, additives and fibres, or a combination of these, to improve the tensile, flexural and shear strength resistance of the shotcrete. It is classified as unreinforced shotcrete when no fibres are incorporated in the mixture, and as fibre reinforced shotcrete when fibres (e.g steel or polypropylene) are incorporated. “The addition of fibres to the shotcrete mixture adds ductility to the material as well as energy absorption capacity and the impact resistance" (Gedeon, 1993). Shotcrete can be applied by two distinct application techniques, the dry-mix process and the wet-mix process.

1.2 Problem Statement

Sprayed liner supports have been used extensively in both civil engineering construction and the mining industry for decades. The purpose of these sprayed liners is to support the rock mass between rock bolts and assist in ensuring the effective operation of the bolts. Different thin spray-on liners have been developed in the market and it is important to understand the way in which these liners support the excavations, and the mechanisms in which they fail. Knowledge and understanding from the literature on how thin spray-on liners offer support, and their failure mechanisms, is very limited. Laboratory and field tests have been developed to aid in better understanding of the properties of the liners, as well as the way in which liners interact with the rock mass.

There have been verbal reports that the application of a thin spray-on liner on top of shotcrete has improved the performance of the shotcrete. This is probably because the liner enhances the tensile strength, and inhibits the tensile cracking of the shotcrete. However, the benefit has not been quantified, hence the research contained in this proposal, which investigates the extent to which different spray-on liners, applied on both reinforced and unreinforced shotcrete, enhance the tensile strength of the shotcrete.

1.3 Objectives

The overall objective of this research is to investigate the extent to which various spray-on liners, coated on shotcrete, will enhance the tensile strength on the reinforced and unreinforced shotcrete. The primary objective is to compare the physical properties and the mechanisms of behaviour of these sprayed liners on shotcrete under laboratory conditions. Brazilian indirect tensile strength tests will be performed on shotcrete specimens, both uncoated and hand coated with various thin spray-on liners for this research. The curing period of the TSL is the main test parameter to be checked for sensitivity.

1.4 Research Methodology

A literature review of the current knowledge of the mechanisms by which the shotcrete and thin spray-on liners provide surface support has been carried out. Available library facilities and related topics from past research papers were used for this research. This research will build an understanding of the effects of different thin spray-on liners coated on shotcrete. Laboratory tests involve drilling of test specimens from panels of both fibre reinforced and unreinforced shotcrete, and three different types of liners available in the market have been considered. The Brazilian tests are performed at times of 2hours, 24hours, 7days and 28days after the application of the thin spray-on liner onto the specimen.

According to Naismith and Steward (2002) the requirements below should be satisfied for a well-designed thin spray-on liner testing procedures: the test should be

- Simple (easily prepared sample)
- Cost effective
- Repeatable
- Practical
- Representative of relevant behaviour
- Related to in-situ performance; and
- Statistically valid data should be generated.

The Brazilian indirect tensile strength test is used for this research. The curing period of the shotcrete specimen will be the main parameter tested and checked for sensitivity. To meet the objectives of this research the following are performed and consulted:

- Understanding of the test machine used and the development of its test procedures.
- Identification of problems in the preparation of shotcrete specimens and mixing of different thin spray-on liners.
- Re-trial and modification of the test specimen until confidence is gained on the test results.
- Set up and the execution of tests.
- Initial test trials on the shotcrete specimens.
- Testing as many shotcrete specimens as possible to increase the confidence level in the laboratory tests results.

1.5 Facilities required

Use has been made of the following functional resources with regard to the research required:

- Genmin Laboratory facilities, including the workshop, testing machines and technician assistance.
- Spray-on liner materials provided by liner suppliers
- One panel each of unreinforced and reinforced shotcrete from suppliers
- Relevant research papers from various available sources
- Consultations with the suppliers of the liners

CHAPTER 2

REVIEW OF RELEVANT LITERATURE ON SHOTCRETE AND THIN SPRAY-ON LINERS

2.1 Introduction

The previous chapter has commented on the background of the thin spray-on liner and the shotcrete. It included the problem statement, objectives of the research and the research methodology as well as the facilities required. Based on a review of relevant literature on the subject, this chapter gives an overview of sprayed liners, functions, failure mechanisms, load transfer mechanisms, and their physical properties. Both the advantages and disadvantages of using sprayed liners and a summary of various TSL applications are presented in the form of tables. The review focuses on shotcrete and TSL as rock surface support.

2.2 Overview of the Shotcrete

Shotcreting is a process in which concrete is projected or "shot" under pressure, using a feeder or a "gun", onto a surface to form structural shapes including walls, floors, and roofs (Ghiasi and Omar, 2011). It is simply a generic name for cement, sand, and fine aggregate concretes which are applied pneumatically and compacted dynamically under high velocity. The primary role of the shotcrete is to prevent the dilation of the loose rock blocks and eventually fallouts, which, if not prevented, could lead to propagation of failure. Shotcrete can be applied in two distinct application techniques, the dry-mix or the wet-mix processes. Dry mix is a process whereby dry cement and aggregate together with any prescribed additives, are batched and thoroughly mixed. The mixture is then fed into a special machine containing a pneumatically operated gun which delivers a continuous flow of material through the delivery hose to the nozzle, where water is introduced as a spray to wet the mixture, which is then projected continuously into place. Wet mix is a process whereby cement, aggregate and water, together with any prescribed additives are batched and thoroughly mixed as well. The mixed material is fed into the delivery equipment such as concrete pump and conveyed through a pipeline to a nozzle, where the mixture is pneumatically and continuously sprayed into place. The mixture contains ordinary Portland cement (OPC), aggregate (sand and stone), additives (retarder, accelerators, dust suppressant, plasticisers) and fibre (steel or polypropylene). The main difference between the two systems is the stage at which water is applied to the shotcrete ingredients: at the nozzle for the dry-mix, and during mixing for the wet-mix (Hoek et al, 2000). The difference in equipment cost, operational features, maintenance requirements, placement characteristics, and the product quality makes one or the other more attractive for a particular application.

2.2.1 Comparison of the dry mix and wet mix processes

Both pros and cons of using shotcrete are recognized and mentioned extensively in the literature. A comparative summary of the advantages and disadvantages of the two processes are given in Table1 below (Gedeon, 1993):

Table 1 : Comparison of features of dry-mix and wet mix shotcrete processes

Dry mix process	**Wet mix process**
1. Mixing water instantaneously controlled at the nozzle by operator to meet variable field condition.	1. Mixing water controlled at the plant and measured at time of batching.
2. Longer hose lengths possible, if necessary	2. Normal pumping distances necessary
3.Limited to accelerators as the only practical admixture	3. Compatible with all ordinary admixtures. Special dispensers for addition of accelerators are necessary.
4. Intermittent use easily accommodated within prescribed time limits.	4. Best suitable for continuous application of the shotcrete
5.Exceptional strength performance possible	5.Lower strengths, similar to conventional concrete
6. Lower production rate (e.g Mining)	6.Higher production rates (e.g Civil Engineering)
7. Higher rebound	7.Lower Rebound
8.Equipment maintenance costs tend to be lower	8.Equipment maintenance costs tend to be higher
9. Higher bond strength	9.Lower bond strengths, yet often higher than conventional concrete
10.More dust produced	10. Less dust produced

The final product of either the dry or wet mix shotcrete process is very similar. The decision on which shotcrete process to use is usually made on a site by site basis.

2.2.2 Fibre reinforced and unreinforced shotcrete

Unreinforced shotcrete refers to a plain shotcrete when no fibres are incorporated in the mixture. It is a brittle material that can experience cracking and displacement when subjected to tensile stresses or strains (Gedeon, 1993). When fibres are incorporated in the mixture, the shotcrete is reinforced. Fibres that are used in the shotcrete are available in different forms, e.g steel, glass and synthetic fibres. The addition of fibres to the shotcrete mixture adds a ductile component to the shotcrete as well as energy absorption capacity and impact resistance (Gedeon, 1993). The fibre material in the mixture is capable of sustaining post-crack loading and displays an increase in the ultimate strength, particularly the tensile strength. Therefore its performance will differ from the unreinforced shotcrete when applied to the rock mass (Gedeon, 1993).

According to Golser (1976), Potvin and Hadjigeorgiou (2008) and Stacey et al (2009), shotcrete also carries out the following stabilising functions:

- Shotcrete prevents initial movement along joint planes from developing, thereby stabilising the tunnel surface. The shotcrete also rounds off the sharp corners of a tunnel thereby eliminating stress concentrations which could result in failure;

- Shotcrete acts as a strengthening outer layer to the rock. Due to adhesion the rock and shotcrete acts as a unit with enhanced strength;

- The shotcrete prevents the rock from weathering, thereby preventing rock strength reduction (insulation from moisture, air and running water).

- The shotcrete prevents the additional loosening of the rock mass; and

- The shotcrete can penetrate into joints and cracks to produce a wedging effect like mortar in a wall or arch.

2.2.3 Shotcrete Failure Modes

In recent years, substantial studies have been undertaken by mining and civil engineering industries. Areas of research included:

- Chemical additives and admixtures
- Adhesive strength between shotcrete and rock surface
- The failure mechanisms of shotcrete.

Stacey (2001b) explained some of the sprayed liner failure mechanisms. In his findings he suggested that shotcrete and membranes provide support to the rock mass through the promotion of block inter-lock, the reduction of rock mass degradation by sealing dilated joints and the creation of an arching effect which transfer loads to bolts installed through the layer into the rock mass. The case studies by Holmgren (1987, 1998) and Fernandez-Delgado et al (1981) have shown that the primary modes of shotcrete failure are adhesive loss and flexural. Further studies conducted by Barrett and McCreath (1995) identified that shotcrete capacity in blocky ground, under static conditions, is governed by six failure mechanisms which are adhesive failure, direct shear failure, flexural failure, punching shear failure, compressive and tensile failure (figure 1). Other failure modes include compressive failure, direct tensile failure and buckling. The shotcrete failure modes were explored by using falling block test to simulate the load applied on shotcrete (Fernandez-Delgado et al (1981), Holmgren (1987) and Vandewalle (1992)). The analyses of their tests indicated that for the steel fibre-reinforced and mesh reinforced linings, direct shear failure tends to occur when adhesion to the rock mass is good, whereas flexural and punching shear failure occurs when adhesion is poor and de-bonding has occurred.

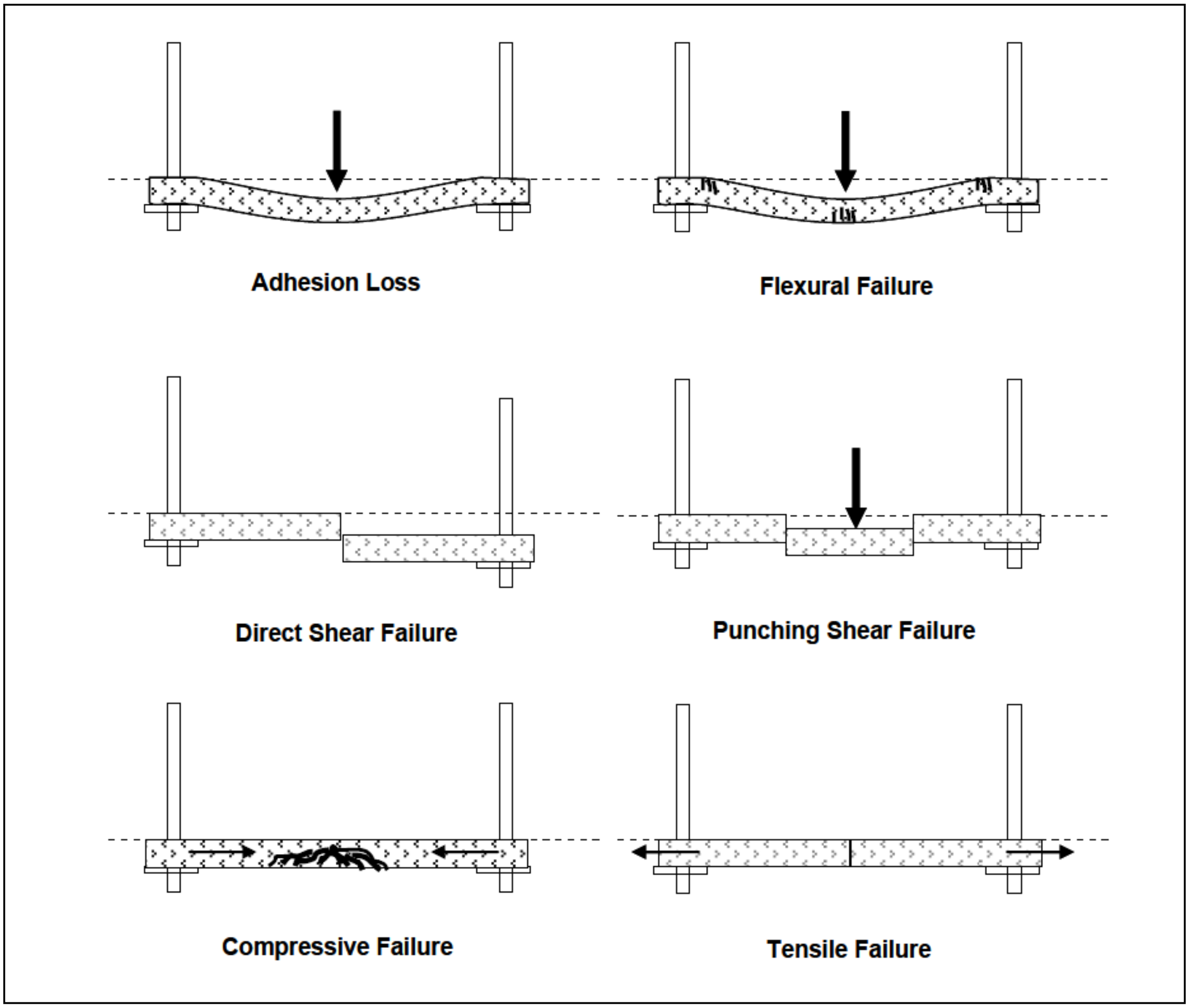

Figure 1: Updated Shotcrete failure mechanisms (modified from Barrett and McCreath 1995)

To understand the above failure mechanisms in depth more detailed research is required to understand the complexity of shotcrete interactions with the rock mass. The following are brief notes on failure mechanisms of the shotcrete.

Adhesive loss

Failure occurs due to adhesion loss between the shotcrete and the rock surface (e.g when shotcrete peels off from the rock). Malmgren and svensson (1999) and Kuchta (2002) pointed out that adhesive failure will occur when the shotcrete-rock bond strength is weak relative to the dead weight of the shotcrete, resulting in the shotcrete falling (figure 1). The fallout only indicates the poor adhesion due to the tension perpendicular to the surface.

Flexural Failure

Failure occurs once adhesion between the rock and the shotcrete has been lost. This is where the shotcrete bends so much, such that a tensile crack opens up at the mid span and the crack grows through the shotcrete. However this is not adequate for the failure to occur, but also initiation of cracks at the surface between the rock and the shotcrete must develop (Uotinen, 2011). Together these cracks form a mechanism resulting in the structural failure.

Shear Failure

Shear failure can occur in two forms through direct shear and/or shear punch failures (Barrett and McCreath, 1995). They indicated that direct shear failure occurs when load applied on the shotcrete exceed its shear strength as illustrated in figure 1. If loading is by a rigid block, then direct shear failure is possible. For a large rigid load or loose rock, the rock bolts may punch through the layer of the shotcrete. All forms of shear failure involve initial development of tensile fracture.

Compressive and Tensile failure

According to Uotinen (2011) compressive and tensile failure are observed after excavation in the vicinity of the reinforced space. For example, failures can be observed by shotcreting too close to the end of the tunnel, which can lead to compressive failure unless the elastic modulus of shotcrete is suitably low.

Summary

All of the above shotcrete failure mechanisms involve tensile failure to varying degrees. This confirms the importance of the current research into the enhancement of shotcrete tensile strength using a TSL coating.

