DEVELOPMENT OF TESTING METHODS FOR COMPARATIVE ASSESSMENT OF THIN SPRAY–ON LINER (TSL) SHEAR AND TENSILE PROPERTIES

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A thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 2011

DECLARATION

I, Halil Yilmaz, declare that this thesis is my own unaided work. Where use has been made of the work of others, it has been duly acknowledged. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before in any form for any degree or examination in any other University.

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ABSTRACT

Spray-on linings in the form of shotcrete have been in use in the mining industry for the past 60 years. The introduction of Thin Spray-on Liners (TSLs) in mining has been more recent (approximately 20 years). There is no doubt that TSL technology, although it has great potential for success, will go through an extremely difficult implementation period as was experienced by shotcrete. Publications describing successful TSL application experiences have started to emerge. However, confusion and carelessness regarding standards, specifications, and design guidelines around the world will have to be addressed to overcome the teething problems experienced by the new TSL technology. There are still many aspects of TSLs that need to be investigated to provide information necessary to formulate a proper TSL design. This thesis is intended to bridge some of the knowledge gaps existing in the area of the mechanical property testing of TSLs.

A literature review provides the background to the concept of TSL technology and gives a summary of the previous testing methods performed to date. The shortcomings of these testing methods are emphasised and their applicability as standard testing methodologies is discussed. In the absence of sound test methods, the assessment of TSL suitability and performance is mainly based on opinion or short term visual observations at mine sites. The description and reporting of previous testing on TSLs, in general, have not been done appropriately and have often been found to lack critical information. Therefore, the absence of generally agreed testing methods results in a lack of parameters which are important in evaluating the quality and performance capabilities of available TSL products. For this reason, the development of appropriate and acceptable testing methods for TSLs is urgently needed so that design standards and requirements can be formulated.

This thesis focuses on four laboratory testing methods. The development of two new laboratory testing methods for the quantification of mechanical properties of TSLs is described, namely, shear-bond strength testing and material shear strength testing. In addition, two other existing testing methodologies were adopted with minor

modifications and included in the TSL testing programme. These are material tensile strength testing and tensile-bond strength testing. Large numbers of tests were carried out for each method as part of the research described. The results of all four testing methodologies have been collated and analysed in an attempt to make the comparison of the mechanical properties of various TSLs and shotcrete possible.

Each of the four testing methodologies is allocated a single chapter of the thesis, with particular focus on the details of the test considerations, and descriptions of apparatus, specimen preparation and test procedures. The results of testing are provided and analysed for the comparison of TSL performance in each of these chapters. A collective and comparative analysis and discussion on the test results is included.

Approximately 4000 tests were performed on 32 TSL products from 12 companies as well as one brand of plain shotcrete. Various factors such as temperature, humidity, substrate type and condition, rate of loading, specimen size, and storage duration significantly influence the performance of TSLs. All of these factors were considered, but their values or conditions remained fixed in the testing programme to limit the number of tests. However, an exception was the curing time, which was selected as the main test variable. Curing times from 1 day to 28 days were used in all the tests.

Subsequent analysis of the test results for the new testing methods provides a comparison of TSLs based on the measured strength properties. Comparison of TSL with shotcrete strength has also been possible through the same test methods, which have not been performed on shotcrete before. The test results also show an obvious strength increase with increasing curing time as expected. The simplicity and ease of performing these tests and the easy understanding of results compared with previous TSL testing has assisted in their general acceptance. The response from the mining industry and the product manufacturers towards the testing methodologies developed under the scope of the research in this thesis has been positive. The test results have been well received and have been used with confidence in the selection, quality control and comparative assessment of TSLs.

The extensive laboratory testing programme and the development of two new laboratory testing methods for TSLs, described in this thesis are considered to be a significant contribution to the state of the art of TSL technology. The database of test results and findings from this research can be used by liner manufacturers as a reference for the comparison of their products. Further improvements and development of new TSL products with better qualities will then assist in the further implementation of TSLs in the mining and civil engineering industries.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude on the assistance and support rendered by the following persons and institutions:

- Professor T. R. Stacey for his supervision, guidance, encouragement and motivation throughout this research.
- The Safety in Mines Research Advisory Committee (SIMRAC) for granting me the opportunity to embark on this research and for their funding.
- The School of Mining Engineering-University of the Witwatersrand for providing the facilities needed to carry out the laboratory tests at GENMIN Laboratories.
- Mr Dave Henderson for his valuable workshop assistance without which this research would not have seen its completion.
- The TSL manufacturers for providing their much needed material in the test trials. These manufacturers are (in alphabetical order); BASF Construction Chemicals, Carbontech, CHC Chemicals, Chryso Southern Africa, Concor Technicrete, Concrete Admixtures, Concrete Lining Products (CLP), Degussa Construction Chemicals (MBT), Hydroflex Pty Ltd, Minova RSA, Nico Durand RC, NS Consultancy, Precrete-Nozala, Pumachem and SA Mining Engineering Supplies.
- Dr. C. Musingwini for help with proof-reading the draft thesis.
- Family and friends for their motivation and support.

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LIST OF SYMBOLS AND ACRONYMS

τ_b	Shear-bond strength (Pa)
σ_s	Shear strength (Pa)
σ_t	Tensile strength (Pa)
σ_{tb}	Tensile-bond strength (Pa)
D	Diameter of rock core (mm)
A	Core-TSL contact or failure area (m^2)
F	Load at failure (N)
t	Thickness of a test specimen (mm)
d_1	Diameter of steel-punch (mm)
d_2	Diameter of bottom plate hole (mm)
r	TSL radius (mm) in tensile-bond strength testing
ΣCV	the sum of coefficient of variations at each curing time for a particular testing method
N	the total number of curing times at which testing takes place
RI	Repeatability Index
SIMRAC	Safety in Mines Research Advisory Committee
TSL	Thin Spray-on Liner
UCS	Uniaxial compressive strength (MPa)
EFNARC	**E**uropean **F**ederation of **N**ational **A**ssociations **R**epresenting producers and applicators of specialist building products for **C**oncrete
ASTM	American Society for Testing Materials
BS	British Standards
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
CAN/UCL	Canada-Underwriters Compliance Listing
RSA	Republic of South Africa
SAIMM	The Southern African Institute of Mining and Metallurgy
CD ROM	Compact disc read-only medium

CHAPTER 1 INTRODUCTION

One of the major causes of instability in underground excavations and resulting rock-related accidents is the lack of areal support coverage between support units in these excavations. Rock tendons or props do not provide adequate support for fragmented rock and therefore blocks of rock from the excavation boundary can easily detach due to gravity, seismic activity or blasting-induced vibrations. Potvin (2002) stated that surface support has been widely used in order to combat rockfalls and resulting injuries and fatalities in the vicinity of active faces (production excavations or development ends), where workers spend most of their time. However, Potvin (2002) further stated that rockfalls still remain the major cause of injuries and fatalities in modern underground mines.

Webber-Youngman and Van Wyk (2009) reported that fall of ground (FOG) fatalities represented 39% of total number of fatalities in underground mines in South Africa between August 2006 and March 2009. Gold mines, with their great depth and seismicity, represented 52% of these fatalities. Such statistics are similar for other mines in rest of the world. The study in the underground metalliferous sector of the Australian Mining industry by Potvin and Nedin (2003) indicated that half of the fatalities in the period 2000-2001were caused by rockfalls.

Various researchers have analysed the size of rock falls that caused injuries. According to Potvin *et al* (2001), over 90% of rockfall injuries involve rocks smaller than one tonne. Most of the rockfall injuries (83%) occurred within 10 metres of an active development face (Potvin and Nedin, 2003). Another study of 273 rock-related injuries and fatalities in metal mines in USA by NIOSH in 1996, found that over two thirds involved rocks of less than 12 kg (Spearing *et al*, 2009). Research during the early 1990s showed that about 80% of all rock falls in underground mines in South Africa involved less than a 1.0 m thickness of rock (Spearing 1990; Roberts 1991). These accident and size statistics indicate that an improvement in surface support technology could be a significant contributor to improved safety.

Lack of areal support coverage is the main factor for the problem of key-block instability. Sometimes it only takes one block, in the complex situation surrounding an excavation, to fall out, possibly due to gravity, to lead to substantial instability (Henderson and Louw, 2001). An understanding of the concept of key-block behaviour is necessary to understand the importance, appropriateness and effectiveness of the use of surface support under these conditions.

The stability of underground or surface excavations will be affected by the presence of natural rock weaknesses (such as joints, faults and bedding planes), as well as stress or blast-induced fractures. The combinations of these weakness planes result in the formation of various sizes of blocks that need to be supported. According to key-block theory if all potentially unstable wedges are supported, then the remainder of the rockmass will remain stable due to an inability to move (Espley-Boudreau, 1999). Potvin *et al* (2001) suggest that the current approaches in controlling small pieces of freshly exposed rocks near the active face can be improved by the use of liners. Liners cement fractures in the rockmass and hence provide resistance to shearing and fall-out of key blocks (Stacey, 2001). One of the main goals of a liner is, therefore, to contain any loose materials, thus reducing or preventing the unravelling, slabbing or loosening of blocks, and finally enhancing the stability of a greater area of rockmass due to retention of larger pieces (Lacerda and Rispin, 2002). The mobilization of the interactions between rock blocks takes place at small rock displacements that are sufficient for the liner to start functioning (Tannant, 2001).

Thin Spray-on Liners (TSLs) are an emerging alternative surface support system for underground rock support, which are receiving increasing attention from the mining industry around the world (Tannant, 2001). According to Tannant (2001) the performance characteristics of TSLs lie between those of shotcrete and wire mesh. New TSL materials are continuously being developed and tested in many parts of the world as replacements for conventional surface support methods such as wire mesh, shotcrete or fibrecrete (Tannant, 2001). The installation of traditional surface support has been associated with many operational, logistical and cost disadvantages due to large material volumes. Logistical problems exacerbate the situation in the context of deep level mines where long tramming distances are common. In contrast, the “thin” nature of

TSL applications, implying much smaller volumes of material, provides numerous advantages in these areas.

1.1 Terminology

In Australia at the Perth Workshop that was held during the 1st International Seminar on Mine Surface Support Liners: Membrane, Shotcrete and Mesh in August 2001, the term "Thin Spray-on Liner (TSL)" was agreed upon to describe a thin layer of surface support made from plastic, polymer or cement based compositions. A detailed definition of each word follows to assist in the complete understanding of this new surface support technology.

1.1.1 Thin

The following definitions for the term "thin" are the most relevant ones for TSLs.

- "*Having opposite surfaces or sides relatively close together*" (Concise Oxford English Dictionary, 2004),
- "*Having little extent from one surface to its opposite; measuring little in cross section or diameter*" (Merriam-Webster's Dictionary).

A TSL material layer of about 5 mm is generally the agreed thickness, which may range between 2 mm and 10 mm in field applications. The thickness range may be narrowed by strict control measures or by the skill of experienced operators.

1.1.2 Spray-on or sprayed

Concise Oxford English Dictionary (2004) describes the term "sprayed" as "*A liquid preparation which can be forced out of an aerosol or other container in a spray; application in a spray; cover or treat with a spray; be sent through the air in a spray; scatter over an area with force*".

Sealants, TSLs, shotcrete and in some cases paint (for demarcation of large areas) are known sprayed materials in mining. The pressure requirement for pumping more viscous materials such as shotcrete and TSLs is higher. All sprayed materials, for the purpose of rock support, are expected to solidify after their application on a rock surface.

1.1.3 **Liner or lining**

A good description of lining is provided by WordNet 2.0 (2001) as "*A protective covering that protects an inside surface; providing something with a surface of a different material*".

All underground excavations can be regarded as having inside surfaces. On the other hand, liners in mining can be applied in opencast operations where the excavation surface may be regarded as an outside, or sun-exposed, surface.

Although shotcrete is a sprayed lining, it does not satisfy the thickness criterion for being a thin liner. In practice, shotcrete thickness will vary commonly from 25mm to 150 mm depending on the support requirements. In some mining operations, in which quality control is unsatisfactory, even thinner "flash coatings" commonly have a thickness of the order of about 10 mm (Stacey, 2010).

The thicknesses of sealants and paint are less than 1 mm, but they are not considered as support components that provide assistance to ground stabilisation. If, in the future, the performance of sprayed materials as thin as 1 mm or less meets the support requirements, then such materials could be called "Ultra-thin Spray-on Liners".

1.2 Definition of the problem

The application of TSL technology in the mining industry is still in its infancy (Tannant, 2001). The mechanisms whereby a sprayed coating acts to provide support are not fully understood (Leach, 2002). Although these statements were made nearly ten years ago, they are considered to be relevant still today. The amount of research, and therefore the knowledge generated in terms of TSL support design, determination of TSL mechanical properties, and feedback from the TSL end-users at the mines, have been limited. One area where the research effort has been inadequate is the development of acceptable, standard laboratory testing methods to determine the mechanical properties of TSLs.

A range of tests exists for traditional liner-shotcrete to allow determination of mechanical and physical properties for design calculations and quality assurance programmes (Naismith and Steward, 2002). TSLs, on the other hand, require the development of novel test methods and the researchers in the testing arena of TSLs have attempted a number of testing methodologies as reviewed in Chapter 2. The validity of these test procedures and results is often questioned by operators and researchers alike (Archibald, 2001).

To date, tensile and tensile-bond strength tests have met with general acceptance from TSL stakeholders; however, there is a need for modifications to these tests since they were originally developed for plastic materials. Other tests developed have not been as influential due to inconsistent testing procedures. The description and reporting of these tests, in general, have not been done accurately. They are often found to lack critical information. In addition, certain tests could only be performed within specialized laboratory sites (Archibald, 2001). Their acceptance was also not well supported due to the complex nature of the testing process and difficulties in interpreting the results.

Standard laboratory tests are needed to be routinely used to reliably evaluate the overall performance capabilities of TSL products in the market (Spearing *et al*, 2001; Nagel and Joughin, 2002). In the absence of standard test methods it is not possible to perform this duty. End users in such cases are forced to assess the performance of TSL applications and suitability of TSLs by carrying out short term visual observations. Furthermore, TSL support design and implementation require the backing of information derived from laboratory testing.

Successful TSL applications, which are discussed in more detail in Chapter 2, have recently resulted in an increase in the number of TSL manufacturers and the variety of TSL products, and this number is expected to increase further in the future. Manufacturers often make claims regarding the quality of their products that need to be checked for validity. The knowledge of only two material properties is insufficient for any sensible quality assessment. There are other important properties such as shear, tear, bend, punch and compressive strengths. Consequently, there is a considerable need for the development of a suite of simple laboratory testing techniques for TSLs, in addition to the already established tensile and tensile-bond strength tests, to better quantify TSL material properties and to facilitate an unbiased assessment and comparison (Tannant, 2001). A decision in this research was therefore made to develop tests for the determination of shear strength properties (shear-bond and material shear strengths) with the aim of addressing the lack of testing in this area. Shear properties are considered to be important physical characteristics that would help in quantifying "*a material's expected support performance behaviour*" (Archibald, 2001, p3).

As TSL technology matures, the setting of standards and product testing criteria will be necessary if mines are to be able to select appropriate TSL products which meet minimum and acceptable levels of performance (Archibald, 2001).

1.3 Research objectives

The primary objective of the research carried out has been to develop new small scale standard laboratory testing methods to measure the mechanical properties of TSL's under laboratory conditions. Special emphasis is given on the shear strength properties, namely the shear-bond strength and material shear strength. The tensile strength and tensile-bond strength tests will be adopted with modifications to suit TSL testing. Once the testing methods are well established, the curing period will be the main test parameter to be checked for sensitivity. Ultimately, the overall aim is to use the strength database generated from these four tests to make a comparison of the mechanical properties of TSLs and shotcrete possible.

The research methodology adopted to meet these research objectives included the following:

- A survey of worldwide literature to identify previous testing methods for TSLs and various applications.
- Design of new testing methods for shear-bond and material shear strengths based on the insight gained from the literature review.
- Adoption and inclusion of tensile and tensile-bond strength testing in the testing programme.
- Manufacture of test apparatus and development of test procedures.
- Initial test trials.

- Identification of problem areas on specimen preparation, test set-up and test execution, and necessary modifications to the testing equipment and test procedures.
- Performing of re-trials and re-modifications until confidence in the test results is established.
- Obtaining as many TSL products as possible from different manufacturers, and including shotcrete as a material to be tested.
- Commencement of a comprehensive testing programme on TSLs and shotcrete using the curing time as the main test variable. Carrying out sufficient number of tests to enable a statistically valid evaluation.
- Analyses of the test results and comparison of the TSLs and shotcrete tested, based on their measured properties.
- Presentation of the results to the manufacturers and end users in the form of published conference papers and journal papers, to receive feedback.

1.4 Scope and limitations

The development of standard testing methodology under laboratory conditions causes limitations on the factors involved in the execution of testing methodology. Environmental conditions, specimen dimensions and parameters during test execution have to be specified to prevent possible influence on the test results. If the loading rate, for example, varies between tests, then the condition for testing method to be considered as a standard test would not be satisfied.

The capacity of testing equipment and the dimensions of test area necessitated the preparation of small scale specimens. This limitation, in fact, assisted in the preparation of more samples as compared to large scale test set-ups.

The focus in this research has been on the measurement of the mechanical properties of liners, and no chemical or occupational hazard (health and safety) related testing was considered. The testing programme included many types of TSL products and a shotcrete brand. The testing has been carried out under normal laboratory environmental conditions. Six curing times were planned with 1 day and 28 days being the minimum and maximum times respectively. Four curing times within the first week were used to capture the early strength development. Five specimens were prepared for each curing time and therefore 30 specimens were required for each of the four testing methods envisaged. The specimen preparation and completion of testing for a single product therefore required approximately one month. The preparation of all the specimens in a single day, and the completion of testing at a particular curing time were found to be strenuous due to the time-demanding nature of both specimen preparation and testing. Therefore, the effect of the following aspects on the test results was not investigated in this research, primarily due to time constraints, since their involvement would have implied an enormous amount of additional tests. These aspects were:

- Sensitivity to environmental factors (particularly temperature and humidity).
- Underground trials and testing in underground environmental conditions.
- Sensitivity to changes in specimen size or thickness.
- Creep and dynamic loading (loading rate).
- Various substrate rock types and strengths.
- Various substrate roughness and surface conditions such as oil, dust and water.
- Sensitivity to spraying compared with hand pouring.
- Mixing method, speed and duration.

Since the research mainly concentrated on laboratory testing, numerical modelling was also kept outside the scope of this thesis.

1.5 Facilities available

The facilities required were available within the School of Mining Engineering, and the liner materials were obtainable from manufacturers that were willing to participate in the development of TSL testing methods. The servo-controlled Mechanical Testing System-815 was available for specimen loading, either in load or displacement control modes. Means of data capturing and processing were also available with a state of the art laptop computer that is Dell Precision M6300. Any test design or alteration of test setup was possible using the material and equipment available in the School's workshop, which also accommodates a skilled technician.

1.6 Content of the thesis

This thesis, in which the development of new laboratory test methods is the underlying theme, is presented in nine chapters. The first chapter is of an introductory nature and deals with the reasons for the research described in this thesis. A survey of international literature on testing methods previously employed on TSLs and TSL applications is presented in Chapter 2. The material presented in Chapter 3 forms the groundwork for the development of the modified and new testing methods that are detailed in Chapters 4, 5, 6 and 7. Each of the four testing methods is discussed in a separate chapter, giving a detailed account of the testing apparatus, procedures and the results. The main analysis and various comparisons of the test results are given in Chapter 8. Finally, the major outcomes, achievements and conclusions are presented in Chapter 9. The appendices include the data sheets of previous test methods on TSLs, and the graphs and tabulated results of tests using the four testing methods.

CHAPTER 2 REVIEW OF RELEVANT LITERATURE ON TSLS

Based on a review of relevant literature on the subject, this chapter gives an historical overview of the development of TSLs. The advantages and disadvantages of using TSLs and a summary of various TSL applications are presented in the form of several tables. Previous testing methods used on TSLs are described in data sheets and the findings from the most commonly performed tests are briefly outlined. Tables are the preferred method of presentation of information in this literature review so that the information is more easily organised, displayed and understood. Tables also enabled the condensation of vast amount of information that would have, otherwise, required a greater space.

TSLs represent a relatively new area of rock support. Stacey (2010) observed that in the early 2000's there was a surge of interest in TSLs and hence the publication of numerous papers. Since then, however, the implementation of TSLs in mining and civil engineering has been slow, and publication activity has been correspondingly sparse. The absence of significant recent publications is reflected in the following review.

2.1 TSL history

The idea of TSLs was originated by the thought that a liner as thin as 5 mm should perform the same as or even better than shotcrete. Unlike shotcrete, which has been around for almost a century and has been used since the 1950s in underground mines (Spearing *et al*, 2001), TSLs have only been used since the 1980s. The term 'superskin' was introduced to the mining industry in 1993 to define sprayable material that will set hard and remain stable with a high yield and high performance (Reynolds and Leach, 2002). Reynolds and Leach (2002) also identified a number of polymer based materials, polyurethanes and cement skins that were tested on surface and underground in the period 1993 to 2000. Liners often developed for applications such as the sealing of dam walls, construction and other civil engineering uses (Borejszo and Bartlett, 2002) represent materials that have been used as TSLs. Initial TSLs were mainly designed as rock sealants to limit the weathering of rock (Spearing and Champa, 2000; Spearing *et al*, 2009) and later on were intended to be used as an alternative to mesh or shotcrete. The first trials on TSL technology in Canada were initiated in the late 1980's (Archibald *et al*, 1992). Bartlett (2002) reported the widespread application of thin skin liners (sealants) and chainlink mesh, prior to shotcrete application, at Premier Mine in South Africa for tunnel support as early as the 1980's. The purpose was to seal the kimberlite in an attempt to prevent the decomposition at the kimberlite/shotcrete interface, thus permitting the shotcrete to be an effective support element.