2.3 An Overview of Thin Spray-on Liners

2.3.1 Uses of the TSL

The sprayed liners that are used in the mining industries are shotcrete and thin spray-on liners. Research on the development of TSLs have been conducted within the mining industry to promote enhanced underground excavation support capabilities and worker safety in current and future deep level mining industry (Archibald and Dirige, 2006). The idea of TSLs was originated by the thought that a liner as thin as 5 mm should perform as well as, or even better than shotcrete (Yilmaz, 2010). Thin Spray-on Liners were used in civil engineering as sealants before being tried or tested in the mining industry (Kuijpers *et al*, 2004). TSLs were mainly designed to limit the weathering of the rock mass (Spearing *et al*, 2009) and later intended as an alternative method to mesh or shotcrete on the surface of the rock mass. TSLs were also used for:

- Reducing seismic damage (Spearing *et al*, 2009)
- Rehabilitation of collapsed areas (Spearing *et al*, 2009)
- Preventing weathering, spalling, and damage in the rock mass as a result of blasting (Spearing *et al*, 2009, Pappas *et al*, 2003)
- Reducing the permeability of shotcrete linings (Hawker, 2001)
- Shotcrete repair (Lacerda and Rispin, 2002)
- Protecting steel support elements from corrosion (Espley *et al*, 2001).

According to Tannant (2001) thin spray-on liners are a form of rock support that is receiving increasing attention by various mines around the world. The thin liner prevents dilation, loosening and unraveling in jointed or fractured rock masses. It forces the rock mass fragments to interact with each other, hence creating a stable beam or arch of rock. Some of TSL features may include that it:

- Is a tough resilient material that adheres strongly to rock surface (Kuijper and Toper, 2002).
- Seals rock against acid water ingress (Spearing *et al*, 2009).
- Prevents oxidation, especially inside fissures (Potvin 2002, Borejszo & Bartlett 2002).
- Prevents washout of fine material from joints and fissures. (Tarr *et al,* 2006; Kuijpers *et al*, 2004; Finn, 2004; Pappas *et al*, 2004)

2.3.2 Review of previous TSL testing

Tests involving TSL material performance have been conducted in the past by various authors. Potvin (2002) conducted TSL tests with the aim of improving understanding of the liner's properties and how it interacts with the rock. He classified the tests under either chemical or mechanical categories. Reviews of some of the tests are presented below in Table 2:

Table 2: Review of some test method reviewed by Potvin *et al* (2004).

Test Description	**References**
Adhesive (bond) strength testing	6,15
Asymmetric core punching of TSL by radiused plunger testing	13
Baggage load testing	10
Coated panel testing	6,9,12
Coated-core compression testing	3,4,6,9
Core to core adhesive (bond) strength testing	7
Double-sided shear strength testing	16
Gap shear load testing	17
Large scale plate pull testing	1,3
Linear block support testing	17
Material plate pull testing	2,5,8
Perforated plate pull testing	2,5
Punch (TSL displacement) testing	7,9
Tensile strength and elongation testing	2,5,6,11
Torque testing method	14
References	
1.Tannant 1997 2. Tannant et al, 1999 3. Espley , 1999 4. Archibald and DeGagne, 2000	
5. Archibald, 2001 6. Lewis 2001 7. Spearing, 2001 8. Finn, 2001	
9. Kuijpers, 2001 10. Swan and Henderson 2001 11. Spearing and Gelson, 2002	
12. Naismith and Steward, 2002 13. Stacey and Kasangula 2003 14. Yilmaz et al, 2003	
15. Tannant and Ozturk, 2003 16. Saydam et al 2003 17. EFNARC, 2008	

The findings on the coated - core compression testing have shown that the application of TSL on the rock specimen changes the post failure behaviour from violent and brittle to smooth and ductile (Espley, 1999; Archibald and DeGagne, 2000; and Kuijpers, 2001). TSL application allows a certain amount of post failure resistance. Different mining companies have done some trials on applications of TSLs which include trials on support, at the gullies, problems associated with key blocks, and many more.

2.3.3 Advantages of the application of TSL's as a support element

TSLs were developed to provide replacement to the currently used containment support. The use of thin spray-on lining material offers advantages of fast application, rapid curing, and high strength including high areal coverage. Below are some of the advantages offered by the application of TSLs as a support element:

- It is easily applied in the areas where the mining rate is fast (Hepworth and Lobato, 2002).
- It has a high rate of spray application and increases the rate of production and development (Archibald, 2001).
- It gives the mine additional time to install other support (Borejszo and Bartlett 2002).
- Strength improvement and enhancement of post-yield failure characteristics of rocks (Archibald, 2001).
- Its application time is shorter and it cures faster compared to shotcrete, and wire meshing and lacing (Rispin and Garshol 2003, Tannant 2001).
- A TSL is capable of achieving significant area support resistance (Archibald, 2001).
- Rapid spray placement and almost immediate mobilization of high tensile strength may prevent gradual loss of rock strength (Archibald, 2001).
- TSL equipment is smaller and therefore maintenance is much simpler than shotcrete equipment (Swan *et al, 2003*).
- The residual strength and load bearing capacity of the rock mass are improved (Laurence, 2001).
- No interference with the bolting patterns. The required number of bolts is reduced by allowing bolt spacing optimization (Finn 2001, Lacerda and Rispin, 2002).
- Initial ground support can be achieved quickly, and in the early stages before it moves too far down the ground reaction curve (Archibald 2001, Borejszo and Bartlett 2002, Lacerda and Rispin 2002).
- TSL application can be kept concurrent with the advancing face (Spearing and Champa, 2000).
- It is less labour intensive in transport and installation compared to conventional mesh and bolts (Tannant, 2001).
- TSL has simpler material handling and less robust equipment required (Rispin and Garshol 2003, Espley, 2001).
- Increased support cycle efficiencies (Archibald, 2001).
- User friendly alternative to the traditional rock containment support (Henderson and Louw, 2001).

- Good bond strength, tensile strength and elongation (yieldability) and TSLs have been demonstrated to remain physically unaffected over large strain ranges (Archibald, 2001 and Espley *et al* 2001).
- Limits the disintegration of ore and could benefit the mines by overlapping two activities in the mining cycle, namely supporting and drilling (Lacerda and Rispin, 2002).

2.3.4 Disadvantages of the application of TSLs

Many benefits that are provided by the use of TSLs have been explored, but disadvantages have also been reported by different authors, and these are summarized below:

- Mixing processes can be complex, requiring specialized crews to operate the equipment. A skilled nozzle man and care are required (Hepworth and Lobato, 2002; Lewis, 2001; Nagel and Joughin, 2002).
- The operators must pay keen attention to detail with regard to cleaning the spraying equipment at the end of a job (Espley *et al* 2001, Spearing *et al* ,2001)
- Consistent TSL thickness application is required (Lacerda and Rispin, 2002; Hepworth and Lobato, 2002).
- There is a need for solvents (Espley *et al,* 2001; Spearing *et al*, 2001).
- Proper curing of the TSL depends on the application thickness (Pappas *et al*, 2003).
- Difficult to adequately prepare the rock surface before application (Potvin, 2002; Hepworth and Lobato, 2002).
- Some of the equipment is heavy limiting its application in stopes (Nagel and Joughin, 2002).
- Availability of compressed air and water is a requirement for spraying (Henderson and Louw, 2001).
- Direct exposure to some TSL component materials can lead to allergic sensitization and the dust exposure may at times becomes a concern for some water based TSL’s (Archibald, 2001).
- It is very critical to “get the mix right”, because poor mixing will affect the curing properties of the TSL (Laurence, 2001).
- If the coating is too thin then it has little apparent strength (Hepworth and Lobato, 2002).

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2.4 Properties of TSLs

Numerous TSL materials of different chemical and physical properties have been developed to create environmentally safe materials, which are suitable for a wide variety of underground usage. Understanding both the physical and chemical properties of the TSL product assists in understanding the pros and cons of the support product. In the different ranges of the developed and tested TSLs, it was found that many did not possess adequate physical or chemical properties (Yilmaz, 2011).

2.4.1 Physical properties of the TSL

Espley-Boudreau (1999) indicated some guidelines that could be used for ideal properties of TSLs, in table 3 below:

Table 3: Ideal properties of a TSL (Espley-Boudreau, 1999)

Characteristics	Recommended Range
Non-Combustible	Flame spread rating <200
High Tensile Strength	> 5MPa
High adhesive Strength	> 1MPa on rock subtrate
High shear strenghth	> 1 MPa
Hardness	Hardness 80
Elasticity	100% to 150% elongation
Rapid curing time	< 1 Hour
Water Resistant	Able to be sprayed onto Humid/ Wet surface
Temperature Tolerant	0 to 40 degrees
Rapid application rate	1 metre sqr/minute
Long Pot life	> 2 hours
Environmentally friendly	Only mild solvents
Low Cost	< R92/metre sqr
Simple Application	Minimal Surface Preparation

The physical properties of the TSL depend on the environmental conditions in which it will be sprayed, i.e temperature, humidity and the substrate surface conditions.

2.4.2 Chemical properties of the TSL

Some TSLs contain diphenylmethane di-isocyanate (MDI) which is a reactive chemical that can be supplied as a liquid or solid. MDI can create hazards if handled carelessly. The primary hazard with the MDI is the inhalation of its powder and amount of time it has contact with the skin. The research showed that up to 20% of the workforces exposed can be sensitive and may develop life threatening asthmatic symptoms following repeated exposure either by inhalation or skin contact (Pappas *et al* 2004, Finn 2004 and Archibald 2004).

2.5 Functions of Sprayed liners as rock support

A combination of several different rock reinforcing units and support elements types, acting together, comprises a support system, in which the combination of the units as individuals may be added to form the overall support system characteristics. A support system may be made up of reinforcing elements such as rock bolts and cable bolts that act directly within the rock mass to increase its inherent strength, and support elements, fabric support or coatings such as shotcrete and TSLs, which act to contain the inherently unstable rock mass between the reinforcing units. Failure of the rock mass will result in the sprayed liner failing.

2.6 Summary

This chapter includes a comprehensive discussion on how liners as surface support provide the rock mass with areal coverage as it is applied between the bolts. Both the shotcrete and Thin Spray-on Liners are used as surface support in jointed rock mass to maintain stability and ensure safety in the underground excavation. The following aspects were also covered:

- Overview of shotcrete.
- Overview of TSLs.
- Sprayed Liners as Rock support.
- Properties of both the TSL and the shotcrete.
- Failure modes of the liner products.
- Review on previous TSL testing.
- Advantages and disadvantages of TSLs.

The main benefits of TSLs include the provision of immediate support, prevention of weathering, and high application efficiency.

CHAPTER 3

Specimen Preparation and Testing

The previous chapter dealt with a review of relevant literature on shotcrete and TSLs. This chapter will indicate the objectives of laboratory testing and the test program followed. Equipment used is discussed and the results are presented graphically and in table form.

Since it is difficult to compare test results obtained under different conditions directly, conditions at the different stages of the testing methodology were maintained at the same levels for comparison purposes. This ranges from the shotcrete panels sprayed, to the specimen test execution for comparable results.

3.1. Preparation and mixing of the shotcrete

3.1.1 Shotcrete Mixing Methodology

The shotcrete underground mixing machine was used by the supplier according to their specification. The machine was connected to the compressor, motor to mix and the nozzle that contained the compressed air. Ten bags of 30kg aggregate mix with strength of 40MPa were used for the unreinforced mixture. The reinforced mixture was the same but with polypropylene fibre. The mixing paddles stirred until a homogeneous product was produced. Both the reinforced and unreinforced wet-mix shotcrete were prepared separately. They included ordinary Portland cement (OPC), aggregate (sand and stone), additives (plasticisers) and polypropylene fibre. The wet-mix shotcrete involved pumping of the previously prepared mixture to the nozzle. Compressed air is introduced at the spray nozzle to impel the mixture onto the surface to be sprayed. Figure 2 below displays how the mixing system works and the components involved.

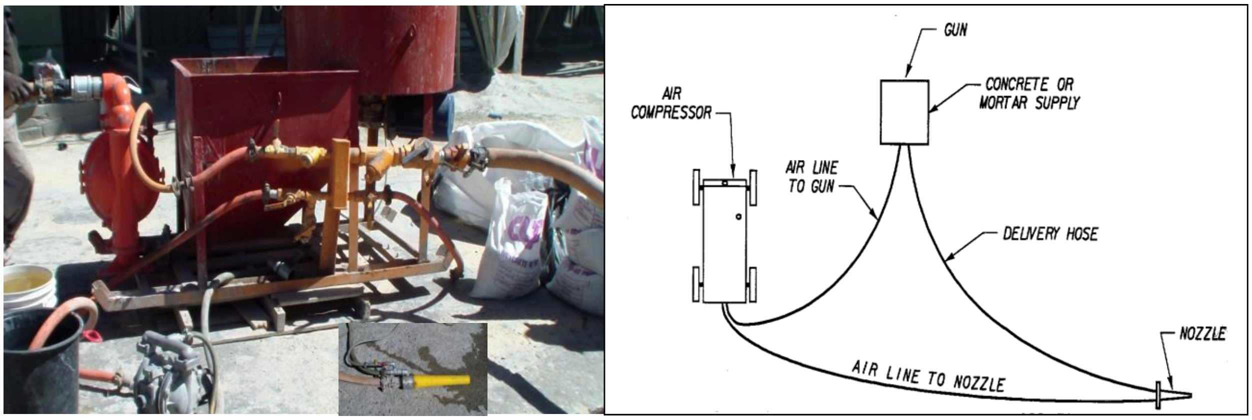


Figure 2: Typical plant layout for wet-mix pneumatic-feed equipment (Gedeon, 1993).

3.1.2 Addition of fibre into the shotcrete mixture

The fibre used in the mixture is from the natural polypropylene homo polymer formed into a flat profile with a profiled surface in order to anchor into a cementitious matrix. The dimensions of the fibre are shown in Table 4 and the physical appearance in Figure 3.

Table 4. Polypropylene fibre specifications

Fibre	Length (mm)	Width (mm)	Thickness (mm)	Elongation at yield (%)	σ_t (MPa)	E (MPa)
FIB SP650	50	1.8	0.13	24.4	275	1580

Polypropylene fibres were used in this project to enhance physical and mechanical properties of the shotcrete by bridging the micro cracks in the shotcrete.

Figure 3. Polypropylene fibre used in the mix

3.1.3 Duration of mixing

The duration of mixing the wet-mix shotcrete depends on the speed of the machinery used and the aggregate material. The aggregate material should be thoroughly mixed to avoid the occurrence of unmixed lobes. Shotcrete specimens containing unmixed lobes will usually fail at these locations before the true failure load of the shotcrete material is reached. For this study mixing with a medium speed machine the mix took ± 5 minutes on average (figure 2).

3.1.4 Application of the mix to the panel tray

The quality of the shotcrete depends largely on the skill and ability of the nozzle man, the surface preparation, thickness and material delivery rate (Moser and Girmscheid, 1999). The optimal distance between the nozzle man and the sprayed surface is generally about 1 metre. At a distance greater than 1m from the sprayed surface, the rebound increases and the compaction and the strength of the shotcrete is affected (Moser and Girmscheid, 1999).

The proper gunning technique is a circular or elliptical movement of the nozzle across the surface. It should not be directed towards one spot for an extended period of time, since this causes an increase in rebound and it becomes difficult to control the thickness of layering. The nozzle should be held at 90^{0} to the plane surface. When these principles are not followed there is excessive rebound and compaction will decrease.

The trays were placed in an upright position to replicate an excavation wall in underground workings. The panels were sprayed by an experienced operator.

The shotcrete panels were sprayed into 750 x 750 x 100 mm trays (Figure 4). The curing time was approximately 4 weeks before shotcrete was cut and drilled. These trays were sprayed using shotcrete obtained from Concrete Lining Product (CLP). The shotcrete was allowed to solidify for a day and then it was placed into the curing tank under water for 14 days before it was taken to the lab.