TSL technology has come a long way from the time the first single component experimental coatings were tested (Lacerda and Rispin, 2002). Spearing and Champa (2000) reported that Urylon Plastics Inc. from Canada and CSIR Miningtek from South Africa basically pioneered the TSL research. Urylon developed a reactive system based on polyurethane and Miningtek developed a non-reactive system based on polymer emulsions. In 1992, INCO Ltd, the largest nickel mining company in Canada, tried the only available TSL product at that time called Mineguard™ for underground rock support (Espley *et al*, 2001). At that time, according to Archibald (2001), six plural component polymer materials had been developed and tested during the late 1990's worldwide, five of these being in Canada.

Lacerda and Rispin (2002) were of the opinion that, due to a number of factors, including occupational health risk and mine safety regulations, it has taken quite some time for the development of non-hazardous TSL products. A single component "glue emulsion" type of TSL, for example, was found to be impractical for normal mine use at a USA mine in 1994 because of health and safety requirements.

Tannant (2001) stated that by the mid to late 1990's news of spray-on liners being used in Canada's hard-rock underground mines reached many other interested manufacturers and vendors of a wide variety of spray-on products. Falconbridge Ltd, a large Canadian mining company, began its own research effort to find appropriate liner materials. According to Tannant (2001), in the late 1990's a hybrid polyurethane/polyurea mixture called Rockguard was introduced and included in the field trials. He also indicated the emergence of the South African versions of latex-based TSLs Everbond and Evermine in 1996. By the new millennium the variety of new products in the development and testing stages increased steadily in Canada. A polyurea-based product called RockWeb, a water-based, polymer-modified cementitous product called TekFlex and a methacrylate-based product called Masterseal 840R01 were given as examples by Tannant (2001). The list of TSLs used worldwide and within the framework of this thesis is provided in Section 2.5.

According to Potvin and Nedin (2003), the Australian Mining industry’s interest in new alternatives for surface support systems was “fuelled” in 2000, with reports that the Fraser mine in Canada was using a commercial TSL as a standard mode of surface support. Meanwhile, product suppliers such as MBT and Fosroc were performing TSL trials in collaboration with a number of Australian mining operations.

Many organizations have subsequently tried to develop other TSL technologies (Rispin and Garshol, 2003). Many products tested did not possess adequate physical or chemical properties. The production of a number of TSLs has been stopped and their names are no longer referred to. However, newer products are continuously being developed and introduced. The increase in the number of new TSLs in the market has been significant.

Recently, TSLs have been tailored to specific underground and rock-related applications, with many success stories (Borejszo and Bartlett, 2002). A list of these applications is provided in Table 7. Recent developments in TSL support continue to receive increasing attention by the mining industry around the world due to their considerable operational benefits, which have the potential to greatly reduce mining costs (Tannant, 2001).

2.2 Advantages of using TSLs

TSL product developers, researchers and mine users have significant experience in the use and application of TSLs. Advantages of TSLs are recognised and mentioned extensively in the literature. The importance and the need for the widespread application of TSLs in the mining world will be more understandable once these advantages are reviewed.

The advantages of using TSLs can be grouped into geotechnical and non-geotechnical categories. The benefits regarding rock reinforcement, ground stability, support performance and TSL material/mechanical properties are considered to be geotechnical, and these benefits are listed in Table 1 and Table 2.

Table 1. Geotechnical advantages of TSLs with respect to rock reinforcement, ground stability and support performance

Rock reinforcement - ground stability - support performance	Source
Confine ground movement as soon as it is applied. Thus, ground deterioration may be slowed and even stopped at an early age.	r
Unravelling or slabbing or loosening of small blocks of rocks is reduced or prevented and the integrity of rockmass is preserved.	o, r
Friction or tension bolts maintain full bolt length support (rock at bolt collar does not deteriorate).	r
Initial ground support can be achieved as quickly as possible and in the early stages before it moves too far down the ground reaction curve.	a, b, r
Advanced headings could be sprayed prior to mucking and bolting providing immediate temporary support.	a, r
Provides effective surface support by containing the blocky hangingwall between roof bolts, having similar capabilities of mesh to hold loose rock in place.	i, j, n
Provides active support by becoming reactive with the minimal of rock deformation (in the order of millimetres) and thus mobilizing rock interactions and generating support resistance under low strain conditions. Therefore, rockfalls can be prevented from happening in the first place.	a, p, s, t, u
In situations where large ground convergence occurs, the more flexible TSLs may provide superior support over the full range of rock deformations.	t
Can be covered by shotcrete at a later stage if deemed necessary.	s
Potential as a temporary support system in many tunnels where the bulk of permanent support can be installed behind equipment used in the development cycle.	s
Earlier installation of permanent support is possible.	h
No interference with the bolting patterns. The required number of bolts is reduced by allowing bolt spacing optimization. The bolting density can match the ground conditions.	f, r, t
By rapid placement of TSL after the drill-and-blast process the inherent strength, overall stability of the rock and underground openings may be enhanced.	a, f
The blocky rock mass is prevented from dilating, loosening and unravelling, thus forcing fragments of rock mass to interact with each other aiding in the development of a stable beam or arch of rock (Voussoir beam).	t
Pillar softening due to the decreasing depth and extent of fracturing and associated dilation is reduced and thus pillar strength may be improved.	l
The chock's residual strength and load bearing capacity are improved.	l
Reduces the rib displacements by half as compared to unsprayed ribs.	l
Strength improvement and enhancement of post-yield failure characteristics of rocks.	a
TSLs act to positively reinforce rock support capabilities.	a
Capable of achieving significant area support resistance.	a
Prohibits rusting or corrosion of screen and bolts, and also provides significant improvements in the support capabilities of the entire system.	e
Rapid spray placement and almost immediate mobilization of high tensile strength may prevent gradual loss of rock strength.	a

Source codes

a: Archibald (2001)	h: Hawker (2001)	l: Laurence (2001)	s: Spearing & Champa (2000)
b: Borejszo & Bartlett (2002)	j: Hepworth & Lobato (2002)	n: Nagel & Joughin (2002)	u: Spearing *et al* (2001)
e: Espley *et al* (2001)	o: Lewis (2001)	p: Pappas *et al* (2003)	t: Tannant (2001)
f: Finn (2001)	r: Lacerda & Rispin (2002)		i: Henderson & Louw (2001)

Table 2. Geotechnical advantages of TSLs with respect to TSL material properties

TSL material properties	Source
TSLs have long shelf lives mostly between 3 to 6 months. The shelf life of products such as Rockhold (Lewis, 2001) and Tunnelguard (Spearing *et al,* 2003) is up to 12 months	r, p
Some TSLs set and cure fast attaining their material properties in matters of minutes and hours after application	a, e, f, h, l, p, r, t, w
Can be covered with shotcrete at a later date, as a remedial ground support measure	r
Less prone to blast damage	j, r, s
Corrosion is not an issue	r, s
Very little (negligible) rebound and product wastage during spraying	f, r, l
TSL ingredients are prepared in advance under rigid quality control standards	r
Seal and consolidate various problematic rock types and prevent rock oxidation, degradation and weathering both on the surface and in any fractures and joints filled by the liner in specific high-risk areas	b, j, n, s, q, w
TSL adheres to the surface of the rock and prevents micro-fractures	b
Some TSLs span and penetrate into the rock mass along open fractures and joints and acts as a hard, rough gouge filling increasing the cohesion across the fracture and the strength of the rock, interlock small blocks and limit the ability of the rock fabric to move	a, b, j, n
TSLs have the consistency of leather that is useful in achieving consistent application thickness. Frictional resistance against air flow is also greatly reduced with smooth surface finish	j, n
Good bond strength, tensile strength and elongation (yieldability)	a, e, l, n, p, t
Polyurea based TSLs have the ability to adhere and cure in the presence of moisture	e, j
Sealant action may be used as a barrier to stop fluid, moisture, gas and radiation leaks	q, w
Some TSLs have white colouration that can also improve light reflection	q, w
Easily repaired if necessary	s
Ability of having intimate contact with the rock and effectively line the entire contour of the rock surface	s , t
Resistance of some TSL's to traffic damage and impact damage	h
The physical and chemical properties of the final polymer can be altered by changing the initial components slightly. This allows the final product to be altered to suit particular circumstances	a, f
Noticeable peak strength and a certain amount of post failure/residual strength beneficiation	a, k, l
TSLs have been demonstrated to remain physically unaffected over much larger strain ranges	a
Capability to be used in the vicinity of production blasting	e
Glue or bond loose pieces of rock to adjacent competent rock	t
Visual confirmation of the quality of the spray application process is easier because TSL colour can contrast against the walls of the mine	y
Functionality covers a wider displacement range as compared to shotcrete	t
Enhance strain energy storage capacities	a
Easy to identify features such as joints and rock type where the rock 'roughness' varies from one type to another	t

Source codes

a: Archibald (2001)	h: Hawker (2001)	l: Laurence (2001)	s: Spearing & Champa (2000)
b: Borejszo & Bartlett (2002)	j: Hepworth & Lobato (2002)	n: Nagel & Joughin (2002)	y: Swan *et al* (2003)
e: Espley *et al* (2001)	k: Kuijpers (2001)	p: Pappas *et al* (2003)	t: Tannant (2001)
f: Finn (2001)	r: Lacerda & Rispin (2002)	q: Potvin (2002)	w: Windsor (2001)

Operational, production, logistics-handling, health and safety, cost of mining-profitability-economic benefits are reviewed under the non-geotechnical category and are listed in Table 3 and Table 4.

2.3 Disadvantages of using TSLs

Although TSLs can provide many benefits, there are also disadvantages reported, and they are summarised in Table 5. The disadvantages are often associated with the application and the equipment, as well as the sensitivity of TSL material properties and technical performance to unfavourable conditions. Some disadvantages relate to health and safety aspects associated with the composition of certain TSLs.

Table 3. Non-geotechnical advantages of TSLs with respect to operation-production, logistics and handling

Operation-production	**Source**
Application time is shorter (quicker) as compared to shotcrete or mesh.	c, t
Very productive in repair situations and in many repair instances is the only reasonable option available.	r
Faster ground support process, therefore accelerated and more rapid development rate in advancing or reconditioning headings and stope access could be achieved.	a, e, m, r
Limits disintegration of the ore.	r
Application is speedy.	b, h, j, n, p, q, t, w
Application is easy.	b, f, r, t
TSL gives the mine additional time to install final support.	b
Increased mobility.	j
Basic and simpler spraying equipment, application procedure and pump application system.	e, g, j, l, w
All of the spray equipment and product can be installed on one mobile carrier to provide support quickly where required.	j
Easily applied in the areas where the mining rate is faster.	j
Increased development and productivity rates.	a, e, f, v
Far smaller quantities are required to support a given area with negligible rebound	i, n, t
Possible to apply near the tunnel face area and on the face itself if needed.	n, t
Remote spraying.	q, s
Higher (improved) productivity due to the reduction of the time needed for support installation.	e, s, t
It can be kept concurrent with the advancing face.	s
High rates of spray application	a, o
The process of producing TSLs is more compatible with the development of automated ground support and reinforcement machinery than say mesh.	e, w
User friendly alternative to the traditional rock containment support.	i
Freshly exposed rock walls after the blast can be covered with relative ease immediately or sooner than any other support type before the rock mass has time to loosen.	a, i, t
TSL equipment is smaller and therefore maintenance is much simpler than shotcrete equipment	y
Less labour intensive in transport and installation as compared to conventional mesh and bolts.	t
No detrimental effects in the milling and mineral recovery process	t
Logistics and handling	
Smaller quantities of material are brought underground in comparison to other ground support products. Reduced TSL material usage results in less materials handling and thus reduced logistical problems of transport and handling.	a, c, e, f, g, i, l, p, t
Reduced backlogs of TSL.	n
Significant time savings in materials handling when compared to shotcrete.	a, h
Disruption to other workings in the vicinity or obstruction of an area for traffic is minimal.	h, i, t
Can be integrated into mining cycle with minimal interference. Support concurrent with excavating.	o, q
Increased support cycle efficiencies.	a
Compression (reduction) of cycle times in mining activities.	a, v
The cycle steps are better balanced and leads to a lower requirement for faces that ensures that the equipment and manpower are better utilized, i.e. fewer pieces of equipment and faces per crew member would be required to achieve a higher level of production.	v
TSL could benefit the mine by overlapping two activities in the mining cycle that is drilling and supporting.	r
Significantly less cage use.	a
Installation and site clean-up time is noticeably reduced.	a
Simpler material handling and less robust equipment requirements.	c, e
Spraying equipment is compact, light and transportable, allowing easy access to stoping and development excavations.	i
Continuous spraying where mixing and pumping can take place concurrently.	i

Source codes

a: Archibald (2001)	h: Hawker (2001)	o: Lewis (2001)	c: Rispin and Garshol (2003)
b: Borejszo & Bartlett (2002)	i: Henderson & Louw (2001)	m: Moreau *et al* (2003)	s: Spearing & Champa (2000)
e: Espley *et al* (2001)	j: Hepworth & Lobato (2002)	n: Nagel & Joughin (2002)	v: Swan and Henderson (2001)
f: Finn (2001)	r: Lacerda & Rispin (2002)	p: Pappas *et al* (2003)	y: Swan *et al* (2003)
g: Hawker & Thin (2002)	l: Laurence (2001)	q: Potvin (2002)	t: Tannant (2001)
			w: Windsor (2001)

Table 4. Non-geotechnical advantages of TSLs with respect to health and safety, cost of mining, profitability and economic benefits

Health and safety	Source
Safer to handle and apply (install) as compared to mesh and lacing, provided that basic precautions are taken	b, e, h, l, r, t
Spraying after washing substrate yields no dust.	g, h, r
Help the rockmass support itself and make bolting and mucking operations safer.	r
Applicability in confined environment.	g
Potential reduction of the resistance (friction loss) to ventilated air velocities on the walls of excavations and dust containment	e, q, w
Capable to both restrict harmful gas inflows (such as methane and radon from rock strata) and to optimize flow capacities of ventilation networks therefore providing additional worker health benefit.	a
Geo-textile fabric can be coated with TSL for construction of ventilation barricades.	e
Lightly coloured or white TSLs improve illumination and visibility in an underground environment. The need for stone dust, used in whitewashing and whitening to improve illumination, is reduced.	a, l, t, v
Less material handling, remote and mechanized method of spraying distant from the development face (less labour intensive) enhances worker health and safety (less exposure to rebound, dust, noise and FOG).	a, m, t, v
Improved and continuous areal support coverage.	
Improved worker protection, safety and stability by confining the perimeter of an excavation and resisting FOG or unravelling/spalling of rocks.	a, h, l
Potential safety benefits in regards to the timing of the application, the effectiveness of the application and the method of application.	l
Enhancement of mine safety through reduction in support installation injuries and material transport injuries due to smaller volumes.	a
Polymer agents in TSLs can be developed to be flame-retardant and non-flammable.	a, l
Environmentally safe for underground mining.	i
Some TSLs can sustain large strains prior to rupturing. This allows for visual identification of areas experiencing problems and allows remedial actions to be taken before a FOG occurs.	t
The immediate support is an important benefit, for added safety to workers during any bolting activities.	m
Acrylic-based polymer TSLs have low toxicity levels.	l
Thin liners can be sprayed on the face of an advancing drift. Enhanced worker protection against possible hazards by constraining FOG or dynamic rock movements (small rockbursts).	a, t
Reduced support cycle time may result in enhanced worker safety.	a
Cost of mining-profitability-economic benefits	
More cost effective to seal the rock and keep it from deteriorating.	r
The time and cost saving for developing through difficult ground such as dykes.	j, s
The use of TSLs would result in additional blasts (and tunnel advance) that can have a very positive impact on overall mining profitability.	s
User friendly and cost effective alternative to conventional forms of area ground support such as shotcrete and other containment support.	a, i, o
Do not require large amounts of capital to be spent setting up plants as is the case with shotcrete	f
Labour cost savings due to smaller number of workers required. Applied by a two man team with standard inexpensive off-the-shelf multi-purpose application equipment.	a, c, i
Massive reduction in the amount of material required to be moved underground to the working face, therefore results in significant savings in handling, transport and support costs.	a, e, h, i, t
Economic benefits due to higher productivity created by reduction of the time needed for support installation.	t
Lower overall mining costs.	t
Optimize flow capacities of ventilation networks therefore reducing mine power costs.	a

Source codes

a: Archibald (2001)	g: Hawker & Thin (2002)	r: Lacerda & Rispin (2002)	q: Potvin (2002)
b: Borejszo & Bartlett (2002)	h: Hawker (2001)	l: Laurence (2001)	s: Spearing & Champa (2000)
e: Espley *et al* (2001)	i: Henderson & Louw (2001)	o: Lewis (2001)	v: Swan and Henderson (2001)
f: Finn (2001)	j: Hepworth & Lobato (2002)	m: Moreau *et al* (2003)	t: Tannant (2001)
			w: Windsor (2001)

Table 5. Disadvantages of TSLs with respect to application, equipment, TSL material properties, technical performance, health and safety

Application, equipment	**Source**
QC concerns with running water, application thickness and improper pump mixing ratio between the mix components.	r, q, p, u, v
A water trap must be used in the compressed air used for spraying to remove moisture, oils and other contaminants harmful to TSL.	r
Airless spraying systems may be needed when excessive compressed air contamination is evident.	r
Consistently applying a TSL thickness of 3 to 4mm requires training and practice as it is difficult to gauge the thickness. One needs to learn the proper spraying motion and speed to build the proper thickness layer.	r, j
The mixing processes can be complex, requiring specialized crews to operate the equipment. A skilled nozzle man (operator) and care are required.	j, o, n
The high cost of the material makes wastage expensive.	j
Extensive impact damage to the TSL due to the movement of the trackless machinery as soon after the application. Some TSLs are slow to set and vulnerable to damage in the first 24 hours after application.	l, n
Difficult to adequately prepare the rock surface.	n, q
Some of the equipment is heavy limiting its application in stopes.	n
Quick setting products cause blockages in the delivery pipe if the spraying process is unduly delayed.	e, n
The demands on the support are usually not well quantified by the Geotechnical Engineer.	f
Operator resistance has been expressed towards the adoption of TSLs in place of more robust, historically-proven support methods (referring to DeGagné *et al*, 1999).	a
Special scaling precautions are advised at the leading edge of a liner, after advancing the round, due to possible damage from venting blasting gas and vibrations.	v
As compared to spraying on just bare rock, greater volumes of material will be required to coat the screen and the areas with highly fractured rock or surface roughness. As thickness increases cost also increases.	e, l, t, n
The operators must apply a keen attention to detail with regard to cleaning the spraying equipment (with most emphasis on the nozzle) at the end of a job. The need for solvents is clearly a TSL disadvantage.	e, u
The availability of compressed air and water is the requirement for spraying.	i
In small headings, the flaps of liner material pose a problem. For example, when mucking out a drift, a scoop can accidentally catch a flap of liner and pull off TSL quite a large section of the still good liner.	t
Equipment development is needed to simplify the trimming away flaps of TSL material created by the blast.	t
Modelling the performance of TSL thin membranes is still very much in its infancy.	s
The air humidity can pose some problems with the application process for certain types of TSL materials.	e
Proper conditions for storing and applying the material are necessary. (Logistics)	p
TSL material properties, technical performance	
Improper substrate preparation would cause poor bonding to substrate due to loose rock, dust, excessive water, diesel fumes and oils. This will require more time when washing down a heading.	a, r, u, e, n, t
Most of the products have poor tear strength, requiring continuous application over the fractured rock surface area overlapping onto more solid rock surfaces with no gaps, to prevent the tearing mechanism.	n
Leaks at the overlap areas.	h
In some circumstances, the properties that are characteristic of plastics may make it an inappropriate alternative or supplement to shotcrete and mesh.	w
Polyurea and polyurethane TSLs have to be sprayed onto a dry relatively clean surface, as water reduces the adhesion to the surface, the product will cure but in wet areas will not adhere to the surface.	f, r, o, q
Shelf life and performance at high or freezing temperatures can be significantly decreased. Mines that have high u/g temperatures may need to store the material outside or in cooler intake airflows.	r, u, e
Materials that exceed the shelf life may have a reduced strength.	p
If the coating is too thin then it has little apparent strength.	j
The change in physical properties caused by altering the ratio or chemistry of the starting components is not well understood, the use of this flexibility is limited in TSL properties.	f
Proper curing of the TSL depends on the application thickness.	p
Critical to "get the mix right"; a poor mix will affect the curing properties of the TSL.	l
Tensile or shrinkage cracks could form with the TSLs having shrinkage problems.	l
Doubts remain about the flexible material properties in the long term for some TSLs.	l
Inability to cover large gaps, such as would exist in badly fractured or jointed rock materials.	a
Latex (water-based) and cementitious products suffer from longer curing times .	e
Some polyurethane liner materials alter their colour and appear to degrade when exposed to sunlight.	t
Material costs for some polymer liner materials are quite high.	t
Vapour/waste generation during and after application.	u
Once prepared for spray application, limitations exist in terms of time before the TSL becomes unsuitable for application, or suffers a significant loss of post-application properties.	c

Table 5. (continued)

Health and safety	Source
Operators have to wear full body and face suits to avoid contact with airborne isocyanates materials (Polyurethane).	o
Some TSLs (acrylic emulsion, polyurea and methacrylate) emit antimony trioxide or formaldehyde vapour, a colourless gas with a pungent odour. Symptoms of high-level exposure include coughing, eye or skin irritation or allergic reactions.	a, f, l
Some TSLs readily adhere to skin. PPE must be worn.	l
Polyurethane TSLs; The polymerisation is an exothermic reaction and the temperature conditions of 200°C could be expected. Some of the MDI may volatilize (evaporate) at high temperatures and be released into discharge air volumes.	a, f
Polyurethane TSL concerns with regard to flammability and chemical hazards.	o
Exposure to polymeric materials,"A" component, may cause workers to become sensitized, and may manifest debilitating or even life-threatening asthmatic symptoms following repeated exposures either by inhalation or possibly skin contact.	a
Direct exposure to some TSL components materials can lead to allergic sensitization.	a
Specific procedures are needed for the proper handling of the cleaning solutions and for disposal of empty chemical and product containers.	e
Dust exposure may become a concern for some water-based TSLs.	a

Source codes

a: Archibald (2001)	j: Hepworth & Lobato (2002)	p: Pappas *et al* (2003)	s: Spearing & Champa (2000)
e: Espley *et al* (2001)	r: Lacerda & Rispin (2002)	q: Potvin (2002)	v: Swan & Henderson (2001)
f: Finn (2001)	l: Laurence (2001)	c: Rispin & Garshol (2003)	t: Tannant (2001)
h: Hawker (2001)	o: Lewis (2001)	u: Spearing *et al* (2001)	w: Windsor (2001)
i: Henderson & Louw (2001)	n: Nagel & Joughin (2002)		

2.4 List of TSLs used

A listing of the range of TSLs either available commercially or known to be under development was provided by Potvin (2002). This list has been updated in Table 6 including the more recent TSLs in the market. Table 6 shows that TSLs vary in mix base or chemistry. Most of the products are cement-polymer based and a few are polyurethane, polyurea or methacrylate based. Some manufacturers offer a number of products and some of their products are under continuous development.