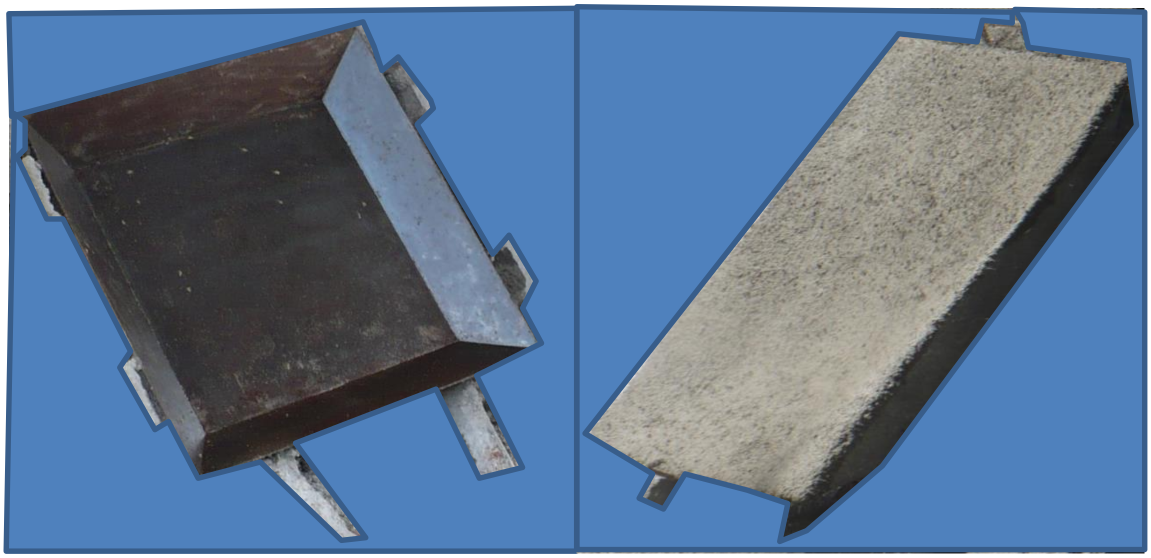


Figure 4: Shotcrete tray and a sprayed panel

3.2 Preparation of the shotcrete specimens

The experiment needed the preparation of shotcrete specimens to be coated with the Thin spay-on liner (TSL's) to determine whether the TSL has any influence on the tensile strength of the shotcrete. Sprayed panels were taken to the lab where a diamond cutter was used to cut the panels into smaller dimensions of 90 x 750 x 100 mm (figure 5b). They were then cored using a 42mm diameter drill and the cores cut to a thickness of approximately 21mm, giving the required diameter to length ratio for the Brazilian test (D=2t). The disc specimens were stored in a controlled environment room at a relative humidity of 50 % and a temperature of 24 ^{0}C. Coring was done in an "even mixture" part of the slab (figure 5c) since during the shotcrete application, it appeared that the shotcrete at the base of the tray was not mixed evenly, as shown in Figure 5c below.

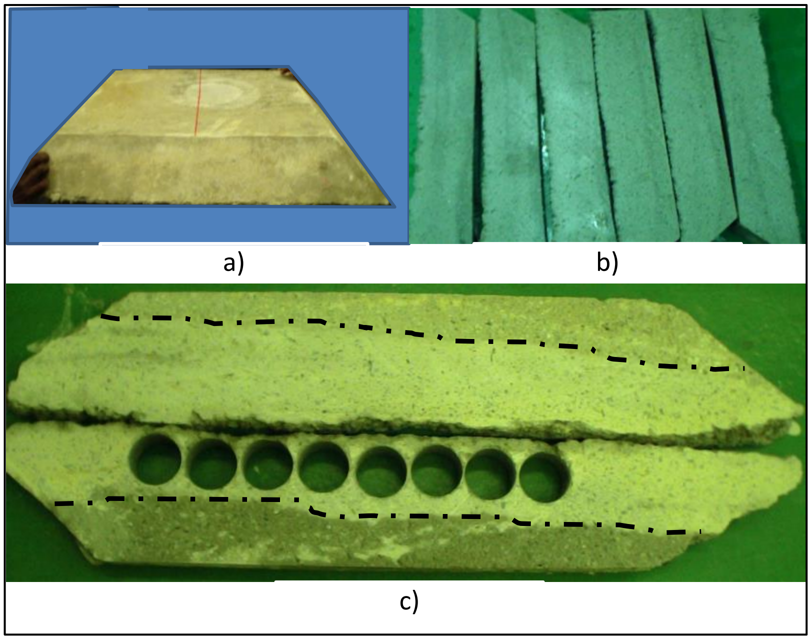


Figure 5. a) Uncut shotcrete panel. b) Cut panel slabs. c) Uneven slabs

3.3 Thin spray-on liner products used

From the range of TSL products available in the market both locally and internationally, only three were selected for coating the plane surface of the shotcrete. Available products are manufactured with a variety of components, some with a single component, some with double components and others with triple components. A single component TSL contains a powder which can be mixed with water before applying (TSL C). A double component TSL consists of powder and polymer liquid (TSL A). Triple component TSLs consist of powder, sand and polymer (TSL B). The liner materials selected for testing were:

- TSL A, which is a cement-based liner with a mixing ratio of 400g of binder to 2.1kg of cement.
- TSL B, with a mixing ratio of 2kg of binder to 2.8kg cement and 7kg sand.
- TSL C, with a mixing ratio of 250g of water to 1kg of mixture

3.3.1 TSL Mixing Methodology

A number of options were available for mixing of the TSL material as shown in figure 6. Firstly the liner material could be mixed using a kitchen food mixture with variable mixing speed which is capable of simultaneous incorporation of opposite rotation (figure 6a). Secondly it could be mixed using a hand held steel scraper (figure 6b). This takes some time since great effort is required to achieve a homogeneous mixture. Lastly, a small hand-held light-weight power drilling machine with a mixer attached could be used.

Mixing of the TSLs for the laboratory tests followed the proportions suggested by the manufacturers. An electrical weighing scale was used to weigh the TSL mixture with the specified ratios for mixing. Since small numbers of specimens were prepared at any one time, it was not practical to mix a whole bag of the TSL material. Therefore small amounts were weighed proportionally and mixed.

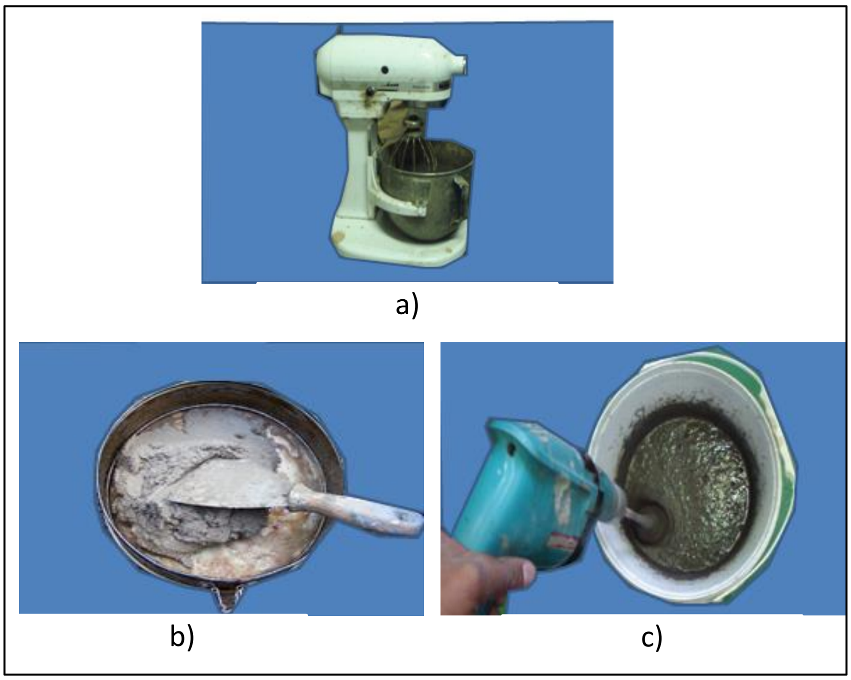


Figure 6. Method of mixing: a) Kitchen food mixer. b) Hand mixing. c) Power drill and mixer

The option of a small hand-held light-weight power drilling machine with a mixer attached to it was used for the purpose of this experiment. The duration of mixing the TSL depends on the following parameters: speed of a mixer, TSL type and amount of TSL material used. Some liner products require less mixing time e.g (cementitious TSL) and others need slightly more mixing time (e.g the polymer-based flexible TSLs). The material should be mixed well to avoid unmixed lobes of the TSL material. Since the setting times of different TSLs vary, some setting earlier than others, small portions should be mixed for those TSLs with short setting times.

3.3.2 Curing time

For the purpose of this research, the option of manual pouring was exercised to apply the required thickness of TSL coating onto the specimen. Curing time is critical to the development of the strength of the TSL in the hours immediately after coating. The samples were coated, wrapped in plastic and placed in a controlled temperature and humidity environment for curing. For the purpose of this research, curing time was chosen as a variable parameter of interest. Tests were performed for four curing times, which were 2hours, 24hours, 7days and 28days to give a range considered broad enough to demonstrate the strength developed by the TSL. Two hours and 28days were selected as the lower and upper limit of the curing period. It is to be noted that TSL performance is also influenced by other factors which may include temperature, humidity, loading rate, TSL material, method of application and specimen size.

3.3.3 TSL thickness

Since the volume of the specimen is directly proportional to its thickness, the thickness of the specimen should be standardized. For the purpose of this research the TSL coating on shotcrete specimens was maintained at a uniform thickness of 4mm, and the shotcrete discs were as mentioned earlier, 42mm diameter and 21 mm thickness (section 3.2).

3.4 Description of apparatus, specimen preparation, TSL coated specimen and test procedures

This section provides a detailed description of test apparatus, the procedures followed in specimen preparation and the test execution.

3.4.1 Description of apparatus used

Three steel rings were used to support the rectangular steel frame containing six circular holes into which shotcrete cores could be placed for coating. The steel rings used were of 20mm thickness. Two of these steel rings were placed at the edges of the rectangular steel frame and the last steel ring was placed in the middle of the opposite side as shown in figure 7.

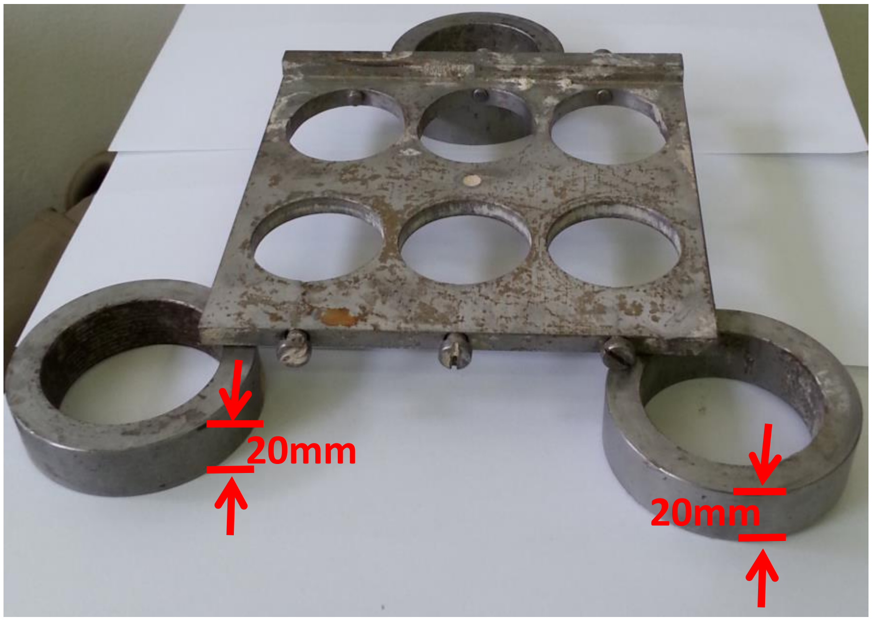
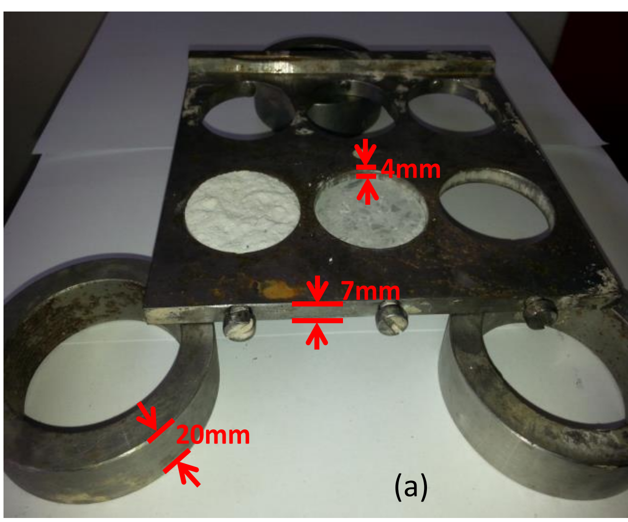


Figure 7. Dimensions of apparatus used: Steel ring that supported steel frame

A rectangular steel frame of 150mm X 150mm dimensions was used in preparation of specimens with dimensions of 42mm diameter and 4mm thickness. The frame enabled the test specimens to be prepared with a controlled TSL thickness (figure 8). The clamping fixtures (knobs), as shown in figure 8a below enabled the specimen to be tightened as not to move when the TSL is poured by tightening the specimen against the steel ring.



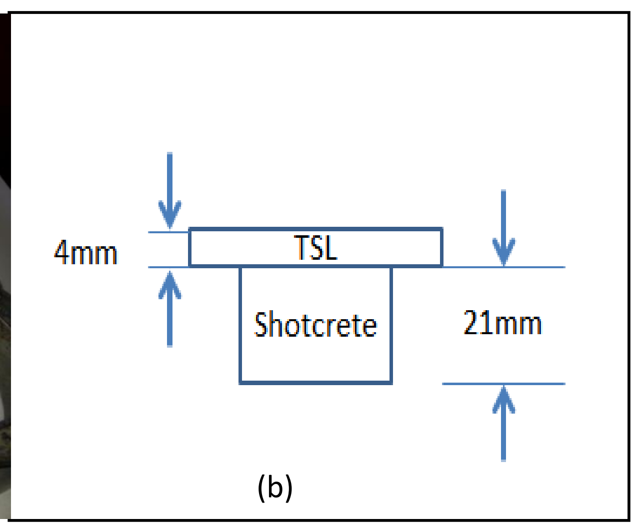


Figure 8. a. Clamping fixture (knobs) and the 42mm diameter holes of the rectangular frame.
b. Cross-section view of the specimen

A Vernier Calliper was used to measure both the diameter and the thickness of the specimen. It was also used to verify the 4mm depth of the specimen in the rectangular frame. In the preparation of specimens, the TSL mixture had to be leveled carefully against the surface of the rectangular steel frame. The scraper was used to flatten the TSL surface (Figure 9).

Figure 9. Spatula and a scraper.

3.4.2 Selection of evenly mixed specimens

The specimens were drilled and cut to the required dimensions and were allowed to dry. Then they were kept in the plastic bags in order to limit their exposure to the air. Only evenly mixed (homogeneous) portions of the slab were chosen and drilled. Samples that were not correctly mixed or sprayed were rejected in order not to underestimate the shotcrete failure strength (figure 10). Both the length and the diameter of the specimens were measured.

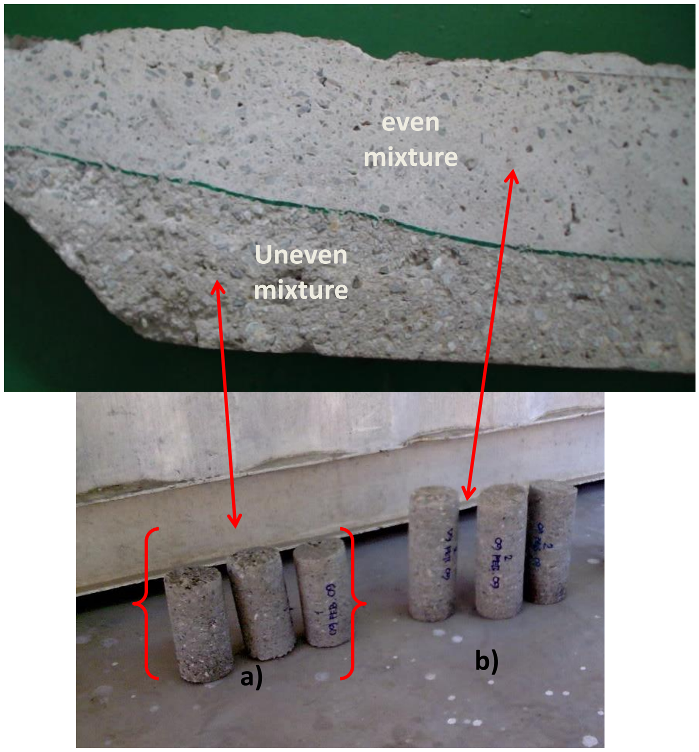


Figure 10. Specimen drilled from two types of mixtures: a) uneven mixture type b) even mixture type.