2.5 TSL applications in mines

It was reported by Belfield (2006) that more than 50 mines worldwide have used TSLs for rock support. TSL trials or applications were commonly implemented at locations with extremely poor ground conditions or ground control problems such as:

- friable and weathered ground with some water seepage, (Hepworth and Lobato, 2002),
- damaged concrete shaft lining (Hawker and Thin, 2002; Potvin, 2002),
- high stress environments (shaft pillar) and rock mass conditions with rockfall and rockburst hazards (Henderson and Louw, 2001; Kuijpers, 2001),
- burnt coal site (Kuijpers, 2001),
- intensely spalled and shattered pillar corners (Laurence, 2001),
- development ends with humid conditions (Nagel and Joughin 2002),

- rapidly deteriorating shale band/green bar (Carstens, 2005),
- running black dykes (Spearing and Champa 2000), and
- old sites (Nagel and Joughin 2002).

Table 6. List of TSL products commercially available or under development (after Potvin, 2002; Rispin and Garshol, 2003; Yilmaz, 2009)

Manufacturer (alphabetical order)	**Product-Trade Name**	**Mix Base-Chemistry**
3M	3M Liner	Polyurethane
Ardex	Ardumin TMO 20	Hyd. cements, admixtures and graded fillers
BASF	Mayco Super lining; BASF white TSL	Cementitious polymer
Carbontech	A-Seal; V-Seal	Cement-polymer-sand-polypropylene fibre
Cementation Lining Products (CLP)	Superseal	Cementitious polymer
CHC	CHC TSL	Acrylate polymer
Chryso	Chryso TSL	Cementitious polymer
CONCOR	D21H; Concor Standard TSL	Cementitious polymer
Engineered Coatings Ltd.	Rockguard	Polyurethane/polyurea hybrid
Fosroc	Polyshield SS-100	Plural component polyurea elastomer
Fosroc Inc.	Tekflex	Cementitious polymer
Geo-Mining	Geo-Mining TSL	Cementitious
Guyric Pipe Company	GPC TSL	Polyurethane
Hydroflex Pty Ltd	Diamondguard	Polyurethane
Kohlbergerer Enterprises Pty Ltd	Polyurethane TSL	Polyurethane
Master Builders Inc. (MBT)(Degussa)	MasterSeal 840R01A; 850C	Methacrylate resin and filler mixture
Master Builders Inc. (MBT)(Degussa)	Masterseal CS1251; 845A; CE1286; CT1266	Acrylate polymer
Minova	Capcem KT (grey, white); Raplok; Tekflex white	Cementitious polymer
Mondi Mining Supplies	Rock Hold	Methacrylate mixed with water
Nico Du Rand Consultants (NDRC)	Super lining	Cementitious polymer
NS Consultancy	Ultraskin	Polyurethane
Precrete	Rockliner A; F2; T1; 916; D50	Cementitious polymer
Pumachem CC	Conseal	Cementitious polymer
SA Mining and Engr Supplies, Reynolds Soil Technologies	Tunnelguard (grey, yellow, white); TGNC; TGNT; TGC	Cement-polymer-sand-polypropylene fibre
Speciality Products Int. Pty. Ltd.	Polyurea TSL	Polyurea
SPI	SPI TSL	Polyurea
Spray-On Plastics	RockWeb	Polyurethane/polyurea hybrid
Stratabond SA Pty Ltd (Mead Mining)	Everbond; Evermine	Water-based polymer-cementitious filler
TAL	TAL TSL	Cementitious
Urylon Plastics Canada	Mineguard	Polyurethane

Table 7 shows TSL applications and trials worldwide. The table indicates the many possibilities and the great potential of TSL use in the mining industry.

Table 7. TSL applications and trials

Applications, trials	Source
The hangingwall and face area of a longwall panel in a gold mine to assist with the hazardous undercutting process and to support the exposed shale band.	ca
In narrow vein mining areas to replace bolts and screen in the walls of a stope and production sills.	e
Coating borehole walls and for maintaining borehole collar integrity.	e
In fast drifting whereby bolts are installed either immediately before or after a TSL is sprayed.	e
Drill drifts and production headings for slot-and-slash (retreat) mining, sublevel cave mining (bulk mining) environment and vertical retreat mining top sill development headings.	e, n
In reconditioning of main trackless ramping areas.	e, m, n
Repair of damaged concrete shaft lining, permanent escape ladderway and for sinking declines and shafts.	c, g, q, u
Sewer tunnel project as a water barrier to reduce the water permeability of the shotcrete lining	h
Longwall lift off process as coal ribs support at the corners, on blockside and chain pillar side and in cut-through operation.	h, l, p, r
Deep level hard rock gold mines in different stress environments and rock mass conditions.	i
Gold Mine deep near-vertical ventilation raise borehole and cubby.	i, m
Gold Mine moderate depth incline shaft equipped with a chair lift.	i
An area of damp Black Shale, shale and fault in the access tunnel.	j
In both stope and development end of drift and fill mining.	j
A burnt coal site at a colliery experiencing serious instability problems.	k
A stope gully at a platinum mine that was subject to instability problems on the gully-side pillars and h/w..	k
A tunnel at a platinum mine experiencing instability problems associated with key blocks.	k
Goldmine up-dip stope gully in the shaft pillar area and advanced towards the old workings. VCR gullies behind stope panels at 2200m below surface to address the very poor ground condition of the gully roof strata.	d, k, s, u
Repairing of drift areas where ground slacking is taking place.	r
A section of belt road blockside in a heading.	l
An Intensely spalled and shattered rib corner.	l
To confine a goaf end chock as the longwall advances.	l
Development ends and orepass slots with extremely poor ground conditions and high humidity.	n
Dyke material in a bullnose.	n
Old site near the main station tip area.	n
Sub stations.	n
Changing out and repairing the worn sacrificial chute liners in the bottom of two underground ore bins.	q, x
'Mine through' support in coal mines	q
Large machine borehole lining and stabilisation	q
Development through running Black dykes.	s
Sealing rock prone to weathering.	s
As a concurrent tunnel face support (both blasted or excavated) for both temporary and permanent support.	q, s, u
Barrier pillar, in-stope gold or coal mine pillar support (reinforcement).	i, k, p, q, s, u
As a support component to help reduce rockburst damage in seismically active areas.	s, u
For highwall stabilization.	u
In trackless/mechanized high speed development ends.	u
Mining adjacent or underneath cemented backfill.	u
Ventilation sealing and repair (not a support application)	u
Between the primary ground support system of bolts in both cut-and-fill stopes with 5m high backs and permanent development drifts and to help support the back of 80 to 85% of all headings.	t, v
Drift that was excavated along a swarm of sub-parallel, steeply dipping narrow veins as part of a drift-and-fill mining method in a bottom-up mining sequence.	t
Concrete liner rehabilitation and concrete material protection.	z

Source codes

c: Carstens and Badenhorst (2009)	e: Espley *et al* (2001)	g: Hawker and Thin (2002)	p: Pappas *et al* (2003)
d: Carstens and Oosterhuizen (2004)	h: Hawker (2001)	n: Nagel and Joughin (2002)	q: Potvin (2002)
i: Henderson and Louw (2001)	k: Kuijpers (2001)	x: Nucifora and Irwin (2001)	u: Spearing *et al* (2009)
j: Hepworth and Lobato (2002)	l: Laurence (2001)	s: Spearing & Champa (2000)	t: Tannant (2001)
r: Lacerda and Rispin (2002)	m: Moreau *et al* (2003)	v: Swan and Henderson (2001)	ca: Carstens (2005)
		z: Archibald and Dirige (2006)	

In spite of the often unfavourable conditions, most of the applications were found to be successful for what they were planned for. TSL applications, in a few cases, resulted in poor bonding, falling of large slabs, peeling, tearing and damage due to blasting and moving machinery (Nagel and Joughin, 2002; Tannant, 2001). TSLs in these applications were principally used as temporary support for strata control and ground stabilisation purposes. TSLs were also used for the purposes of:

- protecting the steel support elements (screen and bolts) from corrosion and from the fly-rock due to production blasts (Espley *et al*, 2001),
- replacing the loose supporting or retaining function of mesh/screen and lacing where geotechnically approved (Potvin and Nedin, 2003; Spearing and Champa, 2000; Swan and Henderson, 2001; Spearing *et al*, 2009)
- reducing the water permeability of the shotcrete lining (Hawker, 2001),
- repairing shotcrete (Lacerda and Rispin, 2002)
- preventing pillar or rock weathering, spalling and damage caused by fly-rock on the pillar as a result of blasting (Pappas *et al*, 2003; Spearing *et al*, 2009)
- reducing rockburst/seismic damage (Spearing *et al*, 2009)
- rehabilitation of collapsed areas (Spearing *et al*, 2009)

2.6 Previous testing of TSLs

A review of previous testing methods for TSLs and the learnings from experience of those involved in these tests are essential in laying the foundation for the initiation and development of any new testing procedures. Potvin (2002) stated that a number of laboratory and field tests have been developed with the aim of improving the understanding of the properties of TSLs as well as characterising the interaction of TSLs with the rock. He categorised TSL tests into two groups, namely chemical and mechanical, as shown in Figure 1. He further proposed a classification of tests based on the scale of the test, the properties tested and the “mechanical action” performed during the test.

Potvin (2002) was of the opinion that large-scale tests provided interesting results, but were found to be difficult to interpret in terms of TSL properties and behaviour. The applicability of data generated from such tests for design purposes is therefore questionable. The majority of the large scale tests are costly and time consuming; therefore, they are mainly performed by their developers and not by any other persons.

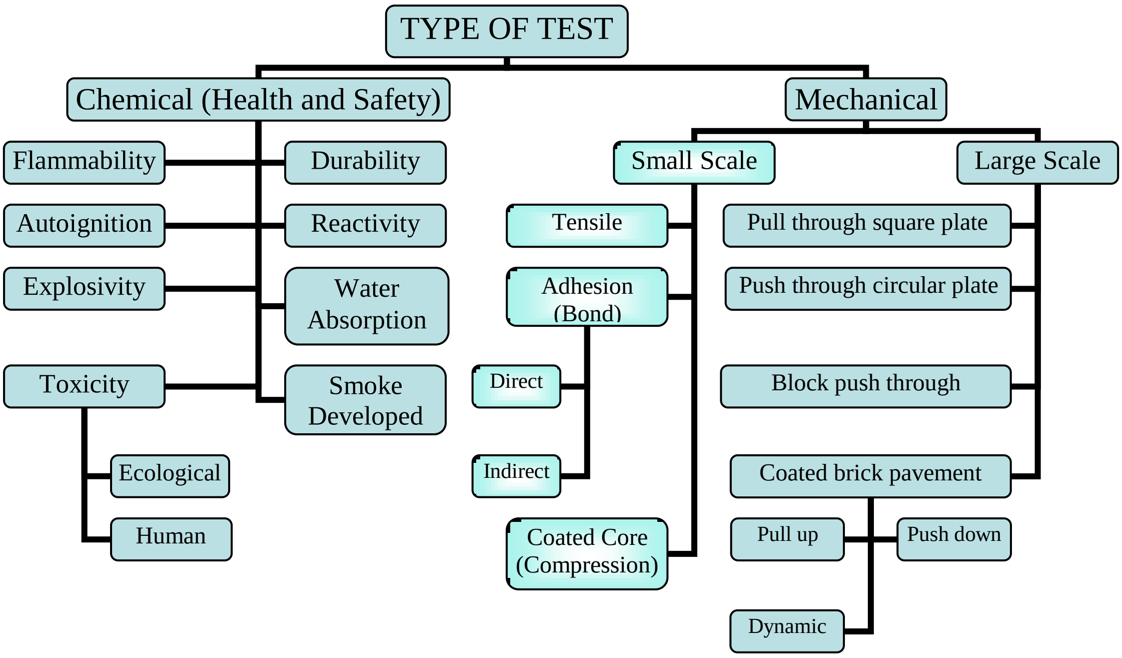


Figure 1. Schematic describing a classification of existing tests to determine properties and characteristics of TSLs (modified after Potvin, 2002)

Figure 1 shows that small scale testing has not received the attention that it deserves. In spite of the fact that small scale tests are simpler, easier and cheaper to perform than large scale tests, the research attempt in this branch has been weak and limited to the measurement of tensile, bond and compressive strengths. Archibald (2001) is of the opinion that small scale laboratory tests are more successful for the generation of controlled results. Two small scale tests have met with the acceptance of the TSL stakeholders so far. They are the tensile and the tensile-bond (adhesion) strength tests. Considering the greater chance of acceptance, the focus of the research in this thesis was, therefore, given to the development of small scale tests, with particular attention to the determination of shear characteristics that have been neglected by researchers so far.

Standard testing methods to determine strength characteristics and physical behaviours of plastics, membranes and geotextiles have been developed by various institutions. The relevant standards from the American Society for Testing Materials (ASTM), British Standards (BS), International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), and Canada-Underwriters Compliance Listing (CAN/UCL) were reviewed by Toper *et al* (2003) and are listed in Table 8. These test standards could be adapted to TSLs either directly or by appropriate modifications. Factors such as the quality of specimen preparation, the speed of testing, temperature and humidity may influence the test results, and they should be taken into account.

Table 8. Relevant standards for testing of TSLs (after Toper *et al*, 2003)

Test type	Standard No	Description
Tensile Strength and Elongation	ASTM D638	Tensile properties of plastics
	ASTM D1708-84	Tensile properties of plastics by use of microtensile specimens
Tear Strength	ASTM D1004-90*	Initial tear resistance of plastic film and sheeting.
	ASTM D1922-89*	Propagation tear resistance of plastic film and thin sheeting by pendulum method.
	ASTM D5884-99*	Determining tearing strength of internally reinforced geomembranes.
	BS 903-A3-3.2:1997, ISO 34-2: 1996	Physical testing of rubber. determination of tear strength. section 3.2 small (delft) test pieces
	BS 903-A3:1995, ISO 34-1: 1994	Physical testing of rubber. method for determination of tear strength
Shear Strength	ASTM D732-90	Shear strength of plastics by punch tool
Adhesion Strength	ASTM D4541	Pull-off strength of coatings
Toxicity	ASTM E1619-95	Standard test method for chronic oral toxicity study in rats
Flammability	ASTM E162	Surface flammability of materials using a radiant heat energy source
	ASTM D568-74	Flammability of flexible plastics
	ASTM E84	Surface burning characteristics
	IEC 707	The determination of the flammability of solid electrical insulating materials when exposed to an igniting source
	CAN/UCL S102-M88	Standard method for test for surface burning characteristics of building materials and assemblies
Water Absorption	ASTM C827	Change in height at early ages of cylindrical specimens from cementitous mixtures
	ASTM D570	Water absorption of plastics
Abrasion	ASTM D4060	Abrasion resistance of organic coatings by the taber abraser
	ASTM D1242	Resistance to abrasion of plastic materials
**: applicable after modification*		

A review of previous tests on TSLs was carried out by Potvin *et al*, (2004) and the list of these test methods is provided in Table 9. A one page data sheet for each testing method is presented in Appendix I. The “Linear Block Support Test” and the “Gap Shear Load Test” of EFNARC, (2008) are two new additions to the list in Table 9.

Previous tests on TSLs involved either TSL material only or both the TSL material and a substrate. The understanding of the interaction between TSL and substrate is important as the specimens used in these tests are more representative of the actual field condition.

Table 9. Previous test methods on TSLs (after Potvin *et al*, 2004)

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

For each of the previous tests, descriptions, illustrations, applicable equations, material and substrate specifications, advantages, disadvantages, loading and failure mechanisms are provided in the data sheets in Appendix I. The popularity of some tests has resulted in the generation and availability of comprehensive data. Large scale tests are generally the less popular tests that are performed by their developers only. The information on these tests commonly consists of descriptions and is often weak with regard to the generation of comprehensive sets of test results. The main findings on the most common test methods will be highlighted in the following sections.

2.6.1 **Adhesion (bond) strength testing**

In the past, many adhesion test procedures have been consulted by mining researchers to assess the characteristic adhesion (bond) strength of TSL agents. The adhesion test measures the adhesion or bonding strength of a TSL attached to a rock substrate.
The bond strength of a TSL may be defined as its ability to adhere to a particular surface (Swan and Henderson, 2001).

Kumar *et al* (2002) reported that two types of bond strength need to be considered: tensile and shear. Tensile-bond strength is a measure of the ability of TSL to remain in contact with the rock when a tensile stress is applied normal to the rock-TSL interface. Shear-bond strength is concerned with the ability to resist stresses that act parallel to the rock-TSL interface. In practice, there is usually some combination of these stresses acting on the TSL-rock interface.

Failure may occur due to the low tensile adhesion strength between TSL and rock surface. Adhesion strength on different rock types and the factors influencing the adhesion are important test considerations. Therefore, investigations are carried out to determine the effect of the following factors on bond strength:

- rock properties and environmental conditions (Ozturk and Tannant 2003)
  - curing environment (temperature and humidity)
  - rock mineralogy
  - various rock substrates
  - rock surface roughness (grain size, fracture/joint roughness)
  - surface contamination (oil or dust), and
  - rock strength (tensile/compressive strength)
- TSL thickness and substrate type (Ozturk and Tannant 2010).

Archibald (2001) selected and used a paving stone product as the standard test material for all adhesion tests to avoid problems associated with variable strength and surface conditions when using rock slabs.

Tannant *et al* (1999) showed that the TSL's bond to the rock normally increases with time, provided that the rock is firm, clean and dry. Adhesion to smooth, wet and soft rock surfaces is generally poor. Underground adhesion testing performed by Espley *et al* (2001) also confirmed the decreasing adhesion strength as the surface moisture increases.

The manner in which material adhesion loss occurs was shown to vary between materials assessed as shown in Figure 2. The following failure modes were observed by Archibald (2001):

a) Partial failure of the adhering layer beneath the pull plate, with material remaining attached to the concrete slab after failure of the top encapsulating layer. This effect occurred because the top cover was placed in too thin a layer, and could not provide an effective anchor over the top of the pull plate.
b) Full detachment of the layers from the concrete slabs at the limit of extensional failure.
c) Shearing failure of the liner product at the interface between the perforated pull plate and the bottom layer material, indicating that the material tensile strength was exceeded by the adhesion strength existing.
d) Failure of the lining material accompanied by localized tensile failure of the concrete surface, resulting in attachment of concrete fragments to the TSL layer

after ultimate bond failure. This would indicate that the adhesion bond strength of the TSL material exceeded the concrete tensile strength at localized contact sites.

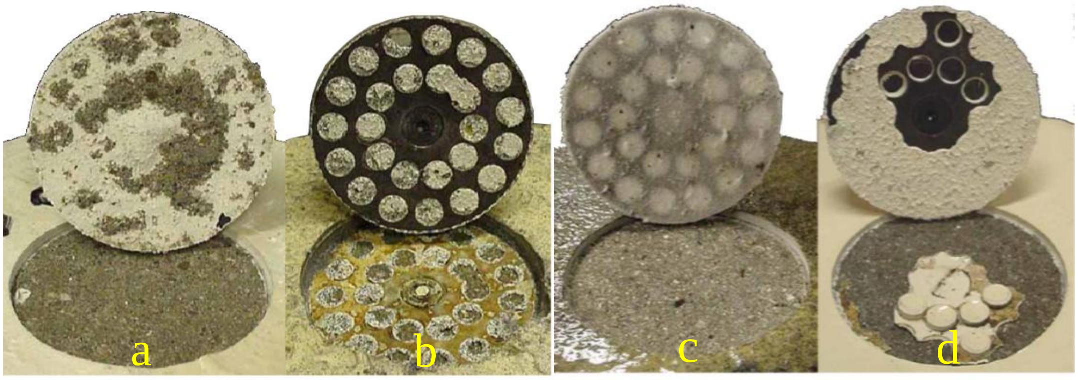


Figure 2. Typical views showing adhesion bond surfaces after completion of failure tests. (after Archibald, 2001)

No residual adhesion bond strength is quantifiable, as the test process is designed to be carried to ultimate bond failure (Archibald, 2001). The test does not assess typical conditions which may be encountered by spraying onto rock surfaces in-situ.

Leach (2002) recognized the bond strength as the most important test criterion for a TSL and warned of a number of issues that need to be considered with regard to the assessment of bond. He first pointed out the lack of reliable correlation between laboratory results and field results, whether on surface or underground. Secondly, the failure cannot simply be indicated from a reading on an instrument gauge. The result and the interpretation of the failure should be treated separately. The location of the failure should be determined and if it is in the bond plane, the amount of the applied material remaining should be assessed. From there it is necessary to use 'judgement' as to the reason for failure, whether it be the product or the host rock.

2.6.2 **Tensile strength testing**

Kuijpers *et al* (2004) reported that this testing method was selected and used by most researchers (Tannant *et al*, 1999; Archibald, 2001; Spearing and Gelson, 2002) as a primary liner characterisation test. Other material properties that can be assessed using this test are the in-line stiffness (modulus) and elongation capacity or degree of tensile extension at failure.

Archibald's (2001) average test results for tensile strength, elongation capacity and modulus of deformation for different products and various thicknesses are displayed in Table 10. Tensile strength results indicate considerable variability in load-deformation response between different TSL materials, most likely due to differences in layer thickness. Composite cementitious materials exhibited lower tensile strength. Tensile yield strengths for most TSL products were similar. In some cases significant elongation capacities produced no break failures at the extension limit of test.

Table 10. Tensile properties of TSL materials according to ASTM D638 (after Archibald, 2001)

Material	**Tensile Strength (MPa)**		**% Elongation**		**Modulus of**	**Range of Liner**
	@ Break	**@ Yield**	**@ Break**	**@ Yield**	**Def. (MPa)**	**Thickness (mm)**
Mineguard*	15,58	9,78	+200	94,72	22,35	1,21 – 1,83
Rockguard	11,36	8,78	86,69	61,28	28,48	1,43 – 1,65
RockWeb*	13,05	9,00	+200	61,56	41,38	2,06 – 2,82
Masterseal	2,50	-----	65,91	-----	3,60	4,84 – 7,90

* - All specimens exhibited 50 mm limit of extension with no break of test specimen occurring

2.6.3 Pull strength determination

Tannant *et al* (1999) stated that TSLs are expected to support the weight of loose rock. The adhesive strength and tensile capacity of TSLs are necessary to bridge joints and to carry loads from the loose rock to the surrounding stable rock, therefore inhibiting loose rock movement away from coated surfaces.

TSL performance is sensitive to its applied thickness and continuity over the rock surface. Tannant *et al* (1999) therefore drew attention to the importance of achieving a continuous and uniformly thick layer of material over the sprayed surfaces during the application of a TSL for ground support purposes.

Archibald (2001) also assessed the material pull strength to demonstrate the combined strength properties of TSLs which can be mobilized both by liner adhesion to rock surfaces and by the tensile strength of the liner material. He considered that the bonding strength at the perimeter of a displacing block provides a liner anchoring capability, as the liner will be attached both to the displacing block and adjacent intact rock. TSL thickness and tensile strength assist in providing support resistance around the perimeter of the displacing block. Archibald's (2001) test procedure is similar to Tannant *et al*'s (1999) procedure, with only minor differences.

The failure modes observed during Archibald's (2001) pull testing can be seen in Figure 3 and are summarised as following:

i) Failure of adhesion bonds about the plate perimeter and/or tensile failure through the material. Then, immediate and progressive shearing follows with a gradual loss of pull resistance.
ii) Shearing induced by tensile stresses ("tensile shearing" as stated by Archibald, 2001) and gradual adhesion bond release beyond the plate perimeter.
iii) Gradual and progressive release of material adhesion with no "tensile shearing". Total loss of pull capacity only develops after very large plate displacements and full release of the layer coating from the outer perimeter surface of the concrete paving stone.
iv) Shearing failure of the pull plate through the overlying TSL coating due to strong adhesion bonding and brittle tensile deformation behaviour.

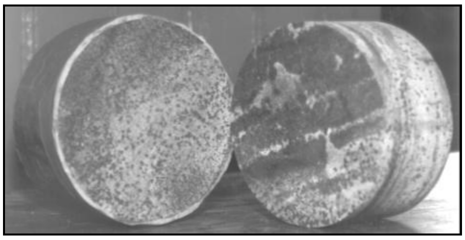
2.6.4 **Coated-core compression tests**

Espley *et al* (1999), Archibald and DeGagne (2000), and Kuijpers (2001) showed that the application of a TSL can change the post failure behaviour of a rock specimen from violent and brittle behaviour to smooth and ductile behaviour by confining the fractured rock with a limited resistance against dilation (Figure 4). The presence of a relatively weak TSL allowed the rock specimen to maintain a certain amount of post failure resistance. The explosive failure, which was associated with the non-coated specimens, is shown in Figure 4b. The coated discs suppressed the explosive failure as shown in Figure 4c. An additional effect of the TSL induced confinement was seen as an increase in the peak strength. Similar tests on concrete cylinders resulted in similar strength enhancements and failure developments with limited TSL failure.

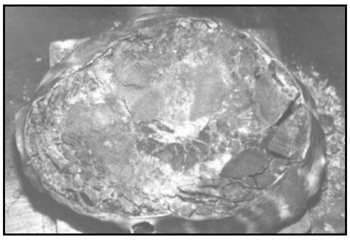
Mineguard Rockguard

RockWeb Masterseal

Figure 3. Typical views showing pull test failure conditions at completion of failure tests (after Archibald, 2001)



a)



b) c)

Figure 4. a) Coated and non-coated specimen before loading. b)Non-coated specimen after violent failure. c) Coated specimen after failure, (after Kuijpers, 2001)

2.7 Summary and conclusions

TSL trials and applications have been increasing over the years even though TSL technology is a more recent technology than other traditional areal support such as shotcrete and mesh. The increased use of TSLs could be attributed to the numerous geotechnical and non-geotechnical advantages offered by their use. The continuous developments in the TSL products and the application technology appears to have reduced the small number of disadvantages related to application, equipment, TSL material properties/technical performance, health and safety.

Amongst the many testing procedures reviewed, only two are commonly performed tests that meet the requirements for standard testing; namely tensile strength and tensile-bond strength testing. In addition, past research efforts have focused on these two properties since they are viewed to be important to the liner's ability to hold loose rock in place, and therefore would be key factors in the determination of TSL performance. However, variations in the specimen-preparation and test execution procedures by a number of researchers are observed. Standardisation of these tests is required to eliminate these differences.

Many of the other testing procedures reviewed are not well known and recognised, and are found to be of limited value in terms of the number of tests and the variety of products tested. Large scale tests, in particular, are time consuming and costly in nature and they involve complex testing procedures, multiple mechanisms of failure and results that are difficult to interpret. These are, in fact, the main reasons behind their unpopularity.

The review of previous tests on TSLs proved to be useful in the consideration of new testing methods. It was seen that small scale tests are more attractive due to their simple set-ups, and their easy, quick and cost effective nature.

In Chapter 3, the general considerations and requirements for the proposed testing methodologies are discussed. These discussions are necessary to establish the guidelines to be used during the initial design and developmental stages of testing methods.

CHAPTER 3 GENERAL CONSIDERATIONS FOR THE PROPOSED TESTING METHODOLOGIES

The previous chapter dealt with a review of relevant literature on TSLs. In this chapter, an analysis of possible test options on TSLs is carried out, and then the requirements for the proposed standard testing methodologies are identified. Subsequently, factors that may have a direct influence on test results are discussed. The development of new testing methodologies is done in the light of these discussions.

Test results obtained under different conditions cannot be compared directly. Therefore, the conditions at all stages of a testing methodology, from specimen preparation to test execution, should be maintained and applied equally for all specimens in order to obtain repeatable testing and comparable results. For example, the comparison of test results between a weak TSL tested at 28 days of curing and a stronger TSL tested at 1 day of curing is invalid and should be avoided. Otherwise, the weaker TSL could be taken to be the favourable option if the curing times are not mentioned. In all cases, the test conditions should be reported thoroughly to avoid confusion in the interpretation of test results at a later stage.

3.1 TSL mechanical properties and test options

The tests were performed in a stiff servo-controlled loading frame (MTS, Material Test Systems Corporation, Minneapolis MI, USA; model-no.: 815.313-58). A high accuracy load cell with a range of 0-100 kN ± 10 kN was used. The MTS machine also contains a built in LVDT capable of recording the machine displacement. Displacements, however, are not included in the analysis of test results since they do not reflect the actual deformations of the specimens.

The following mechanical properties are considered to be the most relevant in defining TSL strength characteristics, and research effort so far has mainly focused on the development of test methods for some of these properties, i.e.:

- Tensile strength and elongation
- Shear strength
- Tear strength
- Bond (adhesion) strength
- Compressive strength
- Bend (buckling or flexural) strength
- Impact (abrasion) strength

Boundary conditions and mechanisms of loading that need to be considered for the development of the abovementioned strength tests are summarized in Figure 5. The extent of loading is indicated in red. The expected positions of failure are shown as yellow lines. Loading direction remains unchanged in all tests; nevertheless, the loading position may change during a test, particularly in the tear strength testing due to progressive tear. Fixed boundaries are for clamping or support purposes; therefore TSL bonding only takes place on the substrate, but not on fixed boundaries.

Tear and bond strengths of liners can be measured in tension or shear as seen in Figure 5C and D; therefore both tension and shear characteristics need to be assessed. Shear force could be applied on a liner material in a number of options. In the case of shear loading as shown in Figure 5B ii), the liner material should not de-bond before the material shear strength is reached.

Tests involving TSL material only are simpler and easier to develop and implement. More complicated testing methods need to be developed for the cases where the interaction of the TSL with a rock substrate needs to be taken into account.

Details of location of failure, loading characteristics and specimen composition are given in Table 11. While tensile, compressive, shear, tear and bend strengths involve TSL material only, specimens for bond and impact strength testing should incorporate a rock substrate.

The locations of failure in tests involving tension (tensile strength, tensile tear and tensile-bond) will be arbitrary depending on the location of the weakest zone in specimens. This behaviour is characteristically associated with tensional loading. On the other hand, the failure surface for tests involving shear, bending or impact loading will occur along the positions where load concentration occurs.

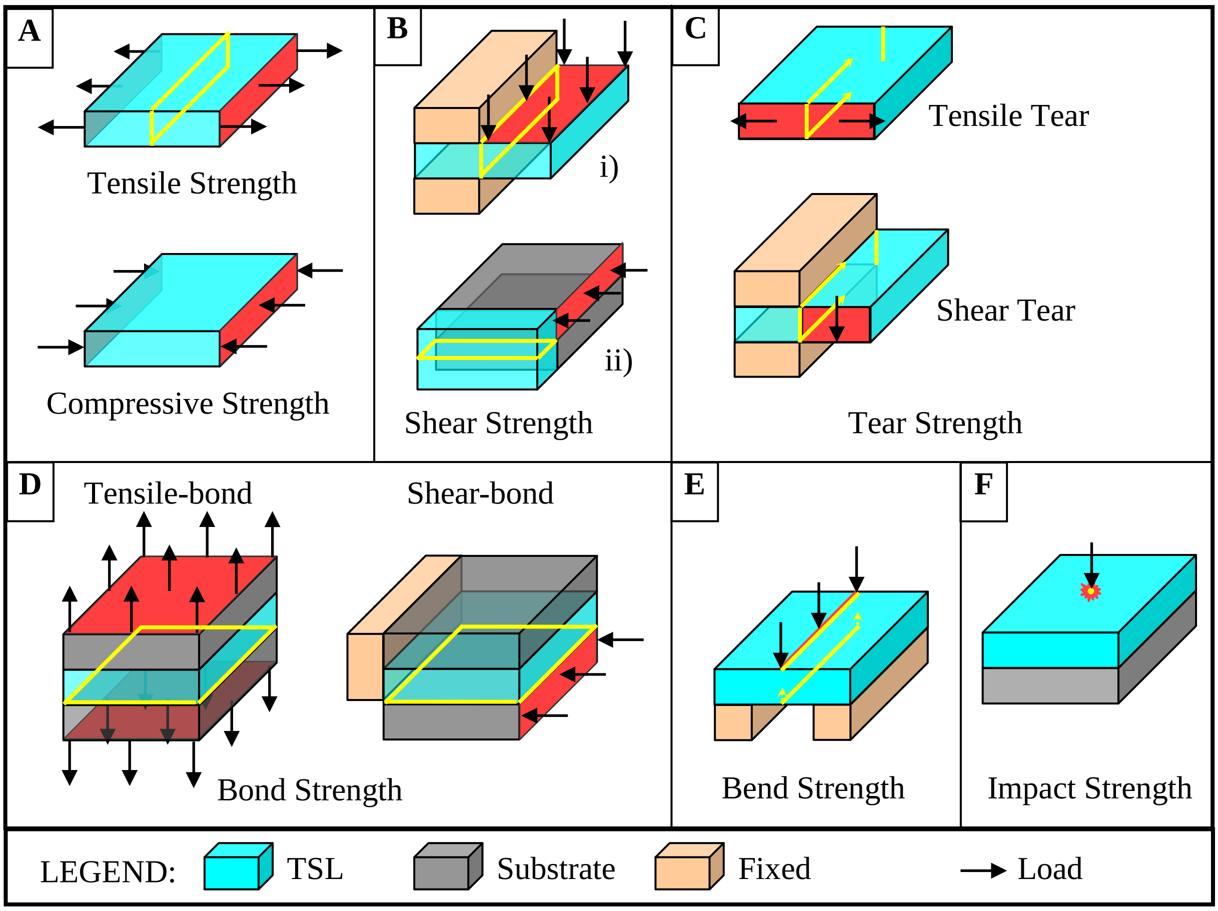


Figure 5. Boundary conditions and mechanisms of loading for testing the mechanical properties of TSLs

Table 11. Failure, loading and specimen characteristics of TSL testing

Mechanical property	**Location of failure**	**Extent of failure**	**Loading**	**Specimen composition**
Tensile Strength	Random	Area	Distributed	Material
Compressive Strength	Random	Area	Distributed	Material
Shear Strength	imposed	Area	Distributed	Material
Tension tear	random	Progressive line	Line	Material
Shear tear	imposed	Progressive line	Line	Material
Tensile-bond	random	Area	Distributed	Material and substrate
Shear-bond	imposed	Area	Distributed	Material and substrate
Bend Strength	imposed	Progressive line	Line	Material
Impact Strength	imposed	Line or point	Point	Material and substrate

The loads required for TSL material failure in the cases of point, line and distributed loading will be respectively higher. Expectedly, the greater the size of specimens, the greater the load capacity required from a load cell.

3.2 Test requirements

The following requirements are used as guidelines during the initial design and developmental stages of testing methods:

- *Manageable Size*: Due to greater difficulties associated with large specimens in terms of preparation time, costs and manageability, specimen and apparatus size should be as small as possible.
- *Simplicity*: A complicated test method results in difficulties in specimen preparation, test execution, and interpretation of test data, and therefore requires more time to complete the tasks.
- *Time*: Easy specimen preparation and testing would eliminate unnecessary delays. Curing of the TSL before testing inevitably takes time. Testing should preferably be completed within 3 minutes from the start of specimen loading. Tests requiring longer time periods will reduce the number of specimens that can be tested in a day.
- *Cost*: This constraint is directly proportional to specimen size and time spent in specimen preparation and test execution. If a TSL property could be measured by a variety of testing methods, obviously the most cost effective one would be preferred.
- *Repeatability*: Testing should exclude any factors that cannot be controlled in order to increase statistical validity and comparability of results.
- *Relevance*: TSL in-situ support mechanisms and/or loading mechanisms should be incorporated in any testing method as much as possible.
- *Re-use of test components*: Test material, other than TSL material, such as rock core, rock substrate, perspex mould and steel dolly should be cleaned for re-use in subsequent tests for cost effectiveness.
- *Adaptability*: Any testing method, with all of its components, should easily be transferred, adopted and performed at any laboratory. Implementation of large scale tests may not be possible at some laboratories due to unavailability of large capacity testing equipment.

Any testing method satisfying most of the above requirements will have a greater chance of being accepted by manufacturers and end-users of TSLs.

3.3 Test parameters

The most significant factors, that are considered to have a potential influence on the performance of TSL materials in testing, can be summarised as follows:

- Substrate characteristics
  - Surface condition (roughness, dust, water or oil on surface)
  - Rock type and strength
- Type of liner product
  - TSL
  - Shotcrete
- Shelf life
- Shrinkage
- Mixing and specimen preparation
  - Method of mixing
  - Duration of mixing
  - Method of TSL application (pouring versus spraying)
- Specimen dimensions
  - TSL thickness
  - Specimen size
- Number of specimens
- Environmental conditions
  - Temperature
  - Humidity
- Curing time
- Setting time
- Rate of loading, (quasi-static, dynamic or creep loading)

The abovementioned factors should be carefully observed and noted. Their standardisation to the most acceptable conditions and values should be done to prevent the generation of test results that cannot be compared. The importance of each factor and its effect on test results are discussed in the following sections.

3.3.1 **Substrate surface condition**

Substrate in the context of TSL testing refers to a contact surface between TSL and rock or similar surface such as brick or concrete. Tests requiring a rock substrate, such as tensile-bond and shear-bond strength testing, as seen in Figure 5D, require attention to surface roughness and presence of any obstructions on the substrate surface. The area of rough surfaces compared with smoother surfaces is bigger, and the quantification of the difference between the two becomes complicated. Failure load, in tensile-bond strength testing in particular, is directly proportional to TSL-substrate contact area; therefore rougher surfaces would likely to result in higher failure loads. Care should be taken to eliminate differences on roughness profiles of rock substrates. The preparation of substrates with a diamond saw cutting machine is highly recommended since this cutting process is found to result in comparable surface finishes.

Most TSLs are sensitive to the presence of dust, grease, oil or water. Bonding, and in some cases the composition of the TSL, may be affected by the interaction of such materials with the TSL. Preparation of dry and clean surfaces in a laboratory environment is much easier than preparation of surfaces for the application of TSLs in mines.

The surfaces of the specimens incorporating TSL material should be kept smooth in order to prevent fluctuations in specimen dimensions. Levelling of TSL surface with a spatula can be done. However, the best results are obtained when a sheet of overhead-projector transparency film or x-ray film is laid over the TSL before levelling with a spatula. The transparency sheet leaves a very smooth TSL surface and the transparency sheet can easily be removed after some period of TSL curing.

3.3.2 **Rock type and strength**

One of the intentions of conducting this research is to increase the knowledge of TSLs in order to assist in the choice of TSLs in mining applications; therefore the selection of substrate should be done in a way to represent one of the rock types encountered in mining. Rocks having high UCS should be preferred since their surfaces are competent and their structure is more resistant to any type of loading. The use of weaker rocks, such as shale, sandstone, mudstone, coal, kimberlite, tillite, and conglomerate is associated with the risk of rock failure before the TSL fails. Rocks with cracks or structural weaknesses should also not be used in tests.

3.3.3 **Type of liner product**

TSL

TSLs from various international and local manufacturers were used in the research. Table 12 provides a summary of the 17 manufacturers and 35 of their products that were made available for the testing programme. A number of TSLs listed have no established brand names as they were still in the research and development stage. Some of these products were not pursued due to unfavourable test results in the initial trials. Only 21 of the 35 products were subjected to the full range of testing and their results are available for analysis in the following chapters. Product names are not revealed when discussing the results in order to preserve confidentiality.

Table 12. TSL products tested

Manufacturer (alphabetical order)	**TSL Product Name**
BASF Construction Chemicals	Mayco Super lining, BASF white TSL
Carbontech	A-Seal, V-Seal
Concrete Lining Products (CLP)	Superseal
CH Chemicals Pty Ltd	CHC TSL
Chryso Southern Africa Pty Ltd	Chryso TSL
CONCOR Technicrete	D21H, Standard (version 1 and 2)
Geo-Mining	Geo-Mining TSL
Guyric Pipe Company	GPC polyurethane TSL
Hydroflex Pty Ltd	Diamondguard
MBT (Degussa)	Masterseal 845A
Minova RSA	Capcem KT grey and white, Tekflex, Raplok
Nico Du Rand Consultants (NDRC)	Super lining (version 1, 2 and 3)
NS Consultancy	Ultraskin
Precrete-Nozala	Rockliner A, F2, T1, 916, D50
Pumachem CC	Conseal
SA Mining Eng. Supplies	Tunnelguard (2005, 2007, 2009 versions), TGNC, TGNT, TGC
TAL Pty Ltd	TAL TSL

Shotcrete

Shotcrete, being a liner with a larger scale of thickness, was also included in the testing program. It should be possible to see whether TSLs would be suitable alternatives to shotcrete by simply comparing the results of testing between TSLs and shotcrete.

Only one commercially available plain shotcrete commonly used in the mining industry was selected. Inclusion of similar plain shotcrete types from different manufacturers is thought not to significantly affect the test results.

Unlike TSLs, shotcrete contains aggregates with or without fibre reinforcement. Shotcrete sieve analysis tests were not available. However, a few aggregate pieces were measured with their maximum dimension being 15 mm. Due to bigger sizes of aggregates in shotcrete compared to TSLs, shotcrete testing was carried out with modified specimen dimensions for tensile and material shear strength testing. Shotcrete aggregate and fibre content would not interfere with the bonding process.

Steel or polypropylene fibre reinforced shotcrete is excluded from the testing program. Firstly, the mixing of shotcrete with long fibre content, especially steel fibre, is difficult. Secondly, the lengths of fibres are unsuitable for the size of specimens intended for testing. Modifications to the specimen sizes are done considering the aggregate content of shotcrete. Testing of fibre reinforced shotcrete would be possible after further modifications to specimen dimensions to accommodate fibres; however, this option was not exercised due to time constraints. Fibre reinforced shotcrete would not affect the test results for tensile-bond and shear-bond strengths. However, fibres would result in higher strength levels and increase the yield range in tensile and shear strength testing.

The shotcrete curing should be done properly in order to ensure that strength gain is not sacrificed. The issue of shotcrete curing is dealt with in more detail in section 3.3.10.