3.4.3 TSL coated specimen preparation

The steps that were followed during the preparation of the TSL coated specimens are illustrated as follows:

- Preparation of the rectangular steel ring frame (figure 11a)
  - Establish a conducive flat surface where the steel ring is to be placed.
  - Position the shotcrete specimen centrally in the 42mm circular cavities and measure the 4mm depth from the top of the specimen to the top of the frame using a Vernier.
  - Tighten the specimens with the clamping knobs in the rectangular frame.
  - The inner surface of the ring was lubricated to prevent the sticking of the TSL on steel.

- TSL components are taken and mixed thoroughly according to the manufacturer's specification using the small hand-held light-weight power drilling machine and a bucket (figure 11b).

- Pouring of the TSL (figure 11c)
    - TSL mixture was carefully poured onto the shotcrete discs in circular cavities with the assistance of a scraper or spatula.
    - Excess TSL was, cleaned away and the TSL surface levelled with a spatula to control the thickness.

- Removal of the specimens from the rectangular steel frame.
    - TSL has to set, the setting time will depend on the TSL product been used.
    - Hold the specimen from the bottom and untighten the knob, then push the specimen upwards to remove from frame.
    - Clean the unwanted "edges" from the specimen
    - Clean the steel rings for the next application
    - Three specimen per application were considered

- Storage of prepared TSL coated specimen.
    - TSL was allowed to set before specimens were stored in plastic for curing purposes.
    - Only the number of specimens required for testing is removed from storage on the day of testing (24 specimens).

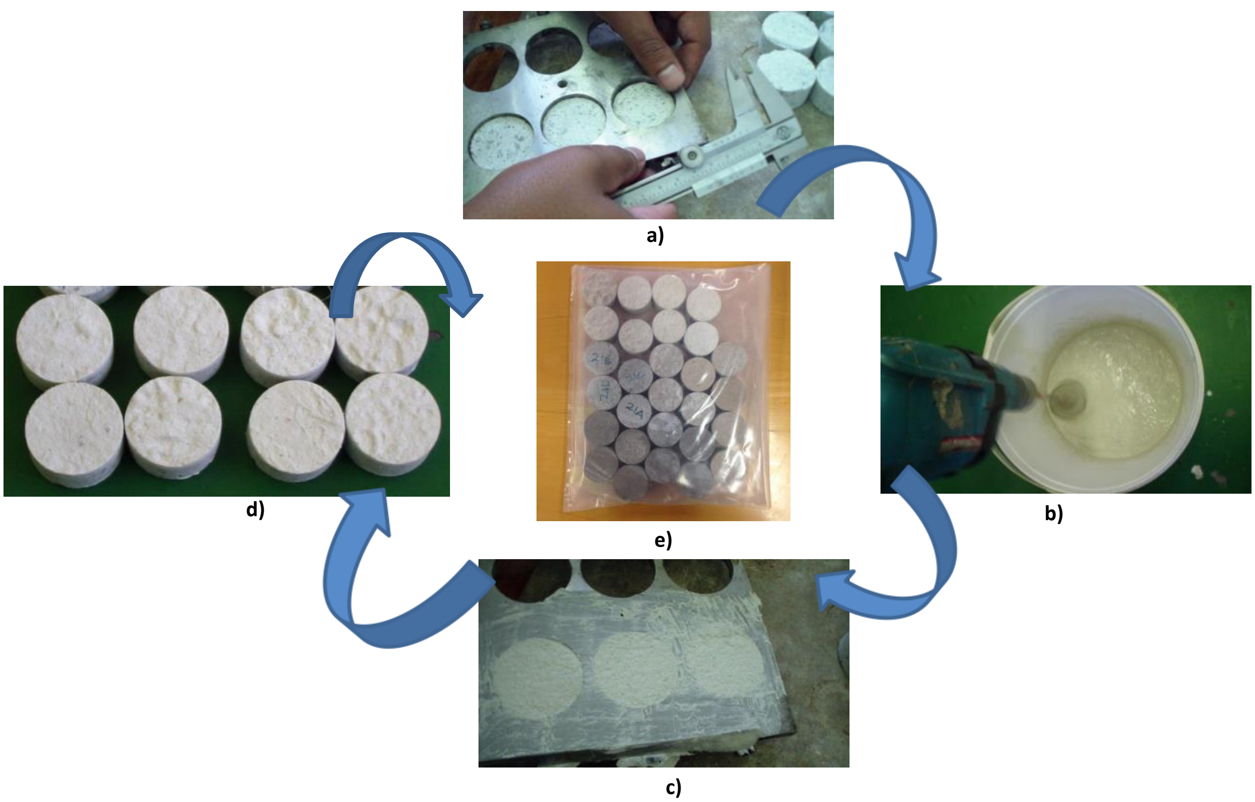


Figure 11: Steps followed during coating of the TSL onto the specimen.

As indicated earlier, specimens with all three TSL types were tested for curing times of 2hours, 24hours, 7days and 28days. Uncoated specimens were also tested as controls at the same curing time.

3.5 Testing Method

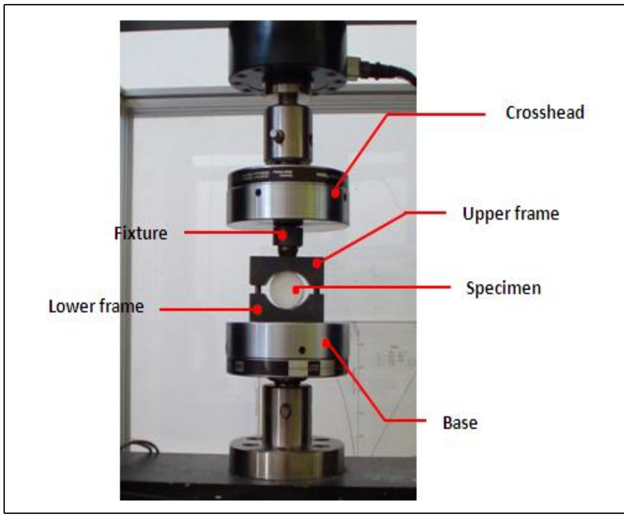
3.5.1 Brazilian Indirect Tensile Test

The Brazilian test is a method intended to measure the tensile strength of the prepared specimen indirectly. It was developed to overcome the difficulty associated with performing a direct uniaxial tensile test. A cylindrical specimen is compressed across its diameter and a nearly uniform tensile stress is induced in the loading plane. The Brazilian indirect test is justified based on the experimental fact that rocks in a biaxial stress field fail in tension at their uniaxial tensile strength when one principal stress is at the tensile strength and the other is compressive with a magnitude not exceeding three times that of the tensile stress (Napier *et al,* (1995), Ryder and Jager (2002) and Ndlovu, (2007)). The indirect tensile strength of the shotcrete was used to characterize different liner properties and the results are compared for the different liner products used.

Brazilian strength testing was carried out using an MTS testing machine with a loading rate of 0.001mm/s. The final dimensions of the specimens were 42mm in diameter and their lengths varied between 21-22mm. The TSL liners were applied on one side of the specimens with a consistent thickness of 4mm.

Specimens were randomly selected from curing storage as required. The prepared specimen is carefully installed in the testing machine, such that the specimen is well centered and a good line load applied. On the MTS machine both displacement and load control modes are an available option for the loading of specimens. The safety shield was closed and the machine's crosshead was allowed to make contact with the fixture that applies load on the upper frame and is in contact with the specimen to be tested (figure 12a). This is for the steady and constant initial loading rate to be applied on the specimen before the actual testing takes place.

The recorded thickness and diameter of both the coated and uncoated specimen are entered into the data capturing program before execution. The specimen is loaded at a constant loading rate until failure occurs. Failure normally takes place between 1-10 minutes. Load and machine displacement are recorded by the data capturing program of the machine. The maximum load at failure of the specimen is noted for subsequent tensile strength calculation.



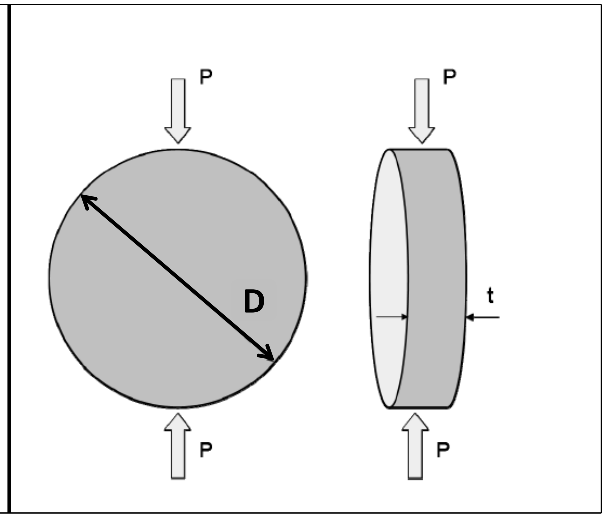


Figure 12: a) Specimen loaded into the test machine. *b) Schematic of Brazilian Disc (not to scale)*

Loading rate is a parameter that affects the results of the specimen strength testing. Slower loading can result in a material failing at a reduced load level. The higher loading rate in a rock specimen results in a higher strength level. Similar behavior can be expected when testing the shotcrete specimens coated with the TSL. Use of a constant loading rate obviates this variability as far as possible.

In the Brazilian test, cracks initiate at the centre of the specimen and propagate outwards along the loaded diameter. If the specimen does not fail diametrically, then the failure mode is invalid. In this investigation all the accepted results of the tests were valid.

3.5.2 Indirect Tensile Strength Calculations

When a force, P, is applied on a cylindrical sample as indicated in figure 12b , with diameter D and thickness t, the indirect tensile strength σ_t (uniformly across the diameter) can be calculated from equation (1) (ISRM, 1978) :-

$$\sigma_t = \frac{2P}{\pi D t} \qquad (1)$$

Where, P - Applied Load (Newtons)
D - Diameter of the specimen (metres) and
t - Thickness of the disc (metres)

The equation is obtained analytically assuming that the tested sample has isotropic and homogeneous material properties. The equation gives the indirect tensile strength of the specimen perpendicular to the loaded diameter. Failure in the form of fractures initiates at the centre when the tensile stress exceeds the tensile strength of the specimen. These cracks then propagate outward along the loading line and split the specimen into two symmetrical halves (figure 13b). TSL coated specimen increases the thickness (t) which is indirectly proportional to the indirect tensile strength (σ_t).Increase in the thickness results in lower tensile strength.

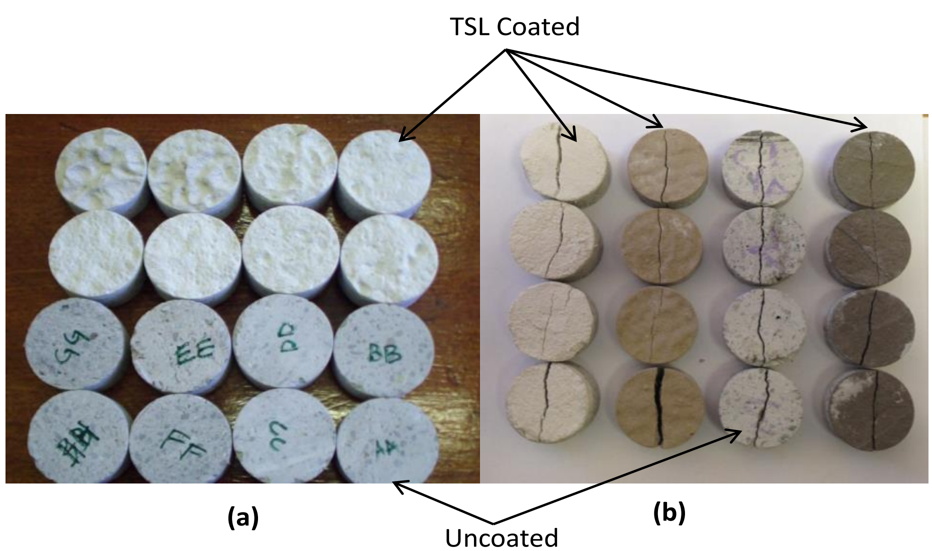


Figure 13: a) Untested specimen and b) Tested Failed specimen.

3.6 Summary of preparation and testing

This chapter covered a comprehensive discussion of the specimen preparation and test parameters that may have direct influence on the test results. Testing of the prepared specimens contains parameters that need to be controlled at all stages of the test process. Curing time was considered to be the most important parameter to be checked for sensitivity. At the early stages, after the TSL was coated on the specimens, curing time had a very short interval to capture the early strength development of the TSL product. In the next chapter, the results of the Brazilian tests and their interpretation are presented.

CHAPTER 4
Laboratory test results and analysis

4.1. Results and analysis

The previous chapter dealt with a specimen preparation and indirect tensile testing of the uncoated and TSL coated shotcrete specimens. In this chapter the laboratory tensile strength results will be determined, and analyzed.

4.1.1. Load displacement curves of tested shotcrete specimens

Typical load-displacement behavioural curves of plain and polypropylene fibre reinforced shotcrete from the Brazilian tests can be seen in Figure 14. The load-deformation curves are an important graphical representation of a material's mechanical behaviour.

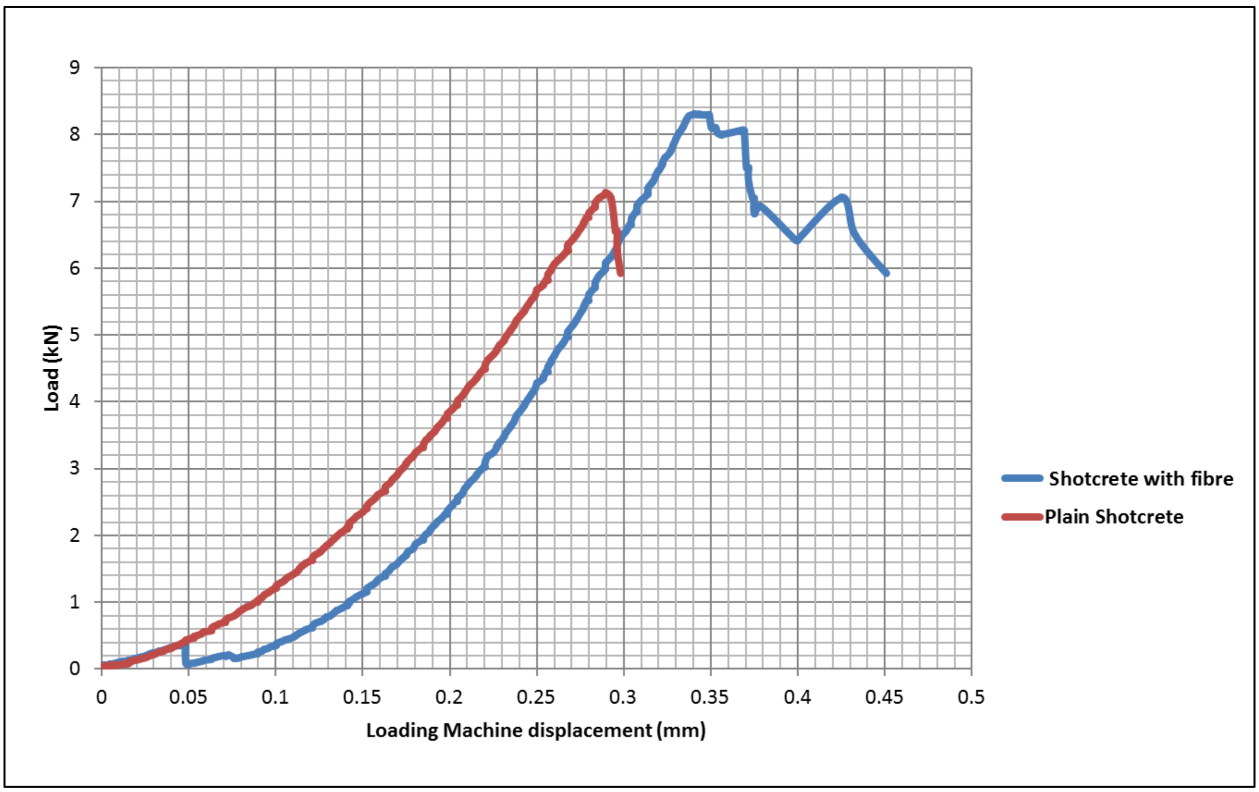


Figure 14. A typical example of the compressive diametrical load versus diametrical displacement behaviour for plain and fibre reinforced shotcrete.

Figure 14 shows that fibre added in the shotcrete mix can change the post failure behaviour of the shotcrete specimen from brittle behaviour to more ductile behaviour. The graph only gives an indication of comparative post peak behaviour of the specimen. Plain shotcrete does not exhibit ductile post failure behaviour, therefore it has less capacity for energy absorption. Polypropylene fibres offer significant advantage by adding the ductile post failure behaviour to the shotcrete. It enables the shotcrete to develop a higher strength and offers energy absorption capacity and impact resistance. The plain shotcrete specimen is more rigid and will therefore deform less (i.e. have a lower strain) under the same applied load conditions. Although not a true indication of energy absorption capability (since the loads and displacements are compressive, and failure is tensile), comparing the areas under the graphs shows that the fibre reinforced shotcrete specimen exhibits much more capacity than the unreinforced shotcrete.

Literature has shown that the application of the TSL on the rock specimen changes the post failure behaviour of the specimen from being brittle to smooth and ductile behaviour by confining the fractured rock with a limited resistance (Espley, 1999; Archibald and DeGagne, 2000; and Kuijpers, 2001). It even gives some additional flexibility or toughness to the shotcrete (or rocks). Brazilian tests performed on anorthosite rocks have shown that TSL's offer potential in controlling pre and post yield rock failures (Mpunzi, 2011). It was observed that the application of the TSL not only controlled the pre and post yield rock failure, but even increased the peak strength of the specimen. Similar tests on shotcrete specimens carried out for this report resulted in similar strength and ductility enhancements as shown in figure 15 below:

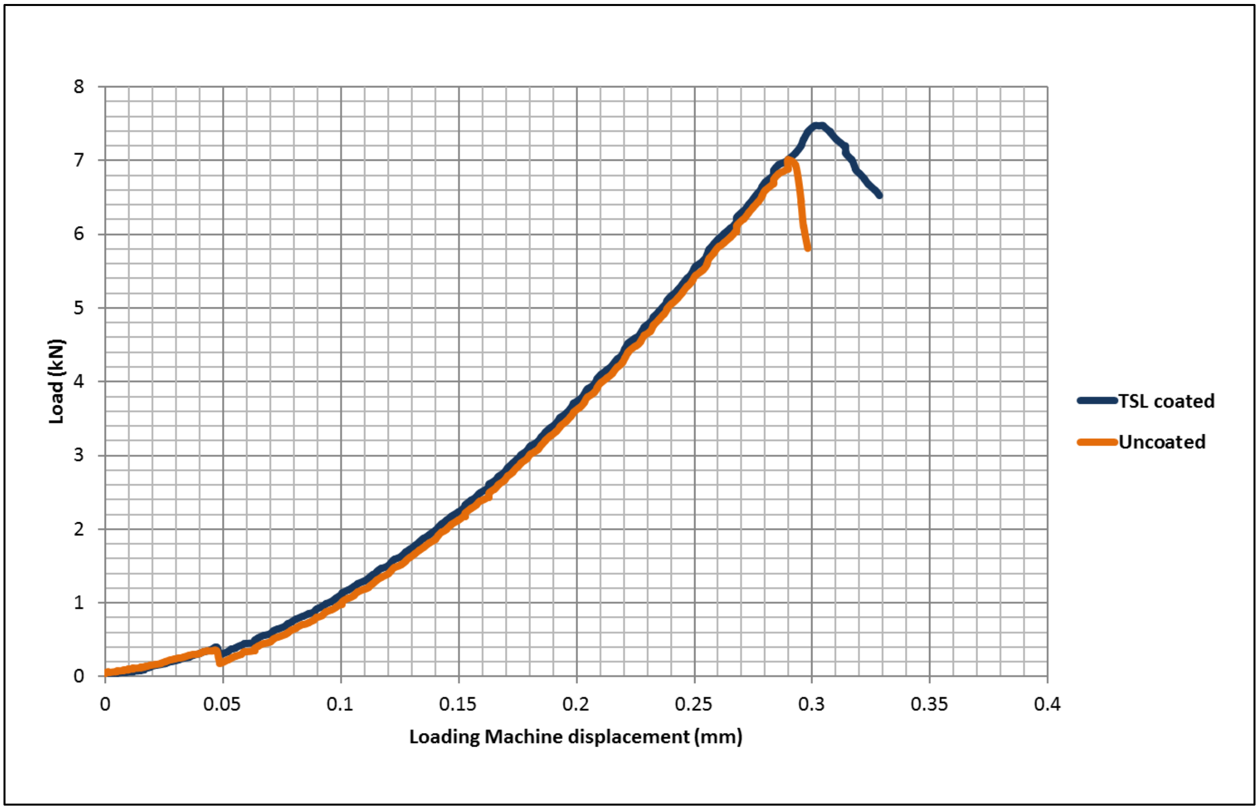


Figure 15. A typical example of the compressive diametrical load versus diametrical displacement behaviour for uncoated and TSL coated unreinforced shotcrete.

4.1.2 Percentage strength increase

The application of the TSL coating increases the tensile strength of the specimen. The percentage strength gain can be calculated by comparing the difference in strength between the coated and uncoated shotcrete specimens. Below is the formula indicating how the percentage strength increases were calculated from the mean strength of both the coated and uncoated specimens:

$$\%\,\boldsymbol{Strength\ increase} = \frac{\boldsymbol{Coated(Mean) - Uncoated(Mean)}}{\boldsymbol{Uncoated(Mean)}}\ \boldsymbol{X}\ \mathbf{100}\%$$

The results shown are from 96 specimen tests carried out, of which the averages of the peak strength for different curing times of the TSL were recorded and analyzed. The averages of the peak strengths for different curing times and different liners at constant thickness of 4mm were recorded and analyzed. Uncoated specimens were used as the base or controls to compare any variation due to the effect of the TSL application on different tested specimens. The calculation assists in determining the TSLs which show significant percentage strength increase. Table 5 outlines the percentage strength gain results on the unreinforced shotcrete coated by different TSL's.

Table 5 Unreinforced shotcrete percentage strength gain

Curing Time (Days)	TSL A	TSL B	TSL C
0.08	16.61	16.61	20.28
1	25.48	19.49	20.42
7	26.14	22.99	22.50
28	35.42	23.43	40.48

These results show that all the applied TSL's improve the shotcrete performance, in terms of the percentage strength gain, with the curing time. Significant percentage strength gain is observed after 28days of curing in both TSL A and TSL C, the increase was on average 19-20% more than their initial percentage strength gain. The corresponding value for TSL B was 7%. The results show that using unreinforced shotcrete coated with TSL A and TSL C would be more significant than using TSL B, after 28days (Figure 16). The strength gain of TSL A was greater than TSL B and TSL C for day 1 and day 7. However, on average TSL C has a high initial strength gain and high final strength gain. TSL C increased on average by 4% compared to TSL A and TSL B during the 2nd hour and 28th day. Detailed results of the percentage strength gains, including the standard deviations for the three TSLs, are summarized in Appendix A. Figure 16 shows curves of strength gain versus curing time.

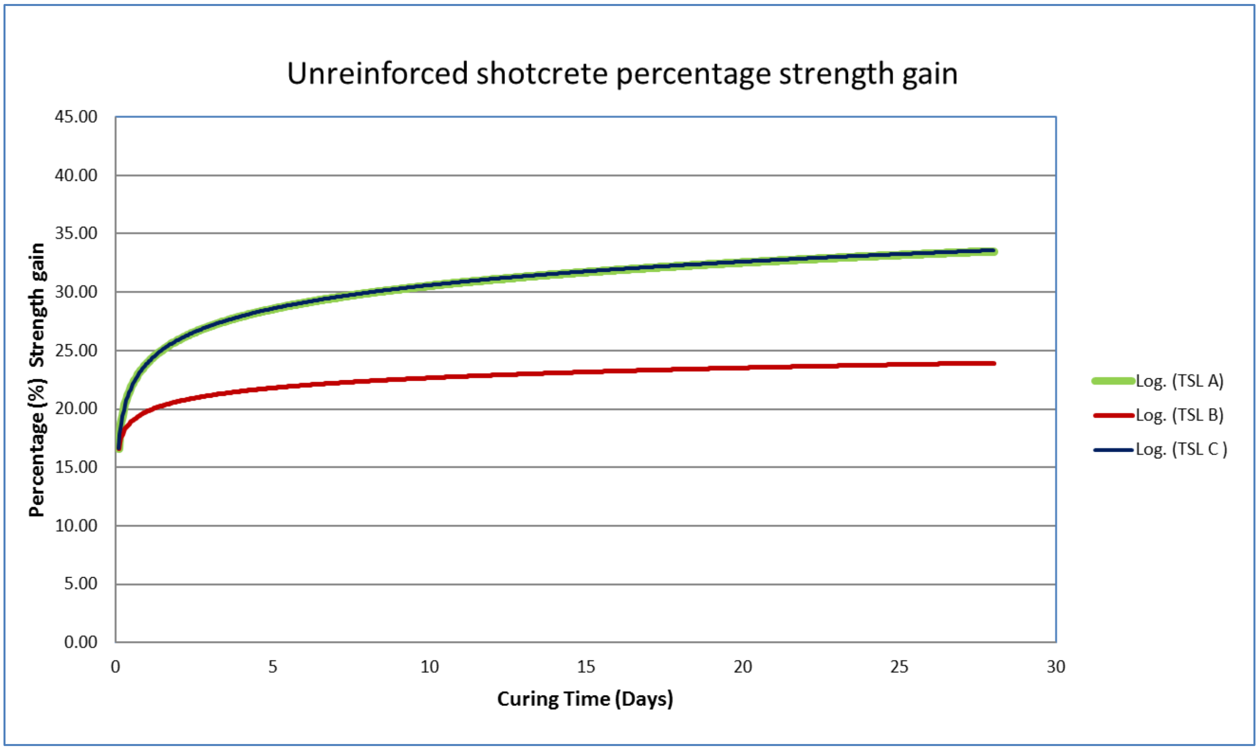


Figure 16 : Graphical representation of the unreinforced shotcrete strength gain.

Table 6 below presents the percentage strength gain equations of the graphs shown in figure 16 above and their correlation coefficients, where x represents curing period in days. TSL C resulted in the lowest correlation coefficient and in this case there is basically no correlation.

Table 6: Percentage strength gain equation of different TSL's

Unreinforced Shotcrete specimens		
TSL	**Percentage Strength gain Equation**	**Correlation Coefficients (R^2)**
A	$y = 1.5118\ln(x) + 2.8499$	0.77
B	$y = 0.3742\ln(x) + 0.7751$	0.89
C	$y = 0.4795\ln(x) + 5.0281$	0.04

Table 7 presents the percentage strength gain of the reinforced shotcrete coated by the three different TSL's. These results show that with reinforced shotcrete, percentage gains are higher than for the unreinforced shotcrete.

Table 7: Reinforced shotcrete percentage strength gain

Curing Time (Days)	TSL A	TSL B	TSL C
0.08	19.48	19.53	24.47
1	26.02	22.61	24.83
7	33.77	25.56	25.55
28	38.94	31.57	45.38

A fibre component in the mixture increases performance of the shotcrete. TSL A and TSL C show a significant improvement of 20-21% on average in strength gain on the 28th day curing time compared to the initial strength gain of each liner. Higher strength gain values are observed for the TSL A and TSL C compared with TSL B on the 28th day. The graphical representations of the table above are presented in Figure 17 below. TSL A and TSL C displayed a significant increase in their percentage strength gain.

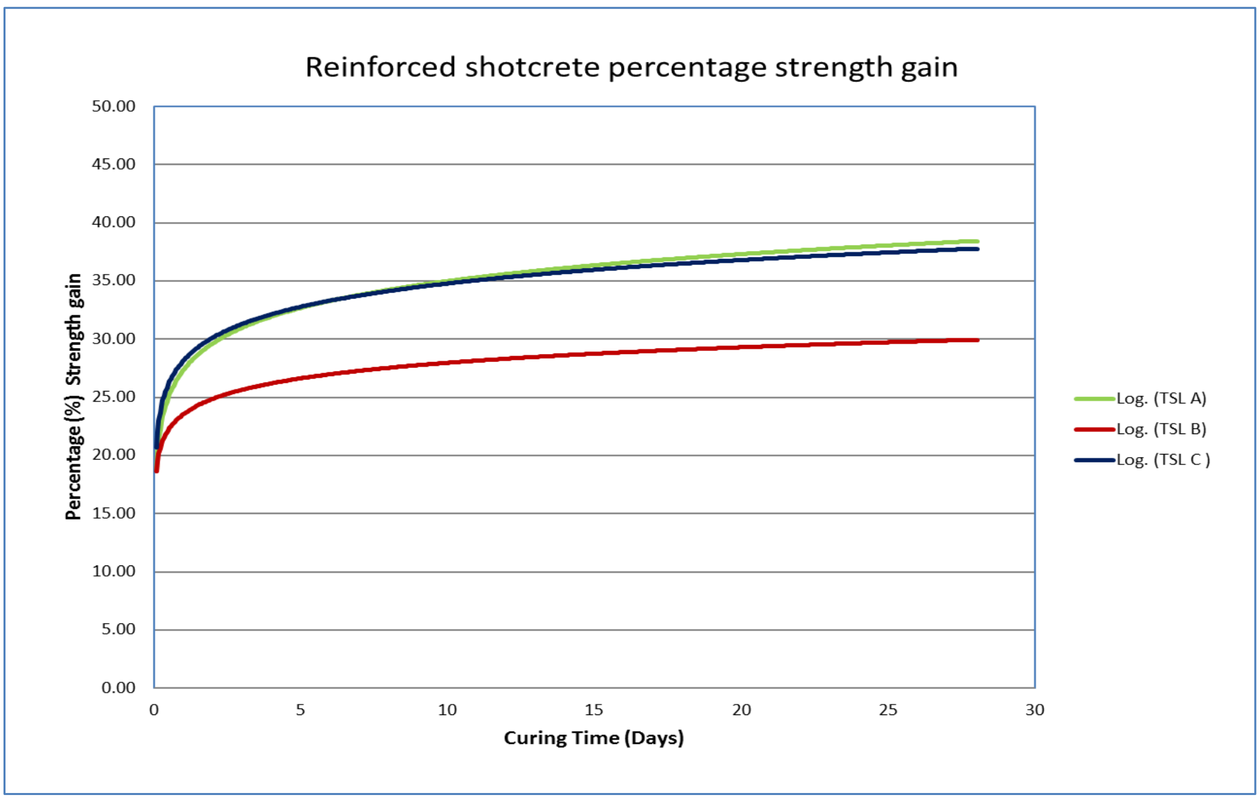


Figure 17. Graphical representation of the reinforced shotcrete strength gain.

The increase in percentage gain is much higher with the reinforced shotcrete than with unreinforced shotcrete. The performance of TSL B was poorer than the other liners over the entire curing period, therefore, it will be more beneficial in underground workings to use either TSL A or TSL C.

The detailed Brazilian test results tables, including the thicknesses of the TSL A, TSL B and TSL C, are summarized in Appendix B. The table below represents the percentage strength gain equations of the curves in figure 17 and their correlation coefficients, where x represents curing period in days.