3.3.4 **Shelf life**

Pappas *et al* (2003) pointed out that the shelf life of liner materials is a critical factor. They stated that shotcrete has an indefinite shelf life (if kept in a warm and dry location), whereas most TSL materials have a shelf life of just 3 to 6 months, and in some cases 12 months. Lacerda and Rispin (2002) observed shelf life to be significantly shorter in warmer environments compared to colder storage. The performance of TSL materials would be reduced when shelf life is exceeded or storage conditions become freezing.

The manufacturers of TSL products, in general, are careful about shelf life when their TSL material is provided for testing. Prompt testing by a laboratory eliminates the risk of testing expired TSL materials. Mines normally purchase their TSL material in bulk which may, in some cases, be stored beyond their shelf life. Expired TSL materials should not be used in mines or tested in a laboratory for quality assurance purposes. Failure to observe shelf life restrictions could result in disagreements between mines and liner manufacturers, and could result in safety issues if applied underground. Testing should also not be delayed unnecessarily in a laboratory, if the passing of the shelf life constitutes a risk of degradation in the strength performance of liners.

3.3.5 **Shrinkage**

Liners with high water contents tend to shrink as the liner material loses the water content while curing. Size reduction causes alterations in the shapes of specimens. The axis of the dog-bone shaped tensile strength specimens particularly become distorted or bent. Distorted dog-bone specimens would fail at a smaller load level due to high tensile stress concentration resulting from the straightening action of the bent axis. A small portion of the tensile strength of such liners can be quantified due to premature failure. Self-detachment of liner material is possible in tests involving a substrate when shrinkage becomes excessive.

The issue of shrinkage could be overlooked during the initial stages of product development. Shrinkage may be noticed during the actual testing of a liner material. Such liner products are either modified by the addition of fibres and admixtures or they are discontinued.

3.3.6 **Mixing and specimen preparation**

Mixing for laboratory tests should follow the proportions suggested by manufacturers. The mix ratios of TSL components are usually indicated on the liner bags supplied. The preparation of a complete set of specimens is not possible in a single mixing of the contents of a whole bag. Therefore, small amounts of one to two kg of TSL components are weighed proportionately and mixed.

Method of mixing

A few options exist for the mixing of TSL materials as can be seen in Figure 6. Firstly, liner components could be mixed by hand with a putty knife, rod or similar object (Figure 6a). Greater time, effort and patience would be required to achieve a homogenous mixture; therefore, this option is not preferred.

Secondly, a small hand-held light-weight power-drill with a mixer attachment, similar to the ones used for mixing paints, could be employed (Figure 6b). Mixing at high speeds causes the formation of a vortex that eventually draws air into the liner mixture. The mixing process should, as far as practically possible, eliminate the incorporation of air bubbles into the liner mixture.

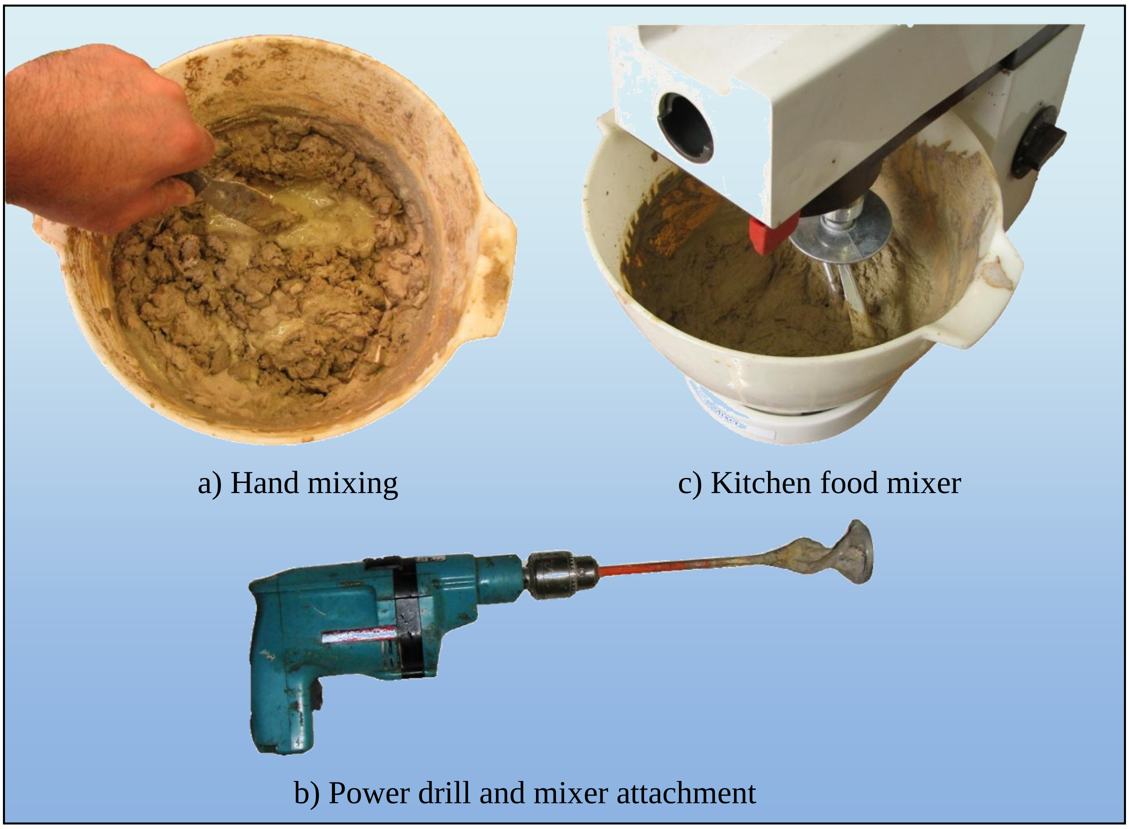


Figure 6. Methods of mixing liners

Thirdly, a kitchen food mixer with variable mixing speeds and several types of mixing adaptors could be used (Figure 6c). Food mixers are capable of simultaneous incorporation of opposing rotations, a similar action employed by some TSL mixers in field applications. This last option of mixing is preferred due to its ease and superior quality of TSL mixture.

Mixing in the initial test trials was done using the second option. Later, a shift towards using a food mixer was made as the testing methods became more established.

Duration of mixing

The duration of mixing of liner components depends on the speed of mixer, type of TSL and amount of TSL material. The cementitious TSLs require less mixing time, typically 1 to 2 minutes, for 1 to 2 kg of liner material at medium mixing speed. A few polymer based flexible TSLs need slightly more mixing time. One polyurethane TSL product requires instant mixing where TSL components are mixed inside a custom made compressed air nozzle.

Duration of mixing should not be shortened as unmixed lobes of material would then be present within the volume of the TSL mixture. A specimen containing unmixed lobes will most likely fail at these locations before the true failure load of the TSL material is reached. Unnecessary lengthening of mixing time should also not be practised to prevent interference with the rheology of the mixture and to prevent the incorporation of more air bubbles into the liner mixture. The setting time of some TSLs may be quite short; therefore, test specimens would need to be prepared rapidly in such cases.

3.3.7 **Method of TSL application**

TSL field applications involve the use of sophisticated pumps and spraying equipment. TSL material is ejected under pressures of 6 to 8 bars (600 to 800 kPa) and the nozzle distance could be 2 to 3 m from the rock surface (Hepworth and Lobato, 2002). Shotcrete also requires compressed air pressure of at least 7 bars (Watt *et al*, 2001). The set-up for preparing laboratory-size specimens cannot handle the pressures from the field type spraying equipment. The forceful impact of sprayed material destabilises or disperses the perspex moulds used in specimen preparation. Therefore, the option of manual pouring of the liner mixture was exercised in this research.

The pouring process after the completion of TSL mixing needs to be faster for some products due to their quick hardening or fast curing characteristics. Alternatively, smaller amounts of TSL should be mixed and smaller numbers of specimens prepared per batch.

TSL spraying in field applications causes the withdrawal of most of the air content from the volume of mixed material. A portion of the air bubbles will burst on the rock surface upon impact. Sprayed TSL, therefore, becomes structurally more compact. The pouring process, on the other hand, does not cause the extraction of air bubbles generated during mixing.

One may argue that the spraying of TSL material would, undoubtedly, influence the test results compared to hand pouring processes. The author's opinion is that whether TSL is sprayed, hand-applied or poured, the differences in the shear-bond and tensile-bond strengths would be negligible. The influence of spraying on UCS, and material tensile and shear strengths would be likely since the material failure is associated with density. Nevertheless, one can say that the overall comparability of test results would still be valid since all of the TSL specimens are prepared using the same technique of mixing and hand pouring. The effect of spraying on the test results is not addressed and quantified within the scope of the research in this thesis and is subject to further research in future.

3.3.8 **Specimen dimensions**

Special consideration is given to specimen dimensions bearing in mind that larger specimens are time consuming to prepare, less cost effective and more difficult to handle on a laboratory scale. Therefore, liner specimens are aimed to be of hand-held, manageable size. The development of testing methods involved several modifications on the specimen fixtures and sizes. As the testing methods became more established no further alterations were done on the specimen dimensions. Therefore, the influence of the change in the specimen size on the test results was avoided. The research results presented in this thesis exclude the results obtained during the initial phases of the development of testing methods.

TSL thickness

The thickness of specimens must be standardised in all the tests since the volume of specimen is directly proportional to its thickness. The TSL thickness in field applications (approximately 5 mm) is taken as a guide in specifying the thickness of specimens used in tensile strength and tensile-bond strength testing.

Small deviations (say up to 20%) in the specimen dimensions or thickness are unlikely to have any significant influence on the test results. Two or three fold increase in the thickness of specimens should, however, be investigated further to understand the sensitivity of TSL testing against thickness.

It is essential that TSL specimens are prepared with uniform thickness. The multiple-cavity moulds made of 5 mm thick perspex shown in Figure 7 prevented variations in specimen thickness. In the preparation of these specimens, the TSL mixture is carefully levelled against the surface of the perspex moulds with a spatula, thus resulting in flat specimens.

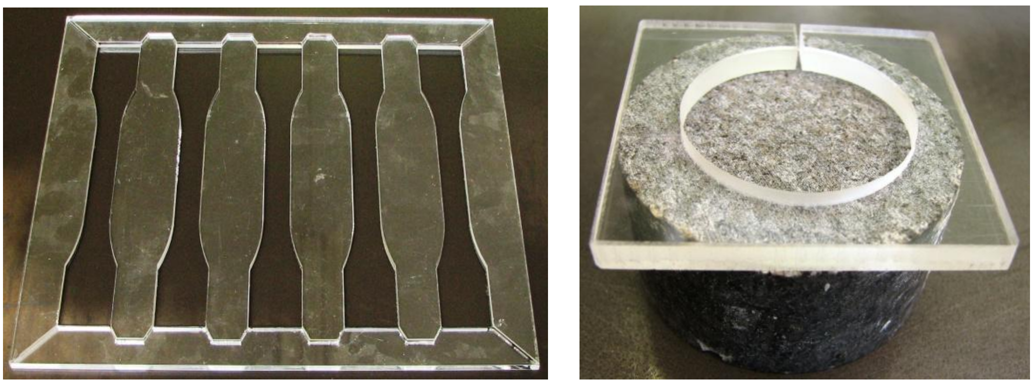


Figure 7. Tensile and tensile-bond strength test specimen moulds for thickness control

3.3.9 Numbers of specimens

Using insufficient numbers of specimens may result in inconsistent and conflicting data brought about by test data scatter. Difficulties and possible errors may also be experienced in curve fitting when the strength increase over the curing period needs to be demonstrated. Therefore, at least five specimens are recommended to be tested at each curing time to be statistically sound. A total of 30 specimens should be prepared in order to comply with five specimens for each curing time.

The requirement of 5 specimens as the minimum number to be tested is not statistically validated. Gill et al. (2005) detailed a rigorous statistical procedure referring to small-sampling theory leading to the determination of the number of specimens to test in the laboratory for the determination of mechanical properties of rocks. The relationships between the number of specimens in a group, the coefficient of variation obtained after testing the specimens, the targeted precision index and confidence interval are given. However, the complicated process adopted by Gill et al. (2005) will not be covered in this thesis. Instead, sample sizes suggested by ISRM for the most common rock property testing are taken as reference as seen in Table 13 in the decision given on the minimum sample size of 5.

Table 13. Sample sizes as suggested by the ISRM (after Gill et al., 2005)

Test type	Sample size
Uniaxial compression: Bieniawski and Bernede (1979)	Determined from practical consideration but at least five are preferred
Direct and indirect tensile strength: Bieniawski and Hawkes (1978)	Determined from practical consideration but at least five are preferred
Point load test: Franklin (1985)	At least 10, more if heterogeneous or anisotropic. The two lowest and highest values should be discarded
Triaxial: Vogler and Kovari (1978)	Determined from practical consideration but at least five are preferred
Shore hardness: Atkinson et al. (1978)	A large number
Porosity/Density: Franklin (1979)	At least three

3.3.10 **Environmental conditions**

Some manufacturers of cementitious TSLs claim increasing strengths at higher temperatures and reduced strengths or slower strength development at lower temperatures. Rispin and Garshol (2003) stated that TSLs involve chemical reactions, and that temperature is a key determinant in reaction dynamics. Therefore sensitivities to changes and extremes in temperature must always be evaluated when considering a TSL for a particular application. Swan *et al* (2003) observed that the 3M Mining Liner contains about 40% water at the time of application to a surface. As this water evaporates the liner's strength, stiffness and adhesion increase significantly. Their tests have shown that the rate of evaporation depends upon ambient rock/air temperature, humidity and airflow or ventilation. Moisture loss from TSL is necessary throughout the curing process. The greater the temperature and humidity differentials between the TSL material and mine air the more accelerated the moisture loss is. The combination of high temperature and low relative humidity causes the highest moisture loss on TSL's. As a result, quicker setting and strength development, which is a desired property, take place. The temperature and humidity levels in a mining environment are, therefore, important and should be approximated when testing and evaluation of TSL's performance are done in laboratory environmental conditions.

Mining environment

Environmental conditions experienced at mines can reach extreme levels. Mines may be hot, cold or humid depending on ventilation and surface weather that is influenced by the global location. Mining activities take place under freezing temperatures in Northern America, Northern Europe and Siberia. Development of tunnels under special circumstances may necessitate the use of ground freeze techniques. In such cases, the temperature of the mine air is kept at workable levels for worker's comfort; however, TSL needs to set on a cold surface that may have significant effects on TSL's curing and performance. During rainy seasons, areas nearby the intake air in many mines may experience 100% humidity which may, again, significantly interfere with the curing and bonding of some TSLs (Pappas *et al*, 2003).

Deep level mines, on the other hand, may experience virgin rock-surface temperatures of around 80°C. Ventilation and cooling plants help to reduce high air temperatures down to workable levels of around 30°C. High temperatures would still be experienced at the times of ventilation difficulties such as fan malfunctions, airflow obstructions due to falls of ground, and major air leaks through ventilation seals. Mineworkers are withdrawn from such areas until the hazardous condition is remedied. However, mining equipment, material and TSL support have to remain behind in a high temperature environment.

It is good practice to record temperature and relative humidity levels at a mine and establish their relationship. In some cases, the relationship may be inverse in that as temperature increases, relative humidity decreases, and vice versa. In other cases on the contrary, temperature and relative humidity may show a direct relationship. The combinations of temperature and moisture in the mining environment need to be taken into account when assessing TSL performance and support design.

Laboratory environment

Seasonal variations in the levels of outdoor temperature and humidity exist, however indoor or laboratory environmental conditions are more stable. The humidity and temperature values were reasonably uniform in laboratory for the required curing periods. The range for temperature and humidity values was between 22° and 28°, and 50% and 60% respectively, as illustrated in Figure 8. In addition, no through-flow of ventilation and direct sunlight, that are the causes of air drying and accelerated evaporation, occurred in the location where specimens were prepared, cured and tested. The approximate 20% variation in the environmental conditions is considered to have had minimal influence on the test results. The influence of temperature and humidity on the test results cannot be neglected; however these influences were not investigated in this research. Figure 8 shows the areas outside laboratory temperature and relative humidity ranges that need further research.

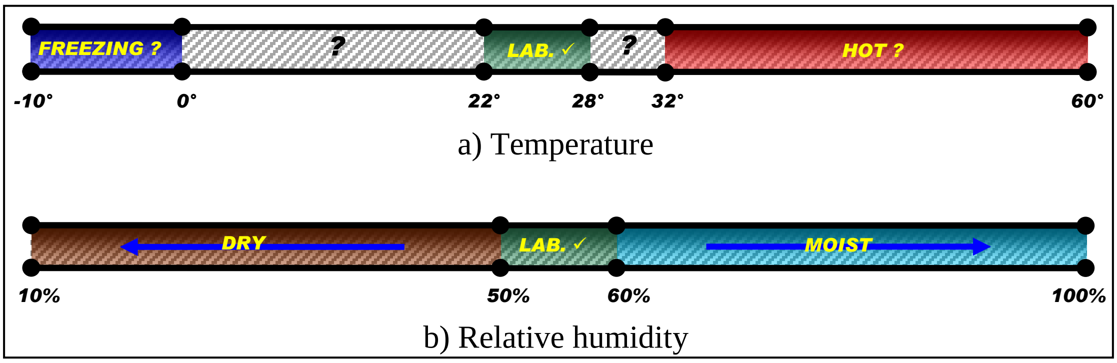


Figure 8. Standard temperature and relative humidity ranges for laboratory testing and ranges that need further testing

Cementitious materials and shotcrete require a moist environment to mature. Windsor (2001) presented a good summary of the rules for curing concrete and stated that the protection of shotcrete against evaporation is necessary during the first most critical hours/days. The cement should be allowed to hydrate continuously. A water-desiccator, as shown in Figure 9, is used to prevent the rapid drying of shotcrete and to maintain humidity levels during the curing process. The shotcrete specimens were kept in the desiccator soon after preparation and only taken out at the time of testing.

Figure 9. Water-desiccator used for the cementitious TSLs and shotcrete

3.3.11 **Curing time**

Various factors, such as curing time, temperature, humidity, substrate type, substrate condition, method of application, specimen size, and rate of loading may significantly influence the performance of TSL materials. Curing time (time elapsing from the completion of specimen preparation to testing) is chosen as the main parameter to be tested in the testing programme described in this thesis.

Spearing (2003) stated that the rate of strength gain, and not only the ultimate strength value at 28 days, is important. One day and 28 days were selected as the lowest and highest limits of the curing period. The tests were performed for six curing times (1, 2, 4, 7, 14 and 28 days) to provide a range that is considered to demonstrate the strength development. Tests for long curing times were excluded from the testing program since the experience with shotcrete demonstrated insignificant strength gain beyond 28 days (Kumar *et al*, 2002).

Tensile, shear and shear-bond tests can be performed at 1, 2, 6 or 12 hours for the fast setting TSLs to observe the early strength development if quick strength development is claimed by any liner supplier. Tensile-bond strength testing cannot be carried out in less than 24 hours since it requires the application of an epoxy that may take up to 24 hours to set and reach its full bond strength.

3.3.12 **Setting time**

Setting time can be defined as the time required for a liner material to solidify after mixing takes place. The pumping of liner material becomes impossible when setting takes place since the material flow stops. Difficulties would be experienced during specimen preparation by quick setting TSLs in that the preparation of the whole set of specimens would not be completed on time. Unfortunately; the process of specimen preparation cannot be rushed and should be done properly. Preparation of all the specimens should, therefore, be done in parts by mixing proportionately smaller amounts of liner material for quick setting TSLs.

3.3.13 **Loading rate**

Loading rate is parameter that affects the result of any TSL testing. Higher loading rates in rock testing result in higher strength levels; therefore, similar behaviour is expected in TSL testing. Kuijpers (2001) experienced larger support resistance with higher loading rates in punch tests. Similarly, slower loading imposes fatigue in the material causing failure at reduced load levels. In order to understand the expected performance of liner materials in actual applications, one may need to consider the behaviour of other support types under the same conditions. Underground performance of timber support, for example, is lower than laboratory performance due to differences in environmental conditions and much slower loading rate. Therefore, laboratory test results for such timber supports are downgraded using loading rate adjustment curves to estimate the underground performance (Daehnke *et al*, 2001).

The standard loading rate criterion adopted is that the peak load should be reached within 3 minutes of the load initiation. A small amount of initial load is applied on specimens before the actual testing takes place in order to position the specimen assembly within the testing machine. Displacement control and load control modes are the available options for the loading of specimens. Long term or creep tests and dynamic testing are excluded from the scope of testing in this research due to the time constraints.

The strengths of weak and strong TSLs may differ by a factor of up to 8 or 10 times. The implication for strong TSLs is that the testing may require 8 to 10 fold increase in time if a single TSL loading rate was to be specified. The loading rate, therefore, should be increased to meet the criterion of failure within 3 minutes. A few test trials may need to be performed to establish the expected strength level of a TSL so that a decision can be made on the required loading rate.

3.4 Summary and conclusions

This chapter includes comprehensive discussions on the following aspects that are found to be useful since due consideration was given to them during the development of testing methods:

- Various test options to address TSL mechanical properties with particular attention to boundary conditions and mechanism of loading.
- Test requirements.
- Test parameters that may have a direct influence on the test results.

The general acceptance of any proposed testing methodology depends on the fulfilment of test requirements. For example, testing methods requiring smaller specimen sizes are always preferable due to their reduced costs and quicker specimen preparation.

Testing involves numerous parameters that need to be controlled at all stages, from the start of specimen preparation to the end of testing. Any variation on these factors will have a direct bearing on test results therefore standardisation is necessary. The curing time is considered to be the most important parameter. The interval of curing times at earlier stages is selected to be shorter in an attempt to capture the early strength development. The sensitivity of testing methods for the remaining factors needs to be established by further investigations. Significant amount of testing and research effort are still needed for the relatively new concept of TSL technology.