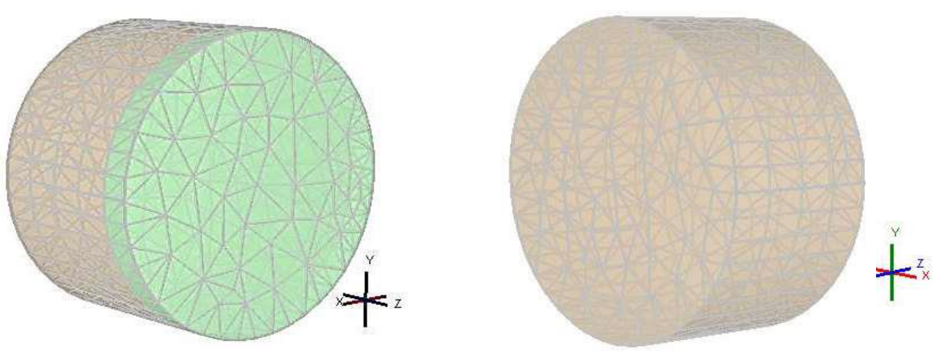
Table 8: Percentage strength gain equation of different TSL's

Reinforced Shotcrete specimens		
TSL	**Percentage Strength gain Equation**	**Correlation Coefficients (R^2)**
A	y = 2.5695ln(x) + 11.615	0.57
B	y = 1.2758ln(x) + 2.8328	0.60
C	y = 2.4945ln(x) + 4.9039	0.43

The correlation coefficients are not as good as for the curves in Figure 16. If there is any inconsistency in the tests results this might be due to anomalous conditions such as air bubbles, unmixed TSL or shotcrete lumps.

4.1.3 3D stress analyses of a TSL coated shotcrete specimen.

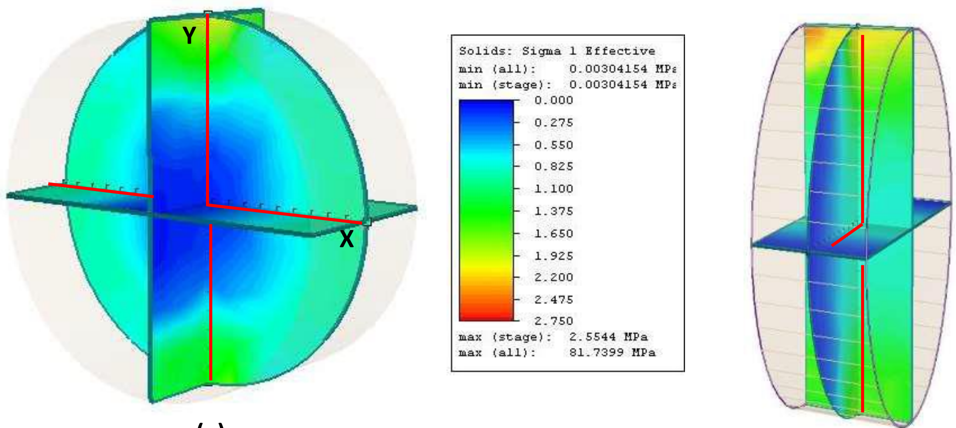
In the above analyses of results, the thickness of the discs used in the calculation ignored the TSL. To check on the validity of this approach, 3D stress analyses of coated and uncoated were carried out (Rizwan, 2014). Figure 18 shows the finite element models used.



(a) (b)

Figure 18. 3D view of the Brazilian disc specimen: (a) TSL coating (b) Without Coating (Rizwan, 2014).

The effect of the application of the TSL was studied by comparing the stress (σ_1, σ_2 and σ_3) distributions on x, y and z axes for the Brazilian disc specimens. Different properties of the TSL's were selected to generate comparative analyses. Vertical (y) and Horizontal (x) query lines passing through the centroid of the specimen were considered and modelling results with equal spacing were analyzed and interpreted (figure 19). Three perpendicular contour planes were considered for the interpretation. Appendix C shows a summary of query results from the modelling.



(a) **(b)**

Figure 19: Modelling Results (a) Vertical and Horizontal Query lines (b) Contour planes (Rizwan, 2014).

The results of the analyses indicated that the inclusion of a TSL coating had a negligible effect on the stress distribution in the shotcrete, confirming that the tensile strength calculation approach was valid.

4.1.4 Calculation and results of the Brazilian strength test on both the reinforced and the unreinforced samples.

Table 9 below presents the Brazilian strength test results from the unreinforced shotcrete specimens that were not coated with the TSL. These strength results are on average constant for the overall testing period of the shotcrete specimens.

The tests on the uncoated specimens were performed to show that the strength increase in the specimen is not due to shotcrete curing, but actually due to the TSL curing with time. The results were determined for the valid tested specimens.

Table 9. Brazilian Indirect Tensile Strength (No TSL): Unreinforced

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Unreinforced Shotcrete	Specimen No.	Diameter Mm	Thickness mm	Mass grams	TSL Thickness Mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	Specimen1	4	42.0	21.0	60.9	0.0	5.326	3.843
	Specimen2	5	42.0	21.0	61.6	0.0	5.244	3.784
	Specimen3	6	42.0	21.0	61.1	0.0	4.836	3.489
	Averages		**42.0**	**21.0**	**61.2**	0.0	**5.135**	**3.705**
1 Day	Specimen 1	C4	42.0	21.0	60.0	0.0	5.021	3.623
	Specimen 2	C2	42.0	21.0	64.8	0.0	5.242	3.782
	Specimen 3	C5	42.0	21.0	65.0	0.0	5.218	3.765
	Averages		**42.0**	**21.0**	**63.3**	**0.0**	**5.160**	**3.723**
7 Days	Specimen 1	14CU1	42.0	21.0	58.7	0.0	5.300	3.824
	Specimen 2	14CU2	42.0	21.0	63.8	0.0	5.200	3.752
	Specimen 3	14CU3	42.0	21.0	64.5	0.0	4.900	3.535
	Averages		**42.0**	**21.0**	**62.3**	**0.0**	**5.133**	**3.704**
28 Days	Specimen 1	CU1	42.0	21.0	59.1	0.0	5.320	3.838
	Specimen 2	CU2	42.0	21.0	58.2	0.0	5.200	3.752
	Specimen 3	CU4	42.0	21.0	62.8	0.0	5.010	3.615
	Averages		**42.0**	**21.0**	**60.0**	**0.0**	**5.177**	**3.735**

Table 10 below presents the corresponding Brazilian strength test results for the reinforced shotcrete specimens that were not coated with TSL. The Brazilian tensile strength results on average are constant for the overall testing period of the shotcrete specimen. These results are slightly higher than those of the plain shotcrete specimens tested due to the presence of the fibre.

Table 10 Brazilian Indirect Tensile Strength (No TSL): Reinforced

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Reinforced Shotcrete	Specime n No.	Diamete r Mm	Thicknes s mm	Mass grams	TSL Thicknes s Mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	Specimen1	R1	42.0	21.0	63.6	0.0	5.338	3.851
	Specimen2	R2	42.0	21.0	63.6	0.0	5.416	3.908
	Specimen3	R3	42.0	21.0	63.0	0.0	5.542	3.999
	Averages		**42.0**	**21.0**	**63.4**	**0.0**	**5.432**	**3.919**
1 Day	Specimen1	CR1	42.0	21.0	62.7	0.0	5.469	3.946
	Specimen2	CR2	42.0	21.0	60.7	0.0	5.387	3.887
	Specimen	CR3	42.0	21.0	61.1	0.0	5.387	3.887
	Averages		**42.0**	**21.0**	**61.5**	**0.0**	**5.414**	**3.906**
7 Days	Specimen1	14CUR1	42.0	21.0	65.0	0.0	5.300	3.824
	Specimen2	14CUR2	42.0	21.0	62.7	0.0	5.300	3.824
	Specimen3	14CUR3	42.0	21.0	66.0	0.0	5.700	4.113
	Averages		**42.0**	**21.0**	**64.6**	**0.0**	**5.433**	**3.920**
28 Days	Specimen1	RU4	42.0	21.0	61.9	0.0	6.010	4.336
	Specimen2	RU2	42.0	21.0	65.6	0.0	5.214	3.762
	Specimen3	RU5	42.0	21.0	57.0	0.0	5.400	3.896
	Averages		**42.0**	**21.0**	**61.5**	**0.0**	**5.541**	**3.998**

Summary graphs of the tensile strength versus the TSL curing period are presented in Appendix D for each of the TSL products used on the shotcrete specimens. Two of the Tensile strength average graphs are presented in Figure 20 and Figure 21. This is to show the spread of the tensile strengths over the curing time range.

The strength development over the curing period is best fit represented by the logarithmic regression curves obtained on the test data. The strength function and the correlation coefficient (R^2) were determined by setting a trend line to the best fit for each TSL. The strength function and correlation coefficients for the three liner products tested are shown in Table 11 and Table 12. In the indirect tensile strength equation, the strength of a liner is represented as a function of days representing the curing period. TSL C showed the lowest correlation coefficient (R^2) compared to the other two liners in the strength equations. The correlation coefficient of TSL B is the highest. All the specimens coated with TSL's display strength improvement for the entire period for the unreinforced shotcrete, in Table 11 and Figure 20.

Appendix C summarizes all the individual graphs of the indirect tensile strength tests for the different TSL coated shotcrete specimens. For the period of 2 hours to 28 days TSL A and TSL C performed best with high average peak strengths compared to TSL B. All the liners reached their maximum average peak strength by the 28th day.

Table 11: Unreinforced shotcrete tensile strength equations and the correlation coefficients

TSL	Indirect tensile Strength Equation	Correlation Coefficients (R^2)
No Liner	y = 0.0034ln(x) + 3.7144	0.32
A	y = 0.1135ln(x) + 4.6086	0.91
B	y = 0.0521ln(x) + 4.4563	0.99
C	y = 0.113ln(x) + 4.6022	0.57

x: curing period in days

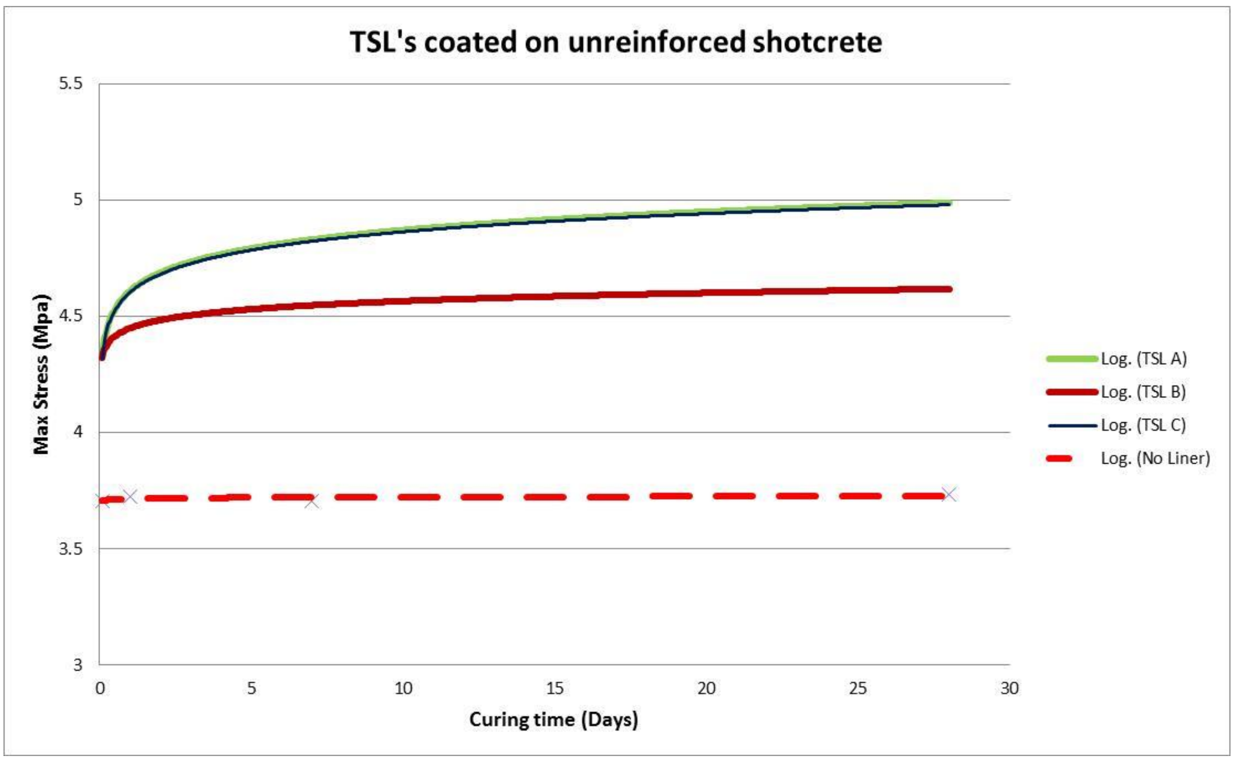


Figure 20. Brazilian Strength Test Results for TSL A, B and C coated on the reinforced shotcrete specimen

For coated the reinforced shotcrete specimens TSL A displays the highest correlation coefficient compared to TSL B and TSL C. The strengths of both TSL A and TSL C are high compared to TSL B. This is represented in Table 12 and Figure 21 below.

Table 12: Reinforced shotcrete tensile strength equations and the correlation coefficients

TSL	Indirect tensile Strength Equation	Correlation Coefficients (R^2)
No Liner	$y = 0.0114\ln(x) + 3.928$	0.47
A	$y = 0.1479\ln(x) + 4.998$	0.97
B	$y = 0.0909\ln(x) + 4.8505$	0.84
C	$y = 0.1616\ln(x) + 4.9642$	0.67

x: curing period in days

The performances of reinforced shotcrete coated with TSL A and TSL C are very similar, generating high average peak strengths compared to TSL B.

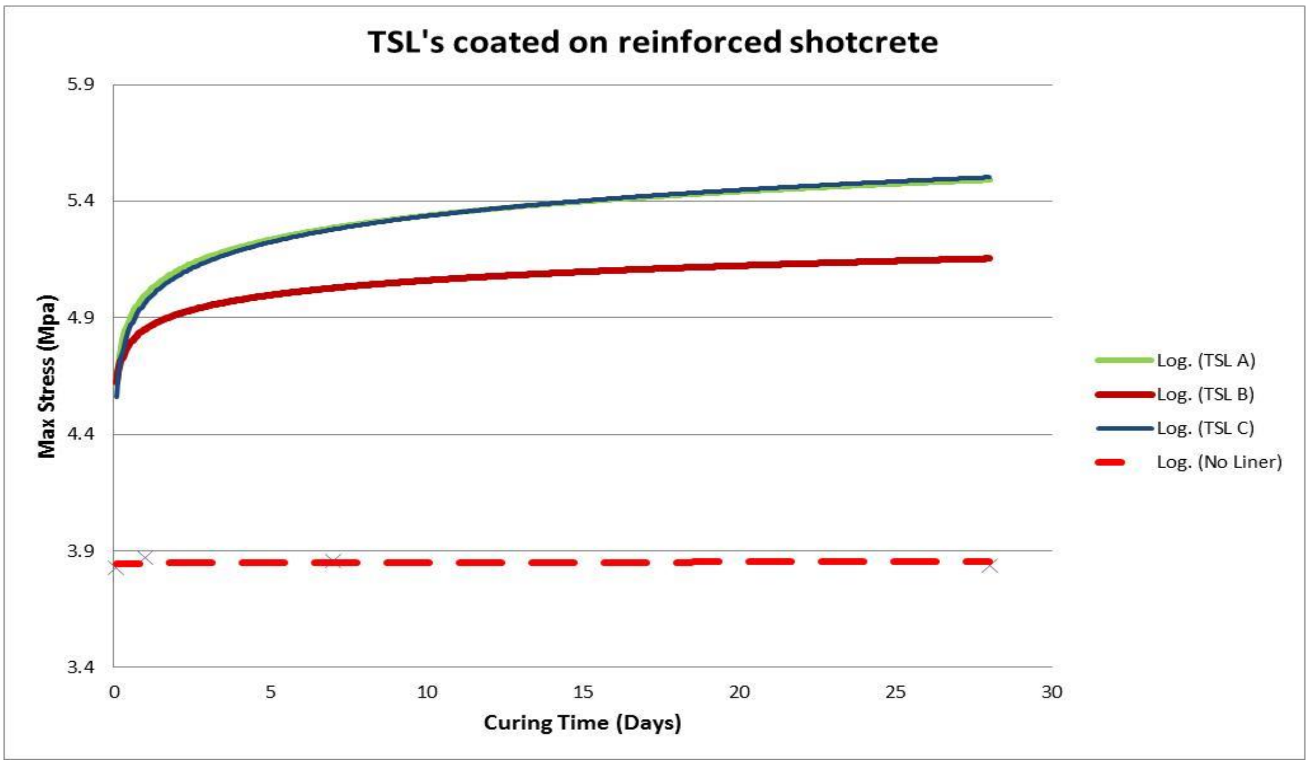


Figure 21. Brazilian Strength Test Results for TSL A, B and C coated on the reinforced shotcrete specimen

TSL B displays lower strength on both the reinforced and unreinforced shotcrete specimens for all the curing periods tested. All the liners demonstrate strength increase over the curing period of 28 days. TSL C appears to provide the greatest benefit followed by TLS A, based on the strength function curves and the strength gain curves.