The next four chapters discuss the shear and tensile strength testing methods that are illustrated in Figure 5 in this chapter. These are the shear-bond, material shear, tensile and tensile-bond strength tests.

CHAPTER 4 SHEAR-BOND STRENGTH TESTING

The preceding chapter indicated various test options and parameters that need to be considered for the development of testing methods. One of these test options involving shear-bond mechanism (illustrated in Figure 10) is the subject of the testing methodology developed in this chapter.

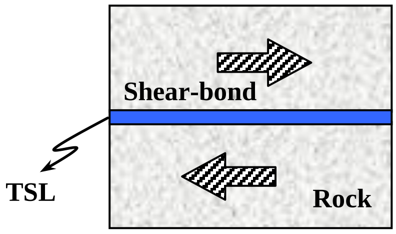


Figure 10. The shear-bond mechanism

The determination of TSL mechanical properties has been attempted by conducting a number of testing methods in the past as mentioned in the literature review; however, no emphasis was given to developing test set-ups for the determination of shear strength characteristics. Considering the penetration of TSL material into the cracks on the excavation surfaces and the type of rock movements that could occur, two shear mechanisms (shear-bond and material shear) were targeted in the development of the new testing methodologies.

The penetration of TSL into cracks and joints in the rock mass is necessary for the mechanism of shear-bond to be effective. Shear-bond strength principally addresses the ability of a TSL to resist stresses that act parallel to the rock-TSL interface.

Potential TSL support mechanisms have been described by Stacey (2001). The following mechanism mentioned, amongst others (air tightness, basket mechanism, slab enhancement, beam enhancement, extended faceplate), is particularly relevant to shear-bond strength characteristics of a TSL:

"Promotion of block interlock: the effect of this mechanism is the preservation of the rock mass in a substantially unloosened condition. There are several sub-mechanisms involved in the promotion of block interlock. The penetration of membrane material into joints and cracks will inhibit movement of block. This mechanism is considered to be particularly relevant in very high stress situations in which some loosening will have taken place and in which on-going stress-induced fracturing is occurring." (Stacey, 2001, p344).

Stacey and Yu (2004) subsequently investigated the influence of several parameters on the liner support capacity by carrying out finite element stress analysis. They demonstrated that liner penetration into joints and fractures results in a significant support mechanism. Quantification of shear-bond strength by a suitable testing method is, therefore, essential and the value determined from such tests could be an important parameter in support design.

4.1 Shear-bond strength test considerations

This section provides a discussion of aspects that particularly relate to the shear-bond strength testing. The common aspects for all the proposed testing methodologies were provided in detail in Chapter 3 and are not repeated here. The shear-bond testing methodology is developed with due regard to these considerations.

4.1.1 **In-situ loading mechanism**

The TSL, as applied to a rock surface, is expected to penetrate into open rock fractures. This is an important requirement that needs to be observed by TSL manufacturers. Figure 11 illustrates the possibility of TSL being applied both on the excavation surface and inside a crack. Any strike, dip or apparent dip movements will cause shear loading of the TSL-rock contact and consequent failure when the shear-bond strength is exceeded. The displacement mechanism employed in the testing method should be representative of this type of shear loading along the plane of the fracture. In some cases, dilation of fracture surfaces is also possible; however, this mechanism is not simulated in the shear-bond testing method developed.

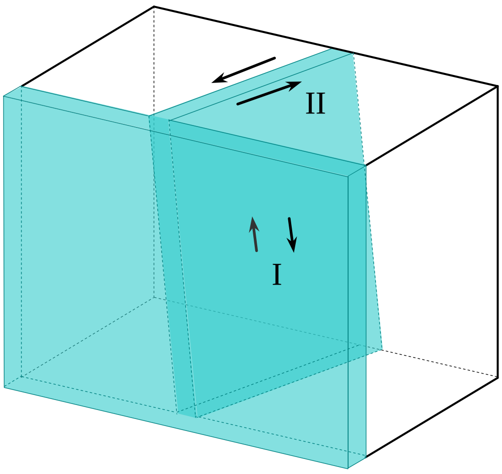


Figure 11. In-situ loading mechanism of TSL relevant to shear-bond strength testing

4.1.2 Complications in the application of shear load during testing

The application of shear loading on a laboratory specimen to prevent or at least minimise any rotation or bending of the specimen is an extremely difficult problem. This is illustrated by the results of Saydam *et al*, (2003) who performed double-sided shear strength (DSS) testing. Their TSL bond failure was influenced by tension rather than shear due to the bending of blocks (Figure 12). Inherently, the interpretation of DSS testing results became complicated. The blocks A and B in DSS testing needed to be clamped firmly on a support base to prevent any rotation of these blocks.

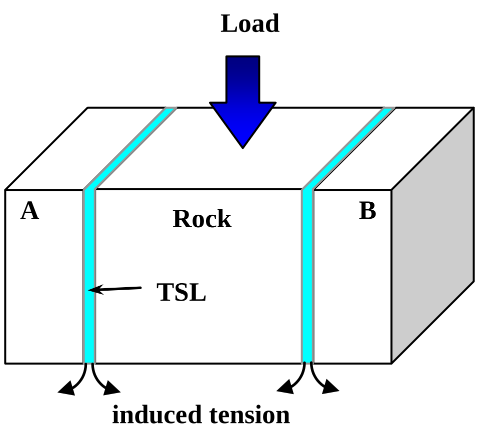


Figure 12. Problem of bending and induced tension during DSS testing due to poor clamping

4.1.3 **Test fixture and specimen assembly**

A 20 mm thick steel-ring with a 52.5 mm diameter inner hole is used for housing TSL and a rock core of 27.5 mm diameter. The rock core is centrally positioned in the steel-ring as seen in Figure 13. The gap between the steel-ring and the rock core is filled with TSL by pouring. After the curing of the TSL for the predetermined period, the specimen is placed on a base which offers support to the steel-ring and the TSL but not to the rock core. A compressive load is applied on the rock core, displacing the core on the rock/TSL contact towards the void in the support base. The loading and failure of the TSL take place due to shear movement at the rock/TSL contact. Load deformation characteristics are observed until the TSL has failed.

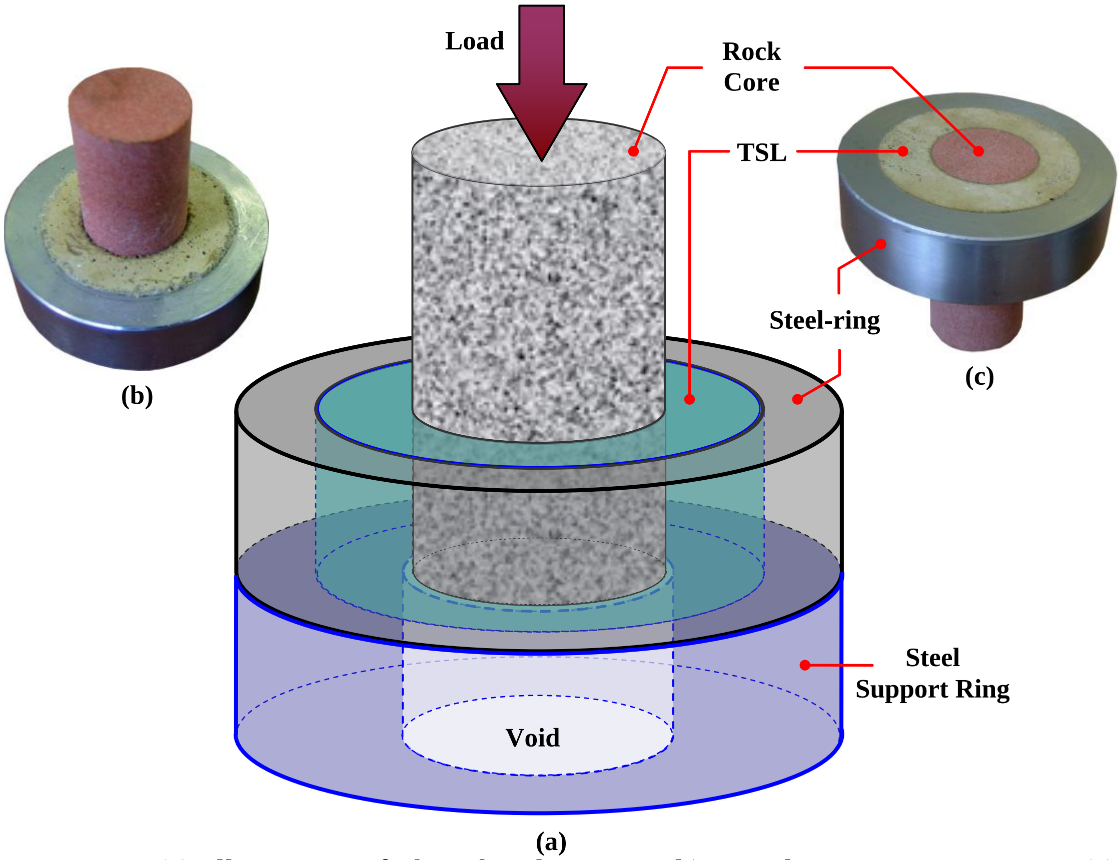


Figure 13. (a) Illustration of shear-bond testing, (b) actual specimen top view, (c) actual specimen bottom view

The problem of bending in the shear-bond strength testing, as discussed in the previous section, is overcome by imposing circumferential continuity of the TSL around a rock core. Therefore, the block rotation resulting from the use of discrete blocks is avoided. When the prepared specimen is positioned on a support ring and load is applied on the rock core, no bending is involved therefore no clamping is necessary.

4.1.4 **Boundary conditions**

The boundary conditions on the specimen assembly are shown in Figure 14. Load is applied on the top surface of the core with the reaction taking place on the fixed support base indicated by the red lines. The green lines are the stress free surfaces. The brown lines are the fixed contacts between *TSL↔steel-ring* and *steel-ring↔steel support ring*. The yellow line is where bonding of rock and TSL takes place. The test is designed to measure the bond resistance at this position due to shear movement. The yellow and green lines on the rock core are displaced when the load is applied in shear-bond strength testing.

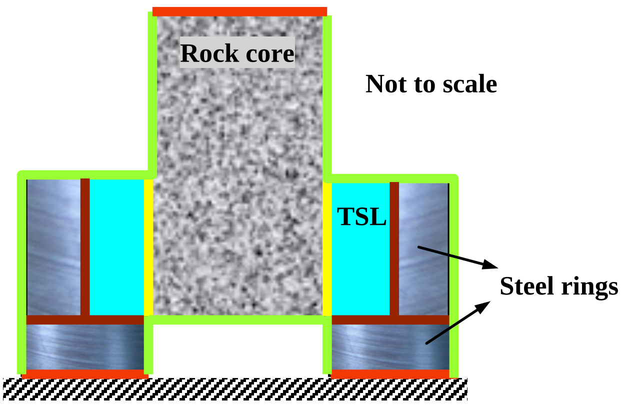


Figure 14. Boundary conditions in shear-bond strength testing

4.1.5 **Loading rate**

The two options for loading are load control mode and displacement control mode. When the load control mode is used the time to failure for high strength TSLs could extend beyond 5 minutes. On the other hand, shear displacement required to achieve failure is expected to be contained in a limited range. Therefore, the option of displacement control mode is exercised for the loading in shear-bond strength testing.

4.1.6 **Substrate rock type and surface condition**

From a range of available rock types, norite was selected to be used as the substrate primarily due to its availability, high uniaxial compressive strength (UCS), which is approximately 200 MPa, and competent surface conditions. Weaker rocks have the possibility of failing in uniaxial compression in the case of TSLs with high shear-bond strength. The easy cleaning of norite after testing was advantageous since it was then possible to re-use the core in many other shear-bond tests. In this manner, the risk of running short of rock cores was avoided.

The surface roughness is another factor that needs to be considered for shear tests. Rougher surfaces inevitably cause higher resistance against shear movements. The surface roughness that is the outcome of the diamond coring process is used as standard substrate finish in all the tests. The difference in the roughness profiles of numerous rock cores is therefore minimised. The sensitivity of shear-bond strength to various rock types (such as kimberlite, which is water sensitive) and substrate roughness profiles is not investigated; however, it will be the subject of future research.

4.1.7 **Calculations**

Shear movement on the rock-TSL boundary develops shear stress (τ_b) which can be calculated from:

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

where; F: applied force (N)

D: rock core diameter (m)

t : TSL depth or steel-ring height (m)

Equation (1) can be further simplified as

Equation 2; $$\tau_b = \frac{F}{A}$$

where; A: Core-TSL contact area (m^2)

The stress at the peak force level is taken as the shear-bond strength.

4.2 Description of apparatus, specimen preparation and test procedures

A detailed description of test apparatus, and the procedures followed in specimen preparation and test execution are provided in the following sections.

4.2.1 **Specimen components and dimensions**

Steel-ring

The steel-ring is used for the purpose of housing the TSL and rock core. The TSL bonds onto the inner surface of the steel-ring and the rock core. While the movement on the core surface takes place, no displacement on the steel-ring contact surface is permitted. De-bonding takes place only on the core surface, the bonding of TSL to the steel-ring is for containment reasons. Steel is preferred for the ring due to its high strength and low cost. The steel-ring dimensions selected also assist in the pouring of TSL into the void between the rock core and the steel-ring. The dimensions used for the steel-ring are illustrated in Figure 15a.

- Outer diameter, (D_o): 72 mm
- Inner diameter, (D_i): 52 mm
- Height, (t): 20 mm

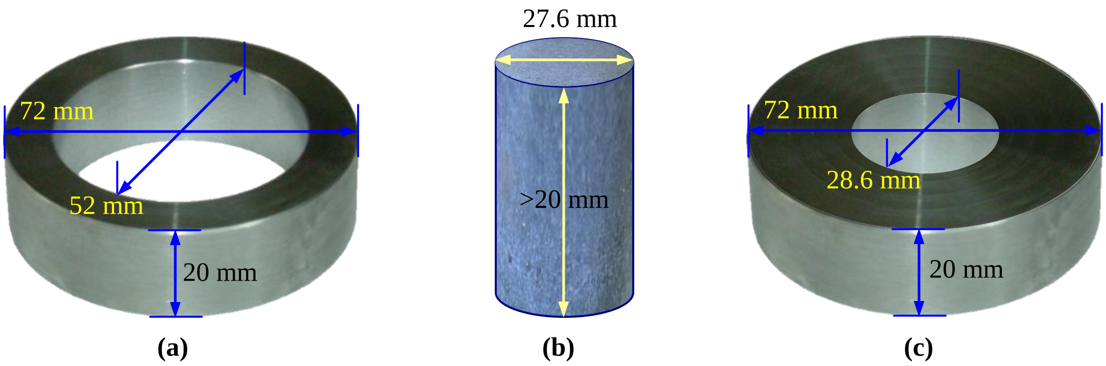


Figure 15. Dimensions of a) Steel-ring b) Rock core and c) Steel support ring

Rock core

The side of the rock core is used as the substrate and no processing of this surface is done in addition to diamond drill machine coring. The top and bottom surfaces of the core should ideally be flat and parallel.

The core dimensions are illustrated in Figure 15b. The two main reasons for selecting a core diameter of 27,6 mm are firstly the availability of a diamond drill barrel at this particular size. Secondly, the space between the inner surface of steel-ring and rock core (annulus approximately 12 mm) is adequate for pouring TSL easily. Early trials have shown that a reduced annulus due to a larger core diameter causes pouring difficulties, especially when TSL material is viscous or fast curing. Increasing this annulus may be considered by increasing the steel-ring size for facilitating the pouring of TSL. The length of core should be more than the steel-ring thickness, preferably two to three times as much.

Steel support ring

The prepared specimen, consisting of TSL, steel-ring and rock core, is placed on the steel support ring which is shown in Figure 15c. Both the steel-ring and the support ring are similar the only difference being that the inner-hole diameter of the support ring is smaller (28,6 mm). This inner diameter, however, is 1 mm greater than the rock core diameter to allow the core movement into the void of the support ring with minimal resistance. The function of the steel support ring is to facilitate the movement of the rock core and to inhibit any movement of the TSL and the steel ring that houses the TSL. In this way the movement of the rock core is such that failure can only take place at the TSL-rock core contact surface.

4.2.2 Specimen preparation

The steps followed during the specimen preparation are illustrated in Figure 16. Firstly, the rock core is centrally positioned in the steel-ring. After that, approximately 1 to 1.5 kg of TSL components are taken and mixed thoroughly according to manufacturer's specification using kitchen food-mixer (See the photo in Figure 6c in section 3.3.6). TSL is then poured into the space between the core and the ring. A putty knife is used to assist in the settling of the TSL in position. Flattening of TSL's exposed top surface will ensure uniform TSL thickness. Flattening may be done by tamping a sheet of plastic against this surface. Most TSLs are found to bond very weakly to plastic sheets that are removed easily after a short period of curing.

The core and the steel-ring axis should remain parallel and preferably be aligned in the same direction. Flat core ends as mentioned above assist in achieving this. In addition, the ring and core should be placed on a flat surface so that they do not move when the TSL is poured.

The bonding of TSL to the working surface, steel-ring and the surfaces of the core other than the intended position causes cleaning problems. A number of TSL products are found to bond strongly, and the removal of spilled TSL material on these surfaces is very difficult if the removal process is delayed. Plastic sheets were used to prevent contact of TSLs with the working surface. Machine oil or grease is applied on the top, bottom and side surfaces of the steel ring. The inner surface of the steel ring is intended to bond with the TSL and therefore is not oiled. Finally, masking tape was used to prevent the TSL from coming into contact with the core surfaces where bonding is not desired.

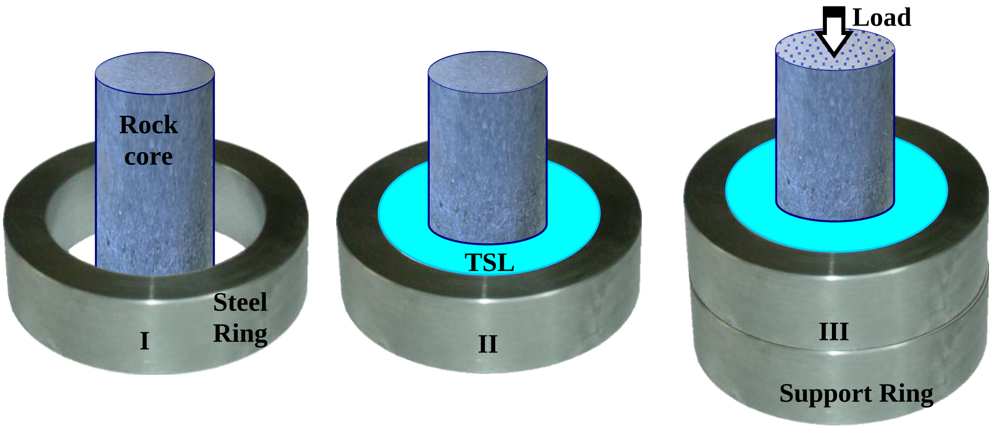


Figure 16. Steps followed during specimen preparation in shear-bond strength testing

4.2.3 Test set-up and execution

The prepared specimen is carefully placed on top of the steel support ring and then positioned in the MTS loading machine. As seen in Figure 17, a spherical seat is used on the top surface of the norite core in order to ensure that the load is uniformly distributed. The machine platen is allowed to make contact with the spherical seat. At this stage a few Newtons of initial load, in the order of 5 to 10 Newtons, is carefully imposed on the specimen. The direction of the movement of the machine platens during testing should be in line with the direction of the bond surface and core axis. Loading is done in displacement control mode. The specimen is initially loaded up to 0,01 mm at 0,001 mm/s for alignment and setting of the specimen, and then at 0,002 mm/s up to failure. Initial trials showed that these loading rates would cause the failure of TSL bonding within 3 minutes of the start of loading. Load and machine displacement are recorded by the data capturing program of the MTS machine. The load at failure was noted for the subsequent strength calculations (Equation 1).

After the test, the loading machine is used to push out the rock core (Figure 18) by means of a smaller diameter steel rod. The remaining TSL is also pushed out of the steel ring in a similar manner by using a rock core that is a few mm smaller than the inside diameter of the steel ring. Figure 18c shows the height of the removed TSL-ring (t). This height must be measured in order to calculate the de-bond area (Equation 2). The TSL height is measured in three positions spaced evenly apart and the average of these measurements is calculated. The height of TSL should, in practice, be equal to the steel-ring height. However, it is good practice to take this measurement to consider any deviations from the expected height.

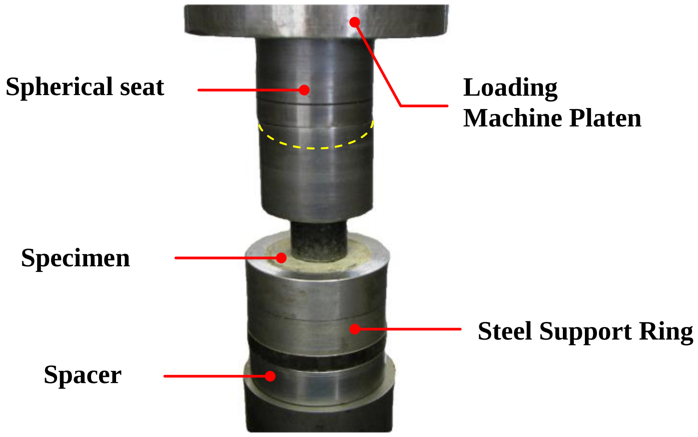
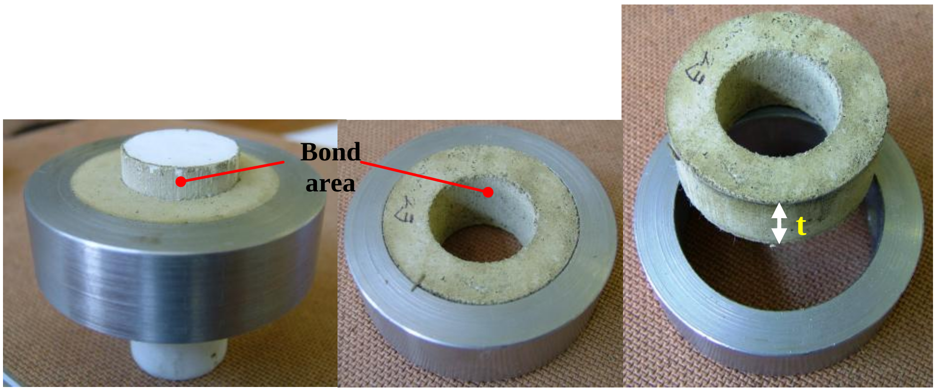


Figure 17. Specimen loading in the testing machine



a) b) c)

Figure 18. Specimen a) after test, b) after core removal, c) after TSL-ring removal

One advantage of this method of shear-bond strength testing is that none of the components of the specimen is damaged during testing. The extraction of the core and the TSL out of the specimen assembly is easy. The steel-ring and the rock core can be used in many other tests. The rock core may, in some cases, need to be cleaned of stains of TSL simply by using sandpaper with no damage resulting to the core surface.