Strength development increases rapidly from day 1 to 7 days and then increases steadily until the 28th day for all the liners on both reinforced and unreinforced shotcrete specimens. Figure

20 and Figure 21, for both the reinforced and unreinforced shotcrete specimens, display higher indirect tensile strength for all three sprayed liners tested.

4.2 Summary of the laboratory tests results and analysis

Brazilian tensile strength tests were carried out on unreinforced and fibre reinforced shotcrete specimens coated with three different TSL products. On average a strength increase of 6% on shotcrete specimens is observed when fibre is added into the mixture, compared with the plain shotcrete before coating with TSL's. Calculated strength results display strength gain over the entire curing period for all the TSL coated reinforced and unreinforced shotcrete specimens. All the tested sprayed Liners demonstrate a strength increase over the total curing period of 28 days. Compared to all the liners TSL B can be classified as an example of a weak liner and TSL A and TSL C as strong liners. The results are comparable with the investigation by Mpunzi (2011) on coated anorthosite rock samples that showed an increase in strength compared to uncoated anorthosite rock samples. Hence, coated samples exhibited less severe post failure behaviour.

Chapter 5

Conclusions

The research described in this report has focused on the performance of reinforced and unreinforced shotcrete specimens coated with thin spray-on liner material. Three different liner materials were used. The laboratory test methodology has provided a means of comparing how these three different liner products enhanced the strength of the shotcrete specimen. Conclusions can be drawn regarding the performance of the TSL coated shotcrete specimens, and the effect of polypropylene fibre reinforcement in the shotcrete.

Homogeneous specimens of both the reinforced and unreinforced shotcrete were tested and it was observed that the addition of fibre reinforcement into the shotcrete yielded a significant advantage in terms of energy absorption capacity. This therefore improves the shotcrete failure behaviour.

Brazilian indirect tensile strength tests provided a method of evaluating and comparing the enhancement of shotcrete tensile strength due to coatings of different TSLs products. The application of the TSL coating on the shotcrete improved the performance of the shotcrete due to the enhancement of the tensile strength of the TSL coated shotcrete, and by inhibiting the development of the fracturing in the shotcrete. The degree of enhancement depends on the quality, tensile strength and adhesive strength of the TSL.

The overall strength of the shotcrete specimens was observed to increase with the increasing TSL curing time for all tested product types. Different TSLs performed differently for all curing periods for both unreinforced and reinforced specimens. Strengths increased rapidly during the first 7 days of TSL curing, and then at a decreasing rate, for all the liner products tested. Strength gains 2 hours after application were of the order of 20%, and this increased to approximately 40% after 28 days. Slightly higher strength gains were recorded for the fibre-reinforced shotcrete specimens.

Chapter 6

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APPENDICES

Appendix A

Table A.1.1 Percentage strength gain for TSL A on unreinforced shotcrete

TSL Type A	Curing Time				Strength
	2 Hours	1 Day	7 Days	28 Days	
Unreinforced	4.32	4.67	4.67	5.06	Mean Mpa
	0.34	0.55	0.25	0.41	Stdev Mpa
	16.61	25.48	26.14	35.42	% Strength

Table A.1.2 Percentage for strength gain for TSL A on reinforced shotcrete

TSL Type A	Curing Time				Strength
	2 Hours	1 Day	7 Days	28 Days	
Reinforced	4.68	4.92	5.24	5.55	Mean Mpa
	0.21	0.23	0.17	0.20	Stdev Mpa
	19.48	26.02	33.77	38.94	% Strength

Table A.2.1 Percentage for strength gain for TSL B on unreinforced shotcrete

TSL Type B	Curing Time				Strength
	2 Hours	1 Day	7 Days	28 Days	
Unreinforced	4.32	4.45	4.56	4.61	Mean Mpa
	0.41	0.14	0.27	0.30	Stdev Mpa
	16.61	19.49	22.99	23.43	% Strength

Table A.2.2 Percentage for strength gain for TSL B on reinforced shotcrete

TSL Type B	Curing Time				Strength
	2 Hours	1 Day	7 Days	28 Days	
Unreinforced	4.68	4.79	4.92	5.26	Mean Mpa
	0.07	0.13	0.35	0.65	Stdev Mpa
	19.53	22.61	25.56	31.57	% Strength

Table A.3.1 Percentage for strength gain for TSL C on unreinforced shotcrete

TSL Type C	Curing Time				Strength
	2 Hours	1 Day	7 Days	28 Days	
Unreinforced	4.46	4.48	4.54	5.25	Mean Mpa
	0.11	0.35	0.42	0.20	Stdev Mpa
	20.28	20.42	22.50	40.48	% Strength

Table A.3.2 Percentage for strength gain for TSL C on reinforced shotcrete

TSL Type C	Curing Time				Strength
	2 Hours	1 Day	7 Days	28 Days	
Unreinforced	4.88	4.88	4.92	5.81	Mean Mpa
	0.24	0.10	0.34	0.42	Stdev Mpa
	24.47	24.83	25.55	45.38	% Strength

Appendix B

Table B.1 Brazilian Indirect Tensile Strength used on 4mm thickness for TSL A on unreinforced shotcrete specimen.

	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
Curing Time	Sample Type. Unreinforced	Specimen No.	Diameter mm	Thickness mm	Mass grams	TSL Thickness mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	Sample 1	SA1	42.0	21.0	75.5	4.3	5.687	4.103
	Sample 2	SA2	42.0	21.0	75.4	4.5	5.742	4.143
	Sample 3	SA3	42.0	21.0	77.2	3.9	6.536	4.716
	Averages		**42.0**	**21.0**	**76.0**	**4.2**	**5.988**	**4.321**
1 Day	Sample 1	1SA1	42.0	21.0	72.6	3.8	7.283	5.255
	Sample 2	1SA2	42.0	21.0	73.5	4.1	5.765	4.159
	Sample 3	1SA3	42.0	21.0	73.9	4.0	6.378	4.602
	Averages		**42.0**	**21.0**	**73.3**	**4.0**	**6.475**	**4.672**
7 Days	Sample 1	7SA1	42.0	21.0	77.1	4.1	6.132	4.424
	Sample 2	7SA2	42.0	21.0	74.6	4.0	6.618	4.775
	Sample 3	7SA3	42.0	21.0	76.9	3.9	6.795	4.903
	Averages		**42.0**	**21.0**	**76.2**	**4.0**	**6.515**	**4.701**
28 Days	Sample 1	28SA1	42.0	21.0	74.1	4.0	7.376	5.322
	Sample 2	28SA2	42.0	21.0	73.4	4.1	6.350	4.582
	Sample 3	28SA3	42.0	21.0	75.0	4.0	7.305	5.271
	Averages		**42.0**	**21.0**	**74.2**	**4.0**	**7.010**	**5.058**

Table B.2 Brazilian Indirect Tensile Strength used on 4mm thickness for TSL A on reinforced shotcrete specimen.

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Reinforced	Specimen No.	Diameter mm	Thickness mm	Mass grams	TSL Thickness mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	Sample 1	SAR1	42.0	21.0	76.8	4.1	6.171	4.452
	Sample 2	SAR2	42.0	21.0	76.3	4.0	6.567	4.738
	Sample 3	SAR3	42.0	21.0	78.6	4.6	6.733	4.858
	Averages		**42.0**	**21.0**	**77.2**	**4.2**	**6.490**	**4.683**
1 Day	Sample 1	1SAR3	42.0	21.0	74.2	4.0	6.721	4.849
	Sample 2	1SAR4	42.0	21.0	75.3	3.9	7.180	5.180
	Sample 3	1SAR5	42.0	21.0	76.7	4.0	6.568	4.739
	Averages		**42.0**	**21.0**	**75.4**	**4.0**	**6.823**	**4.923**
7 Days	Sample 1	7SAR1	42.0	21.0	77.6	3.9	7.479	5.396
	Sample 2	7SAR4	42.0	21.0	72.2	4.0	7.321	5.282
	Sample 3	7SAR3	42.0	21.0	69.0	3.8	7.005	5.054
	Averages		**42.0**	**21.0**	**72.9**	**3.9**	**7.268**	**5.244**
28 Days	Sample 1	28SAR1	42.0	21.0	73.6	4.0	7.615	5.494
	Sample 2	28SAR4	42.0	21.0	74.1	3.9	7.470	5.390
	Sample 3	28SAR3	42.0	21.0	76.6	4.1	8.012	5.781
	Averages		**42.0**	**21.0**	**74.8**	**4.0**	**7.699**	**5.555**

Table B.3 Brazilian Indirect tensile strength used on 4mm thickness for TSL B on unreinforced shotcrete specimen.

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Unreinforced	Specimen No.	Diameter mm	Thickness mm	Mass grams	TSL Thickness mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	Sample 1	CLP1	42.0	21.0	75.5	4.3	5.587	4.031
	Sample 2	CLP2	42.0	21.0	75.4	4.6	5.742	4.143
	Sample 3	CLP3	42.0	21.0	77.2	3.9	6.636	4.788
	Average		**42.0**	**21.0**	**76.0**	**4.3**	**5.988**	**4.321**
1 Day	Sample 1	1CLP1	42.0	21.0	71.1	4.1	6.267	4.522
	Sample 2	1CLP2	42.0	21.0	69.6	4.4	6.282	4.532
	Sample 3	1CLP3	42.0	21.0	76.7	4.2	5.950	4.293
	Average		**42.0**	**21.0**	**72.5**	**4.2**	**6.166**	**4.449**
7 Days	Sample 1	7CLP11	42.0	21.0	74.0	3.8	6.400	4.618
	Sample 2	7CLP12	42.0	21.0	72.1	4.0	5.909	4.263
	Sample 3	7CLP13	42.0	21.0	71.7	4.1	6.631	4.784
	Average		**42.0**	**21.0**	**72.6**	**4.0**	**6.313**	**4.555**
28 Days	Sample 1	28C1	42.0	21.0	73.9	4.2	6.375	4.600
	Sample 2	28C2	42.0	21.0	72.0	3.8	5.975	4.311
	Sample 3	28C3	42.0	21.0	72.7	4.0	6.818	4.919
	Average		**42.0**	**21.0**	**72.9**	**4.0**	**6.389**	**4.610**

Table B.4 Brazilian Indirect tensile strength used on 4mm thickness for TSL B on reinforced shotcrete specimen.

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Reinforced	Specimen No.	Diameter mm	Thickness mm	Mass grams	TSL Thickness mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	Sample 1	CLPR1	42.0	21.0	73.0	4.1	6.493	4.685
	Sample 2	CLPR2	42.0	21.0	75.9	3.8	6.594	4.758
	Sample 3	CLPR3	42.0	21.0	77.2	3.9	6.391	4.611
	Average		**42.0**	**21.0**	**75.4**	**3.9**	**6.493**	**4.684**
1 Day	Sample 1	1CLPR1	42.0	21.0	75.0	4.0	6.618	4.775
	Sample 2	1CLPR2	42.0	21.0	76.7	4.0	6.833	4.930
	Sample 3	1CLPR3	42.0	21.0	75.5	4.0	6.465	4.665
	Average		**42.0**	**21.0**	**75.7**	**4.0**	**6.639**	**4.790**
7 Days	Sample 1	7CLPR1	42.0	21.0	77.6	4.0	7.366	5.315
	Sample 2	7CLPR2	42.0	21.0	71.9	4.0	6.666	4.810
	Sample 3	7CLPR3	42.0	21.0	75.1	4.0	6.435	4.643
	Average		**42.0**	**21.0**	**74.9**	**4.0**	**6.822**	**4.922**
28 Days	Sample 1	28CR1	42.0	21.0	75.9	4.0	6.568	4.739
	Sample 2	28CR2	42.0	21.0	72.5	4.0	7.010	5.058
	Sample 3	28CR3	42.0	21.0	76.3	4.0	8.294	5.984
	Average		**42.0**	**21.0**	**74.9**	**4.0**	**7.291**	**5.260**

Table B.5 Brazilian Indirect tensile strength used on 4mm thickness for TSL C on unreinforced shotcrete specimen.

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Unreinforced	Specimen No.	Diameter mm	Thickness mm	Mass grams	TSL Thickness mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	sample 1	M0	42.0	21.0	76.9	4.0	6.012	4.338
	sample 2	M2	42.0	21.0	73.6	4.0	6.218	4.486
	sample 3	M3	42.0	21.0	75.3	4.2	6.301	4.546
	Average		**42.0**	**21.0**	**75.3**	**4.1**	**6.177**	**4.457**
1 Day	Sample1	1M1	42.0	21.0	70.8	4.1	6.777	4.890
	Sample2	1M2	42.0	21.0	71.9	4.2	5.898	4.255
	Sample3	1M4	42.0	21.0	71.4	4.0	5.967	4.305
	Average		**42.0**	**21.0**	**71.4**	**4.1**	**6.214**	**4.483**
7 Days	Sample1	7M1	42.0	21.0	77.1	4.0	5.914	4.267
	Sample2	7M2	42.0	21.0	74.6	3.9	6.966	5.026
	Sample3	7M3	42.0	21.0	76.9	3.8	5.985	4.318
	Average		**42.0**	**21.0**	**76.2**	**3.9**	**6.288**	**4.537**
28 Days	Sample1	28M1	42.0	21.0	73.6	3.9	7.086	5.113
	Sample2	28M2	42.0	21.0	74.6	4.1	7.597	5.481
	Sample3	28M3	42.0	21.0	71.7	3.9	7.133	5.146
	Average		**42.0**	**21.0**	**73.3**	**4.0**	**7.272**	**5.247**

Table B.6 Brazilian Indirect Tensile Strength used on 4mm thickness for TSL C on reinforced shotcrete specimen.

Curing Time	SPECIMEN PARTICULARS		SPECIMEN DIMENSIONS				SPECIMEN TEST RESULTS	
	Sample Type. Reinforced	Specimen No.	Diameter mm	Thickness mm	Mass grams	TSL Thickness mm	Max. Failure Load kN	Brazilian Tensile Strength Mpa
2 Hours	sample 1	MR1	42.0	21.0	74.1	4.1	6.396	4.615
	sample 2	MR2	42.0	21.0	74.2	4.2	6.878	4.962
	sample 3	MR3	42.0	21.0	72.7	3.9	6.257	4.514
	Average		**42.0**	**21.0**	**73.7**	**4.1**	**6.510**	**4.697**
1 Day	sample 1	1MR1	42.0	21.0	80.5	4.0	6.623	4.778
	sample 2	1MR2	42.0	21.0	74.0	3.8	6.761	4.878
	sample 3	1MR3	42.0	21.0	76.3	4.2	6.892	4.973
	Average		**42.0**	**21.0**	**76.9**	**4.0**	**6.759**	**4.876**
7 Days	sample 1	7MR1	42.0	21.0	78.0	4.2	7.108	5.128
	sample 2	7MR2	42.0	21.0	77.6	4.1	7.077	5.106
	sample 3	7MR3	42.0	21.0	72.0	3.9	6.279	4.530
	Average		**42.0**	**21.0**	**75.9**	**4.1**	**6.821**	**4.922**
28 Days	sample 1	28MR1	42.0	21.0	74.6	3.9	7.503	5.413
	sample 2	28MR2	42.0	21.0	71.7	4.1	8.671	6.256
	sample 3	28MR3	42.0	21.0	76.5	3.9	7.994	5.768
	Average		**42.0**	**21.0**	**74.3**	**4.0**	**8.056**	**5.812**

Appendix C

Table C.1 Shotcrete (*E = 21 GPa) and TSL (*E=10 GPa) – Vertical query line on the Loaded Brazilian Disc Specimen (Rizwan, 2014) .

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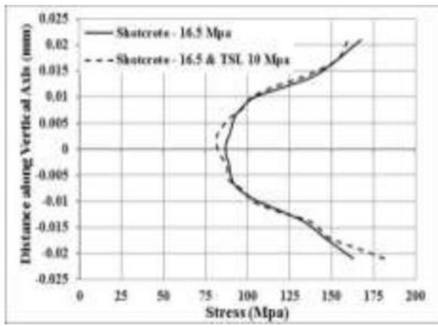
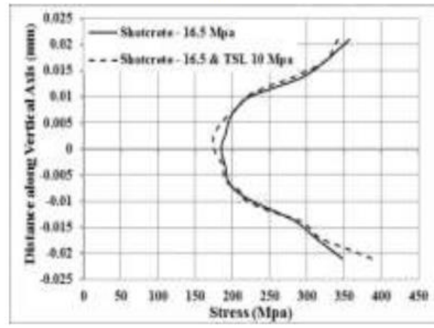
<tr><th>S/no</th><th>Stress</th><th>Half Displacement</th><th>Full Displacement</th></tr>
<tr><td>1</td><td>σ_1</td><td>
</td><td>
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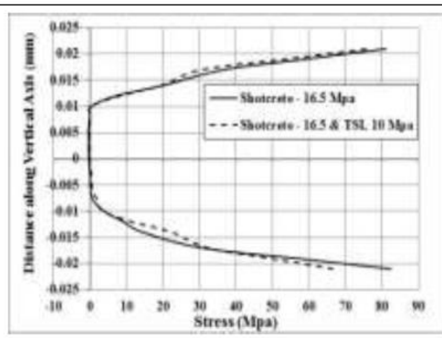
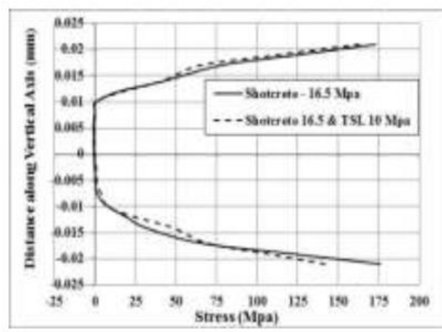
<tr><td>2</td><td>σ_2</td><td>
</td><td>
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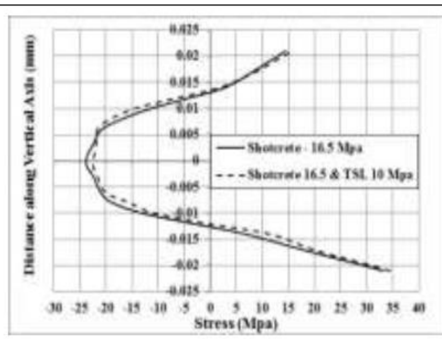
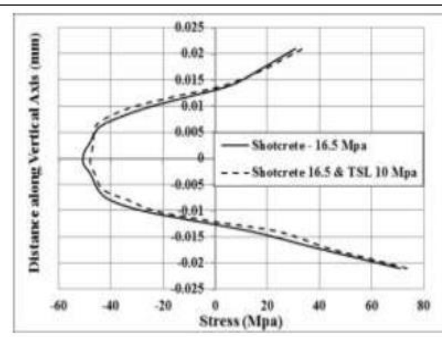
<tr><td>3</td><td>σ_3</td><td>
</td><td>
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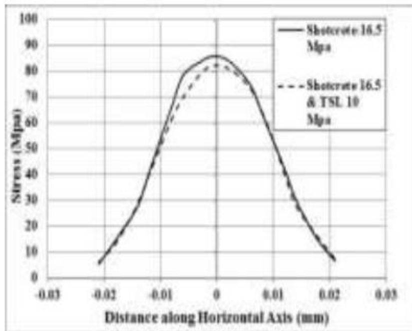
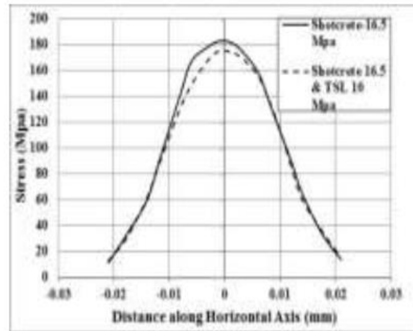
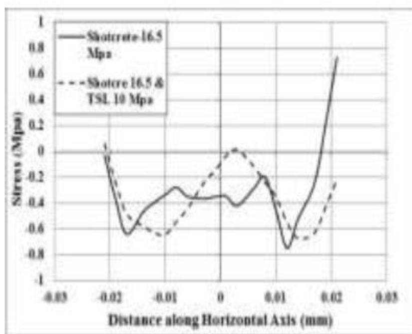
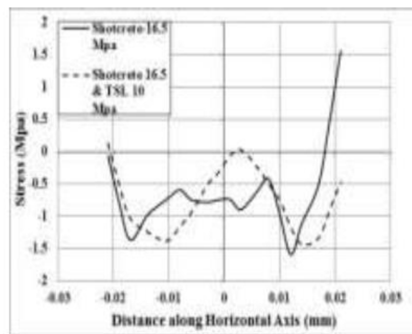
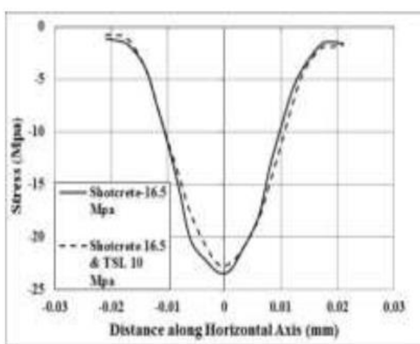
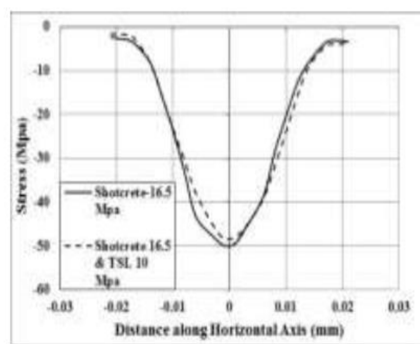
Table C.2 Shotcrete (*E = 21 GPa) and TSL (*E=10 GPa) – Horizontal query line on the Loaded Brazilian Disc Specimen (Rizwan, 2014) .

S/no	Stress	Half Displacement	Full Displacement
1	σ_1		
2	σ_2		
3	σ_3		

Appendix D

Figure D.1 Brazilian test on TSL A coated on unreinforced shotcrete specimen

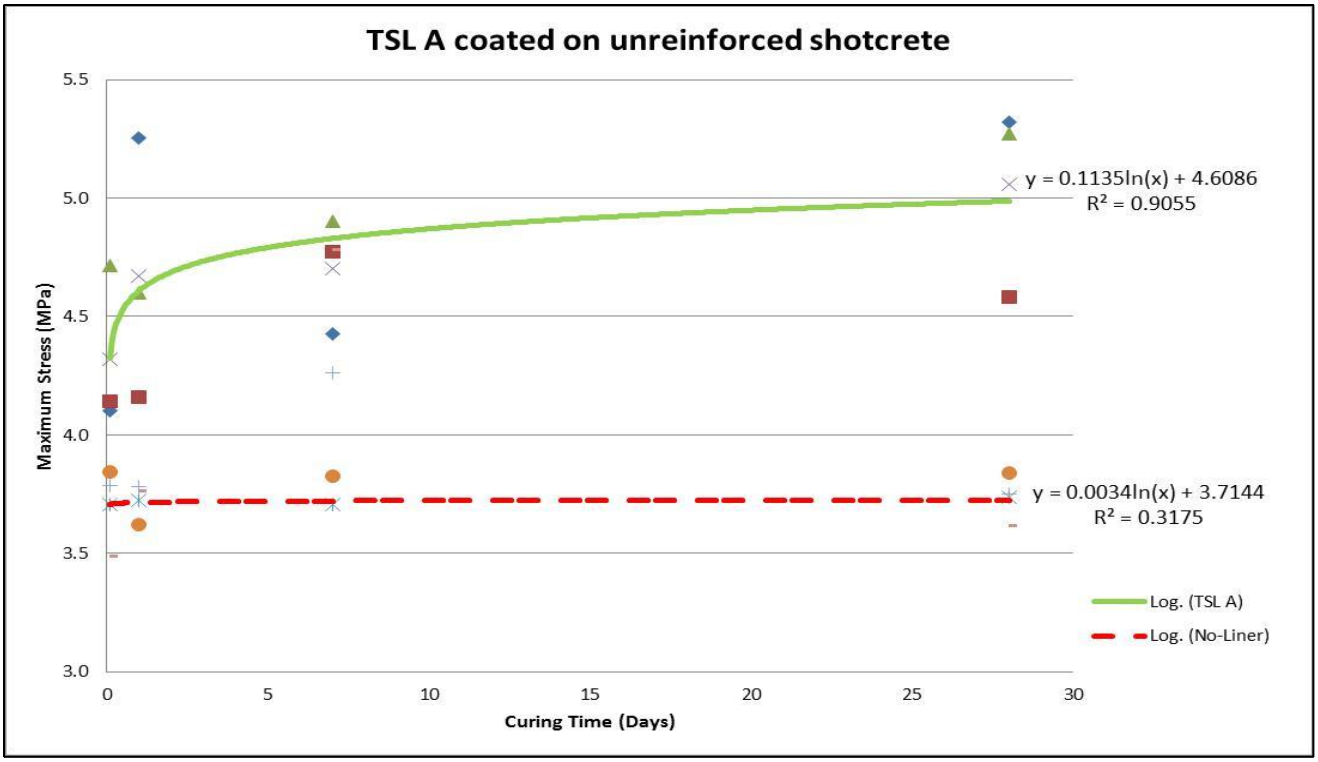


Figure D.2 Brazilian test on TSL A coated on reinforced shotcrete specimen

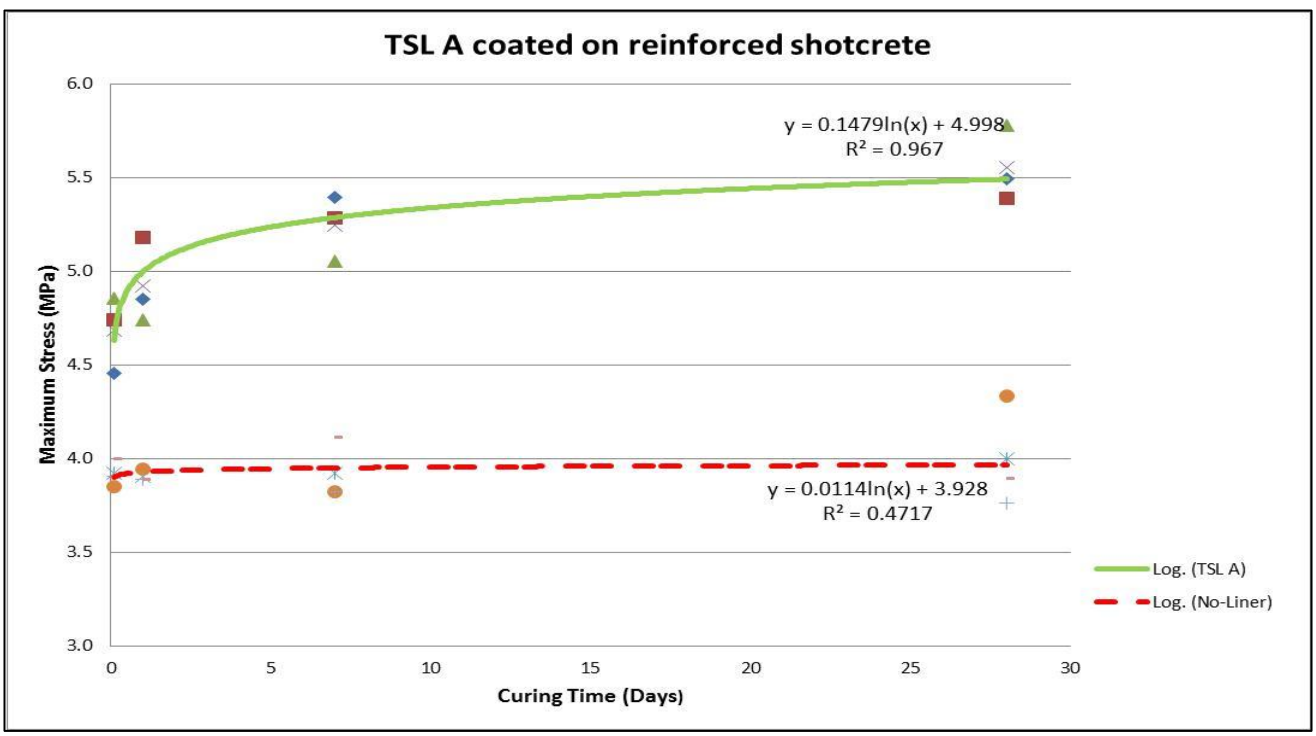


Figure D.3 Brazilian test on TSL B coated on unreinforced shotcrete specimen

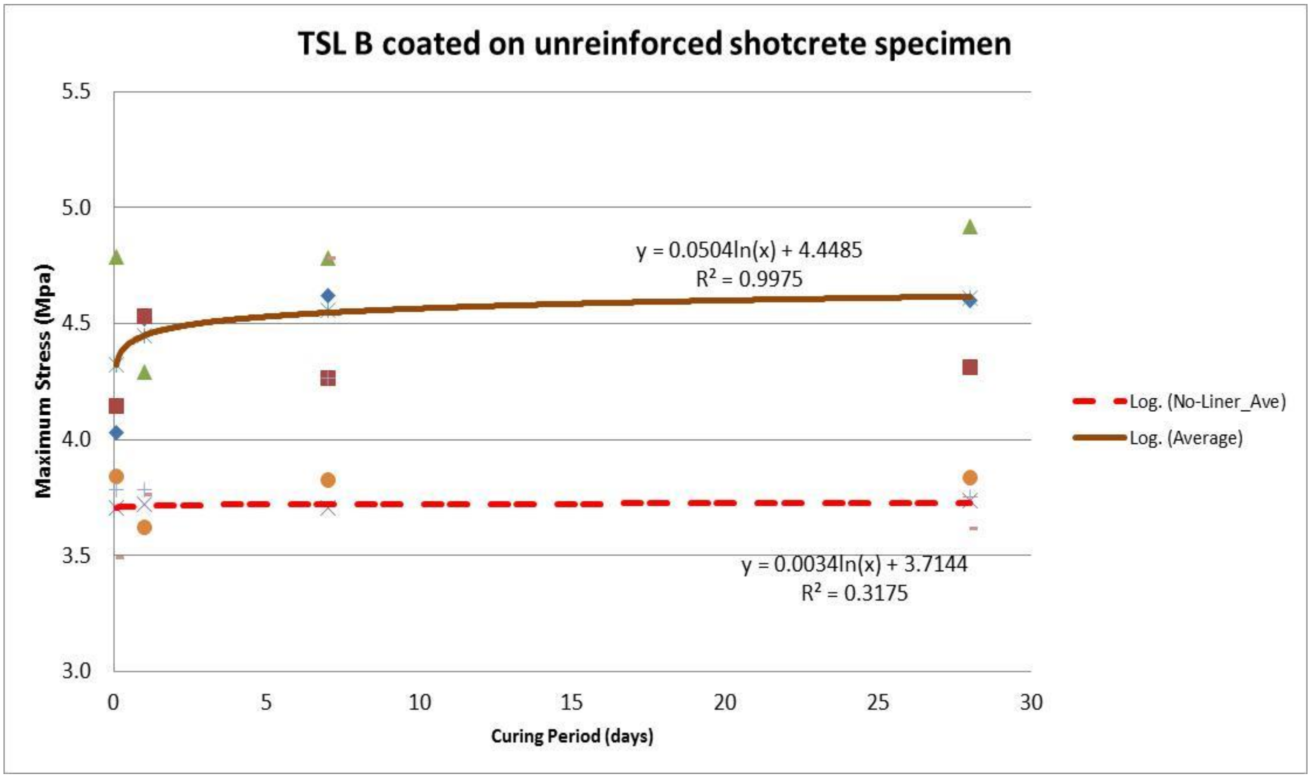


Figure D.4 Brazilian test on TSL B coated on reinforced shotcrete specimen

Figure D.5 Brazilian Test on TSL C coated on unreinforced shotcrete specimen

Figure D.6 Brazilian Test on TSL C coated on reinforced shotcrete specimen