4.2.4 **Failure mode**

The failure of rock core is not a concern since the rock core strength is not achieved. The only failure takes place on the TSL-rock core contact surface as seen in Figure 18a. Once the rock core is taken out, it leaves a well-defined surface where shear de-bonding takes place (Figure 18b). The reason for having the failure particularly on TSL-rock core contact is that the support ring only allows movement along this contact surface. Having consistent failure location for all TSL materials makes the interpretation of test results easier. The bond area could easily be seen (Figure 18a) on the rock core as an imprint after testing.

4.3 Results and analysis

Figure 19 shows a typical example of the load-displacement behavior of one of the specimens during the shear-bond strength testing. The loading is initially concave upwards pointing to the setting of the machine and the specimen. The majority of the increase in loading takes place in the linear portion of the pre-failure stage. The rate of deformation increases shortly before the failure load and the shape of the graph becomes concave downwards. The shear-bond failure is often reflected by a sudden drop in the load level.

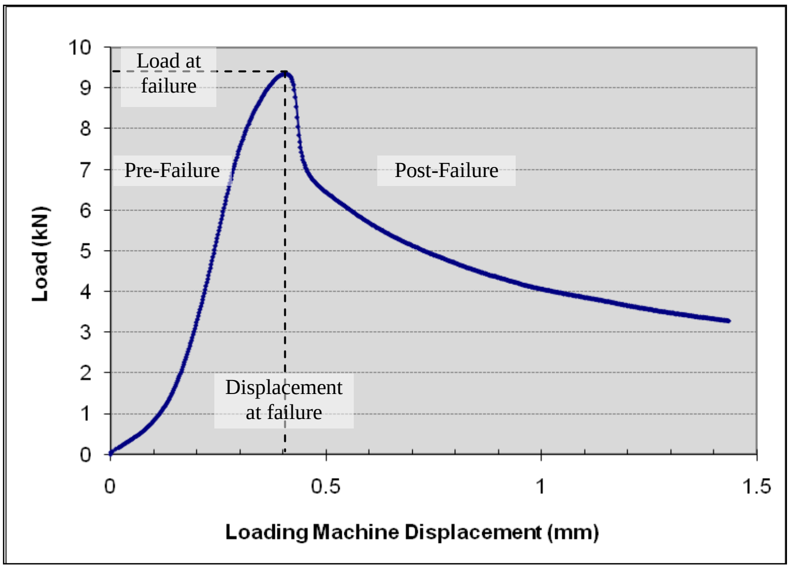


Figure 19. An example of the load-displacement curve during shear-bond strength testing

As the shear-bond failure continues, the load on the specimen progressively decreases. The residual load level cannot be seen during this test due to the progressive de-bonding that reduces the failure area.

Load versus displacement graphs for individual tests are available, but are not shown in the body of this thesis due to the large number of tests done (approximately 900 for shear-bond strength test only). However, the full sets of test results and additional photographs for the four testing methods are contained on the CD ROM in the last Appendix X. Summary graphs of shear-bond strength against the full curing period for three liner products T, E and shotcrete are shown as examples in Figure 20. The result of each shear-bond strength test is represented by a data point in Figure 20. The averages of shear-bond strengths at each curing time are also indicated on these graphs as markers filled in red. The best fit curve is found to be logarithmic and it was applied for all the data points on a graph excluding the averages. Additionally, equations and correlation coefficients (R^2) of the best fit curves can be seen on the graphs. Appendix II presents these summary graphs for all of the TSL products separately. The scales of the graphs in Appendix II are the same for easy comparison.

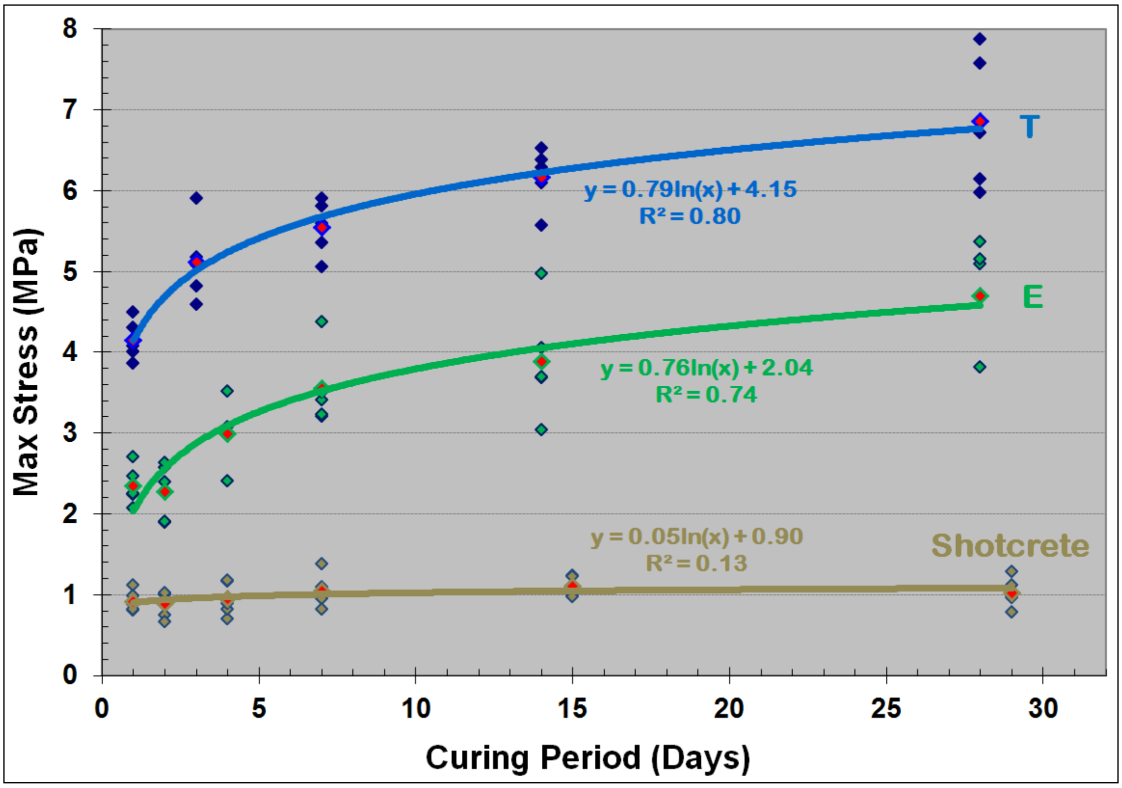


Figure 20. Example curves in the shear-bond strength range

The applicability of the logarithmic best fit curve is limited to the testing period defined by 1 day to 28 days of curing. Extension of the logarithmic function beyond these limits is not valid. The testing and measurement of TSL strength at curing periods shorter than 1 day and closer to time zero is practically difficult due to the following reasons:

- Mixing of TSL components and then subsequent pouring of TSL mixture into the moulds followed by the final extraction of specimens from the moulds require notable amount of time before the testing of the specimen becomes possible. This time for slow curing TSLs could be as much as 24 hours.
- The newly prepared specimens are easily damaged if they are removed at an earlier time from perspex moulds or while handling at earlier stages.
- The epoxy used in tensile-bond strength testing gains its maximum strength in 24 hours. The epoxy is applied on the specimen surface after TSL attains sufficient surface hardness.
- Most TSL products used were cement-polymer based and therefore the development of strength was slow. Therefore, the specimens were weak for testing at earlier periods.
- The applicability of data in the shaded area for support design purposes is questionable.

A power formula for the regression line is an alternative if the trend line is extended closer to time zero, especially for a few quick curing TSLs that could be tested after a few hours of specimen preparation. However, these quick setting TSLs would also not be tested at time zero that is the instant of the completion of the mixing process. The use of the logarithmic regression line is preferred since:

- The testing in less than 1 day was not possible for most TSLs due to the reasons mentioned in the previous bullet points.
- The regression line is only applicable for the curing period.
- The logarithmic regression line resulted in higher correlation coefficients.
- The strength at time zero is not absolutely zero, as the power formula predicts.

Figure 21 shows the best fit curves depicting the shear-bond strength development as a function of curing time for all TSL products. Shear-bond strength behaviour for different products as well as different versions of the same product is clearly distinguishable. For example TSLs G, C and T are the 2005, 2007 and 2009 versions of the same brand product respectively. TSLs A, R and F are polyurethane based; however they are different brands. All the TSL products in the market, in general, show strength improvement over time.

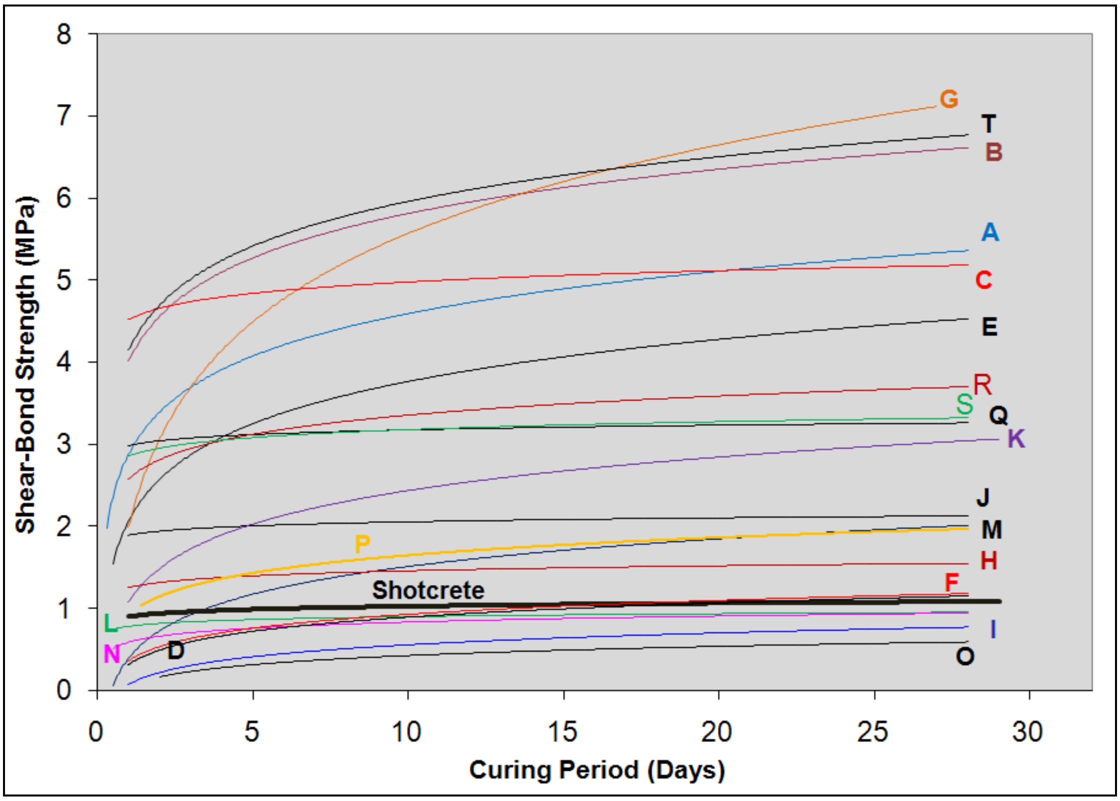


Figure 21. Shear-bond strength results

Shear-bond strengths can be clustered into four groups taking the improvement of strength over 28 days into account as illustrated in Figure 22. The categories of shear-bond strengths in this figure represent weak, medium, strong and very strong TSL materials. The time-dependent strength increase in Group I TSLs is not as remarkable as the TSLs in the other groups. One of the reasons may be the high water content of Group I TSLs which were prepared by mixing powder with water. Interestingly, shotcrete which is prepared in a similar manner falls in the Group I. The powder materials of Groups II, III and IV TSLs are normally mixed directly with polymer, not water. Note that shotcrete lies in the weak shear-bond strength category.

The shear-bond strength equations, correlation coefficients (R^2) and strength rankings for all products are listed in Table 14. The strength equations and R^2 are determined by setting the trend lines to best fit the test results in a spread sheet program. Some of the correlation coefficients in the low and medium strength category products are quite low. Examples are products Q, J H and shotcrete, which are water-based cementitious TSLs. In general, there are more TSLs with high R^2 values; therefore, the testing method confidently displays the strength improvement over the duration of 28 days. Coefficients for products T, G, A, E, D, I and O are, in particular, remarkably high. The ranking of TSLs in Table 14 uses the 28 day shear-bond strength as a basis. The ranking would change slightly if another period was selected.

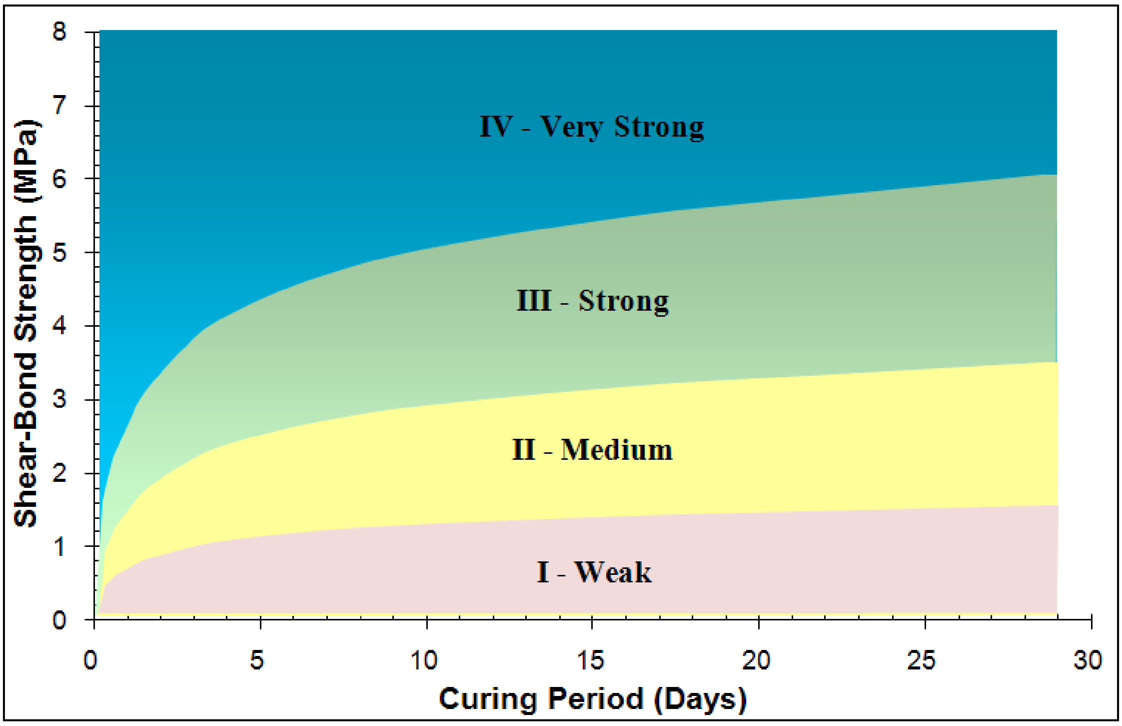


Figure 22. Shear-bond strength categories

The percentage of TSL products tested in the weak and medium strength categories is 71.4%. This means that there are only a few products available in the market in the higher shear-bond strength categories.

Detailed statistics on the test results in terms of mean strengths, standard deviations and coefficients of variation (CV) corresponding with each testing day are summarised in Appendix III for all the TSLs tested. Standard deviations in Category IV TSLs (T, B, and G) are comparably higher than the other categories. Standard deviation increases as the shear-bond strength increases. The main reason for using CV (note that CV is given in %) in Appendix III is that CV is a better parameter to measure the dispersion of the shear-bond strength values. There is no definite trend in the spread of CV over the testing period. Some materials (H, I, N, M and P) show decreasing CV, while the remaining ones show increasing CV over 28 days. CV of shotcrete remains noticeably around similar values.

Table 14. Shear-bond strength equation, correlation coefficients and ranking according to 28 day strength

TSL	Shear-Bond Strength Equation (MPa)	R^2	Rank	Strength Category
T	0.79ln(x) + 4.15	0.80	1	IV - Very Strong
B	0.77ln(x) + 4.00	0.31	2	
G	1.60ln(x) + 1.95	0.73	3	
A	0.71ln(x) + 2.89	0.70	4	III - Strong
C	0.20ln(x) + 4.53	0.17	5	
E	0.74ln(x) + 2.06	0.74	6	
Q	0.07ln(x) + 3.00	0.03	7	II - Medium
R	0.41ln(x) + 2.48	0.27	8	
S	0.16ln(x) + 2.81	0.12	9	
K	0.59ln(x) + 1.08	0.63	10	
J	0.08ln(x) + 1.86	0.02	11	
P	0.32ln(x) + 0.91	0.61	12	
M	0.48ln(x) + 0.47	0.59	13	
H	0.04ln(x) + 1.30	0.01	14	I - Weak
D	0.25ln(x) + 0.32	0.80	15	
Shotcrete	0.05ln(x) + 0.90	0.13	16	
L	0.05ln(x) + 0.78	0.07	17	
F	0.24ln(x) + 0.36	0.55	18	
I	0.21ln(x) + 0.07	0.82	19	
N	0.11ln(x) + 0.59	0.13	20	
O	0.16ln(x) + 0.05	0.78	21	

x: curing period in days

4.3.1 **Repeatability index**

Assessment of the repeatability of testing methods could be done from the test results. However, repeatability comparison or judgement on repeatability would only be possible if data from the other testing methods are obtained under similar test conditions and curing periods. Bearing in mind that the calculation of CV incorporates the number of tests for an individual liner product, a simple "repeatability index" for a particular testing method is proposed in this thesis as following:

Equation 3; Repeatability Index; $RI = \frac{\sum CV}{N}$

Where;

ΣCV: is the sum of coefficients of variation at all curing times for all liner products, and

N: is the total number of curing times at which testing takes place.

The repeatability index calculated using Equation 3 is considered to compare the degree of variation or repeatability from one testing method to another. The smaller the repeatability index the more repeatable the testing method. Appendix III shows that ΣCV is 2091.6 and N is 104 for all the shear-bond strength tests and the value of the repeatability index then becomes 20.1. A general comparison and discussion will be made in Chapter 8 once the repeatability indexes for the remaining three testing methods are determined.

Figure 23 shows the distribution of average CV% for the individual TSLs together with the value of the repeatability index. TSL products T, C and G are different versions the same brand. These liner products are positioned in high strength categories and their testing results indicate low average CV% and therefore higher repeatability. The data presented in Figure 23, otherwise, does not show a distinctive trend in the distribution of average CV between TSLs belonging to different strength groups.

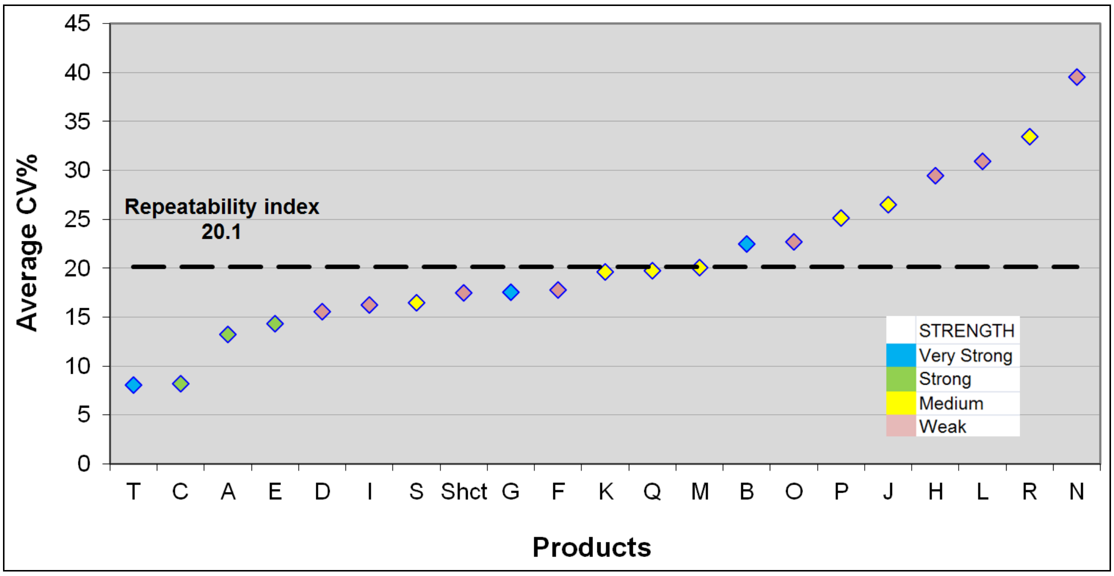


Figure 23. Distribution of average CV% for the TSL products in shear-bond strength testing

4.4 Summary and conclusions

The quantification of TSL bond resistance against shear, taking into account the penetration of TSL into the cracks on the applied rock surface, has been overlooked by researchers so far. Therefore, the main aim of the proposed testing method is to measure the shear-bond strength of TSLs. One of the in-situ loading and failure mechanisms of TSLs is also simulated with the help of the testing method developed. Shear-bond strength testing involves the use of a rock substrate; therefore, the interaction between the TSL material and the rock surface is taken into account.

The components used during specimen preparation are small and manageable. Therefore, specimen preparation is quite easy, simple, quick and low cost. The test execution is also simple. Loading takes place in a compressive manner along the core axis which then translates into shear stresses on the TSL-rock substrate contact. The same test can easily be performed anywhere else with minimal difficulty due to its portable and simple specimen components which can be machined at any workshop. Shear-bond strength testing method facilitates the re-use of the cores and steel rings after cleaning TSL material. The process of removal of TSL, whether strongly bonding or not, from the rock substrate and the steel-ring is also simple and easy.

The selection of substrate rock should be made from competent or high strength rocks such as granite, dolerite, quartzite, andesite, anorthosite, and pyroxenite. The maximum load required for shear-bond failure for high strength TSL materials is 20 kN which is equivalent to a stress of 33,4 MPa for the selected rock core diameter. The problem of rock failure is not an issue since the UCS of any of the rock types mentioned above would not be reached.

Complications commonly experienced when performing shear testing are not experienced throughout the shear-bond strength testing process. The test set-up is stable and the failure takes place only on the TSL-substrate contact.

The curing period is the only test parameter varied in the testing methods employed in this thesis. Strength increases over increasing curing time can easily be distinguished from the test results. High correlation coefficients of shear-bond strengths over the curing time are also indicators of the stability of the testing method developed. The factors such as the substrate type and condition, core diameter, TSL thickness, steel and support ring dimensions, and loading rate that would have had an effect on the test results remained at fixed values or conditions. However, the effect of varying each parameter as well as temperature and humidity on the test results is the subject of future research.

The analysis of the test results showed that the comparison of the shear-bond strengths between TSLs is possible. However, shear-bond strength alone is not sufficient to make decisions on the quality or suitability of a TSL product. Material shear, tensile, and tensile-bond strengths should also be taken into account in decision making process.

The second testing method developed in this thesis, to measure the material shear strength, will be covered in the next chapter.

CHAPTER 5 MATERIAL SHEAR STRENGTH TESTING

The material shear strength is the second testing method developed since there has been no research on this subject to date. Hadjigeorgiou and Grenon (2002) assumed that the shear strength of TSL is equal to its tensile strength in the analysis of the support capacity of liners. Lacerda and Rispin (2002) stated that compressive strength is used in shotcrete testing as an indication of shear strength. Tannant (2001) is in the opinion that the load capacity of a TSL depends on the adhesion loss and tensile or shear rupture. In the light of such information from the literature, the development of testing methods for the measurement of TSL shear properties is therefore considered to be important. Shear-bond strength is already covered in Chapter 4. The discussion on the material shear strength in the current chapter would then sufficiently address the lack of testing methods in the area of shear properties.

5.1 Material shear strength test considerations

The material shear strength testing is not associated with the use of a substrate. Therefore, the issues related to the use of substrate are not applicable. The biggest concern is, possibly, the manner the load is applied during testing to prevent rotation. This section discusses the factors that are important and needs to be discussed in the development of the material shear testing method

5.1.1 In-situ loading mechanism

The mechanism of shear may take place in a number of possibilities as seen in Figure 24. Liner may be sheared on the excavation surface resulting from out of plane or plane parallel movements on cracks. Another, less likely, possibility occurs when the liner material penetrates into a crack and then another crack within rock displaces and shears the liner through (Figure 24c).

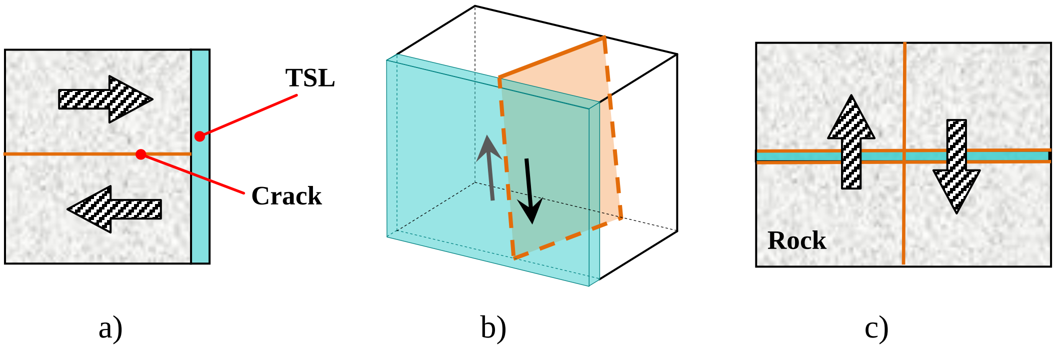


Figure 24. Material shear mechanisms: a) Out of plane on excavation surface, b) In plane on excavation surface, c) Across plane in a crack

5.1.2 Application of shear load

Shear strength testing incorporates difficulty in obtaining a reasonably pure and uniform shear stress state in the test specimen, which is critical if true shear properties are to be measured (Adams, 2009). The material subjected to shear testing should tightly be secured to prevent any rotation and bending moment that would eventually result in the development of complex stress state in the material as seen in Figure 25a.

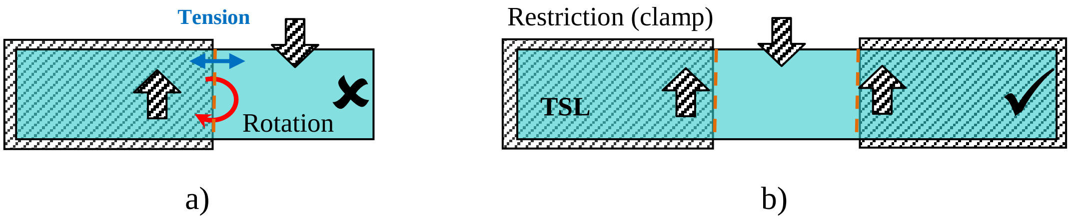


Figure 25. Application of shear load a) With induced rotation b) Stable setup without rotation

Shear testing involves the development of a failure plane within a previously undamaged and continuous material. The failure plane of TSL should be restricted to take place along an intended position for a better control during the test. The positioning of shear load and the restriction applied to prevent liner displacements, as shown in Figure 25b, assist in achieving this purpose.

5.1.3 Loading rate

The loading in material strength testing is done under *displacement control mode*. The loading of specimen is initially done at a displacement rate of 0,002 mm/s up to 0,02 mm and then increased to 0,005 mm/s up to failure. The initial stage of loading was applied at the early trials for the setting of the test fixture with the loading machine and may be skipped. The intention is to apply such a displacement rate that the shear failure takes place within 3 minutes. Note that, any liner material requiring 1 mm of shear displacement would need 3 minutes and 20 seconds for failure at 0,005 mm/s of displacement rate.

A few TSLs with high yield characteristics, on the other hand, may take as much as 10 mm of machine displacement before the ultimate failure which means more than 30 minutes of testing time. The chance of a testing method's acceptability reduces if the testing time is unnecessarily longer. In such cases the displacement rate may be increased to limit the failure time to 3 minutes.

5.2 Description of apparatus, specimen preparation and test procedures

5.2.1 Test fixture and specimen assembly

TSL is applied inside a steel ring and let to cure (Figure 26a). Superimposing holes are drilled on two steel plates (Figure 26c). The TSL-steel ring combination is placed in between the steel plates and then clamped. Another TSL free steel ring is used as a support base for the clamped specimen assembly. A steel punch of slightly smaller diameter (Figure 26b) is positioned in the superimposing hole of the top plate and displaced towards the void on the support ring. The test is continued until the ultimate failure load is achieved. The residual shear load level may also be observed.

5.2.2 Specimen components and dimensions

Steel ring

A steel ring is used for the purpose of housing the TSL that bonds onto the inner surface of the steel ring (Figure 26a). The dimensions are the same as the steel ring used for the shear-bond strength testing (Chapter 4). The TSL-ring depth of 20 mm is adopted, however, 10 mm or 5 mm thicknesses should also be exercised in the future.

Steel punch

The cylindrical steel punch is used to apply shear load on the TSL (Figure 26b). The diameter of the steel punch is kept slightly smaller (29,6 mm) than the holes (30 mm) on the clamping fixture. The difference in diameters leaves an annulus of 0,2 mm along which TSL is sheared.

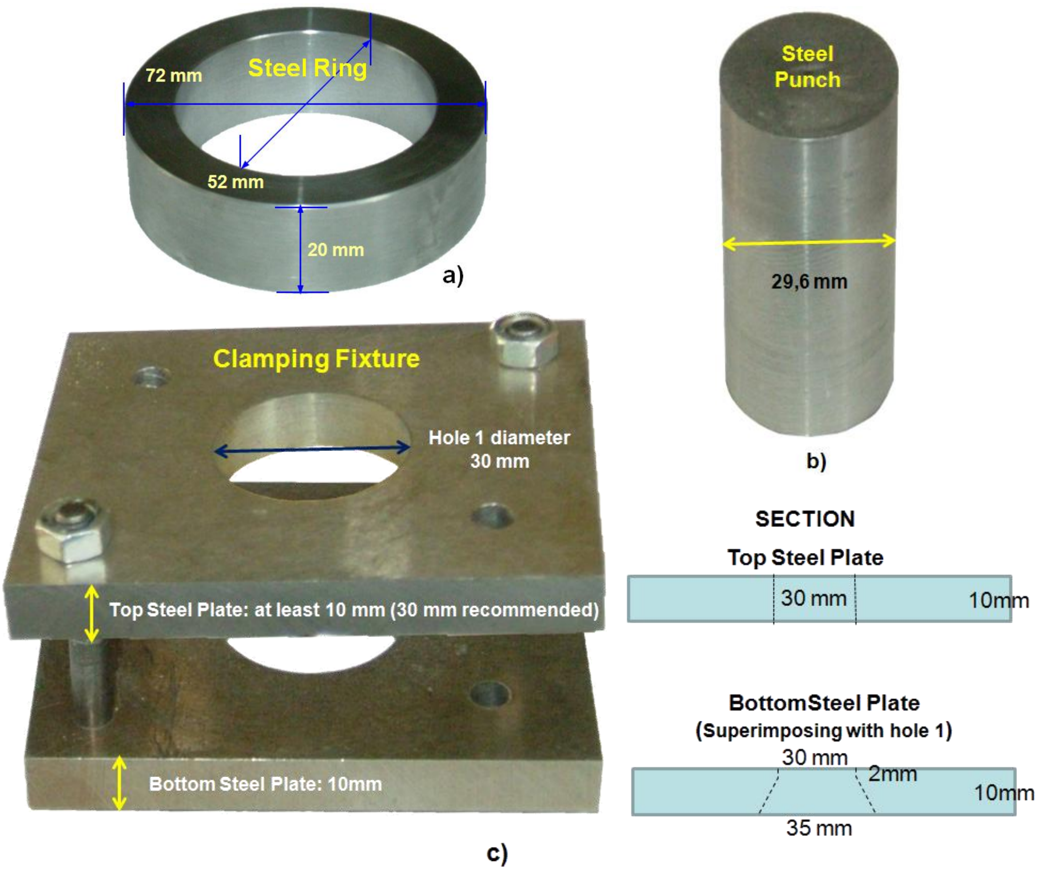


Figure 26. Material shear strength apparatus comprising: a) Steel ring, b) Steel punch, and c) Clamping fixture

Clamping fixture

The clamping fixture, as shown in Figure 26c is designed to accommodate the prepared specimen consisting of TSL and the steel ring (Figure 26a). Two steel plates with superimposing holes are pressed against the surface of the TSL-steel ring using two screws. The purpose of using a single clamping fixture is to ensure continuity of clamping all around the TSL material for the prevention of rotation and premature failure.

The thickness of the top and bottom plates is selected as 10 mm for the testing program. However, the thickness of the top plate can be increased to 30 mm or more in order to provide better guidance for the steel punch. The cross section of the bottom plate is slightly different than the top plate, as illustrated in Figure 26c, to prevent the squeezing of the sheared TSL material. The thickness of the bottom plate is sufficient for the amount of displacement required at the ultimate shear load for most TSLs. However, in case of need for the materials with higher yield range a blank steel ring may be used under the bottom plate.

5.2.3 Modification in the test set up for shotcrete

Unlike TSLs, shotcrete contains aggregates. Shotcrete sieve analysis tests were not available. However, a few aggregate pieces were measured with their maximum dimension being 15 mm. Due to the bigger sizes of aggregates in shotcrete as compared to TSLs; the possibility of shearing through the aggregate is higher if the clamping fixture in Figure 26c is used. Therefore, the diameter of the bottom plate hole is increased to 45 mm in order to prevent shearing of aggregates which would otherwise indicate higher failure loads. The difference between the steel punch and bottom plate diameters results in the annulus of 7,5 mm. No other changes were implemented for shotcrete in the specimen geometry and test execution.

5.2.4 Thickness control

The thickness of the TSL specimen is determined by the thickness of the steel ring used. Pouring of the prepared TSL mixture in the steel ring and then levelling by the help of a spatula or a flat surface against the surface of the steel ring ensures uniform TSL thickness throughout the specimen.

5.2.5 Specimen preparation

The preparation of specimens for the material shear strength testing is one of the simplest and straightforward procedures. The following steps are taken during specimen preparation:

- Apply a suitable releasing agent (machine oil, grease or any commercially available release agent) on the steel ring excluding the inner surface to avoid the sticking of TSL (Figure 27a).
- Arrange a flat working surface for the placement of the steel ring. In case of irregularities on the working surface, 8 or 10 mm thick perspex sheets may be used as the base.
- Place overhead transparency or plastic film between the flat working surface and the steel ring.
- Mix the TSL according to manufacturer's recommended mix ratio by the help of a kitchen food mixer.
- Pour the TSL mixture into the steel ring carefully (Figure 27b). Viscous TSLs are difficult to pour therefore they should be taken from the TSL container and applied inside the steel ring by the help of a putty knife.
- Place another plastic film on top of the steel ring (Figure 27c).
- Press against the plastic film with a flat surface of a suitable material (rock, wood or metal) and flatten the TSL. The excess TSL squeezes out during this process and the thickness of TSL becomes uniform (Figure 27d).
- Wait until the TSL mixture sets. Remove the plastic film from the top and bottom of the steel ring (Figure 27e). Plastic films are flexible and easily detachable from the TSL. Clear the excessive spills of TSL using a spatula (Figure 27f).

Figure 27. Steps followed during specimen preparation in material shear strength testing

5.2.6 **Test set-up and execution**

The specimens cure until the predetermined curing period under normal laboratory conditions. Five specimens are tested at each curing period. Figure 28 shows the shear strength test set up and the photos of the steel rings used. The thickness of the test specimen consisting of TSL-steel ring is measured to the nearest 0,1 mm at several positions. The specimen is placed into the clamping fixture between the plates, positioned symmetrically and then clamped by tightening two nuts. There should be no clearance between the plates of the clamping fixture and the surfaces of the clamped specimen. A steel punch of slightly smaller diameter is positioned in the superimposing hole of the top plate and rests on the TSL surface. Another TSL free steel ring may be used as a support base for the clamped TSL-steel ring assembly as seen in Figure 28. The punching tool assembly is then positioned in the loading machine. Force is applied on the steel punch until the peak shear load is reached on the test specimen. The failure should take place within 3 minutes. The maximum force sustained by the test specimen is recorded for subsequent strength calculation as described in the following section.

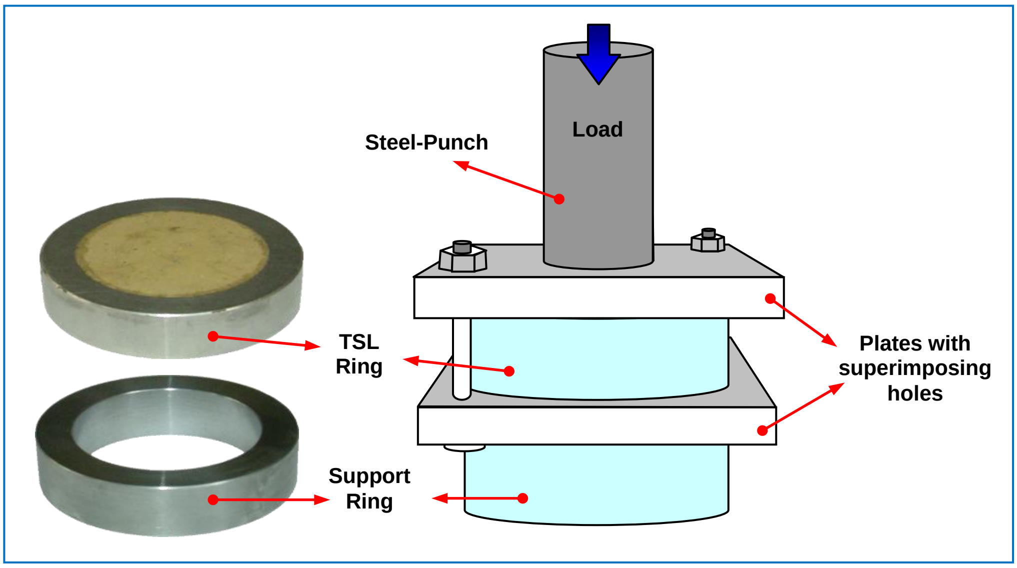


Figure 28. Shear strength test set up

5.2.7 **Calculations**

The shear strength (σ_s) of each test specimen is calculated by dividing the load at failure (F in N) by the area (A in m^2) along which the material fails due to shear i.e.;

Equation 4; $$\sigma_s = \frac{F}{A} = \frac{F}{\pi \times d_1 \times t} \quad (Pa)$$

where d_1 = steel-punch diameter in m

t = mean thickness of the TSL in m

The TSL thickness can be measured before or after testing for rigid TSLs. The shear strength calculation for shotcrete is done differently using the following equation;

Equation 5; $$\sigma_s = \frac{F}{A} = \frac{2F}{\pi \times (d_1 + d_2) \times t} \quad (Pa)$$

where d_2 = bottom plate hole diameter in m.

5.2.8 Failure mode

The loading and failure mechanism of TSL material occur in shear starting at the steel punch contact and continue along the TSL material thickness as seen in Figure 29. The location and shape of the failure plane are consistent and well defined; therefore the calculation of material shear strength and the interpretation of test results become easier.

a) b) c)

Figure 29. Failure mode in material shear strength testing; a) Specimen top view b) Specimen bottom view c) Break up view of a tested specimen

5.3 Results and analysis

A typical example of the load-displacement behavior during the material shear strength testing is presented in Figure 30. The pre-failure stage of this graph is similar to the one for the shear-bond strength testing (Figure 19, Chapter 4). However the post-failure behavior is different. Firstly, there is no sudden drop in the force level after failure. Secondly, the load on the specimen reaches a residual level after failure as the testing progresses

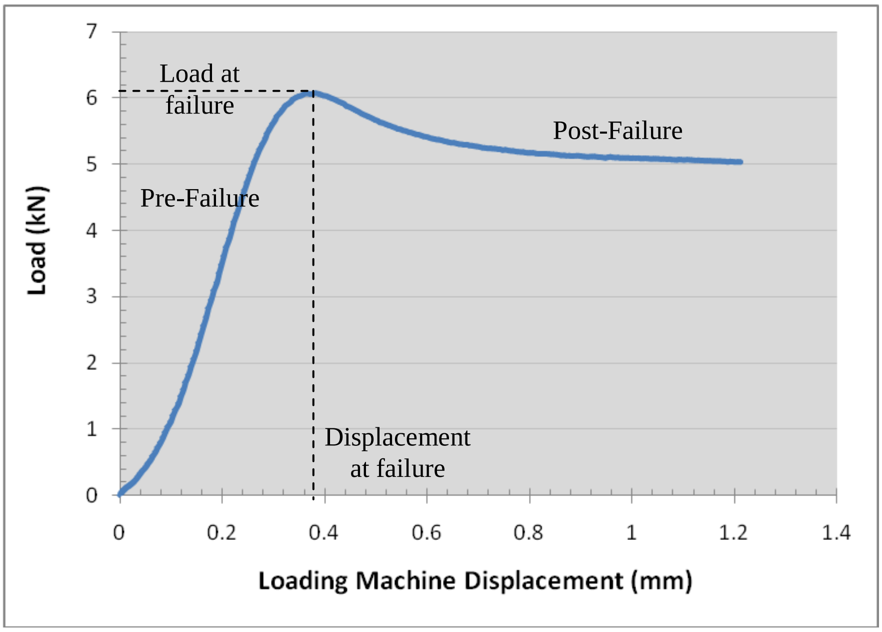


Figure 30. A typical load-displacement behavior during material shear strength testing

The summary graphs of material shear strength against the curing period are provided in Appendix IV for each of the TSL products and shotcrete. The scales of the graphs in Appendix IV are kept the same for easy comparison. Three of these graphs for products B, G and shotcrete are reproduced in Figure 31 in order to show the spread of material shear strength over the curing range. The averages of shear strengths, the equations and correlation coefficients (R^2) for the best fit curves at each curing time can be depicted in Figure 31. The best fit curve is again found to be logarithmic and it is applied for all data points on the graph of a particular liner.

Figure 32 is the summary of all the best fit curves displayed on the graphs in Appendix IV. The behaviour in the material shear strength between various TSLs and shotcrete shows wide scatter and the differences on curves at various strength levels are notable. The TSL R is approximately 30 times stronger than the weakest liners TSL L and shotcrete based on the 28 day strengths. All the liners demonstrate strength increase over the curing period.

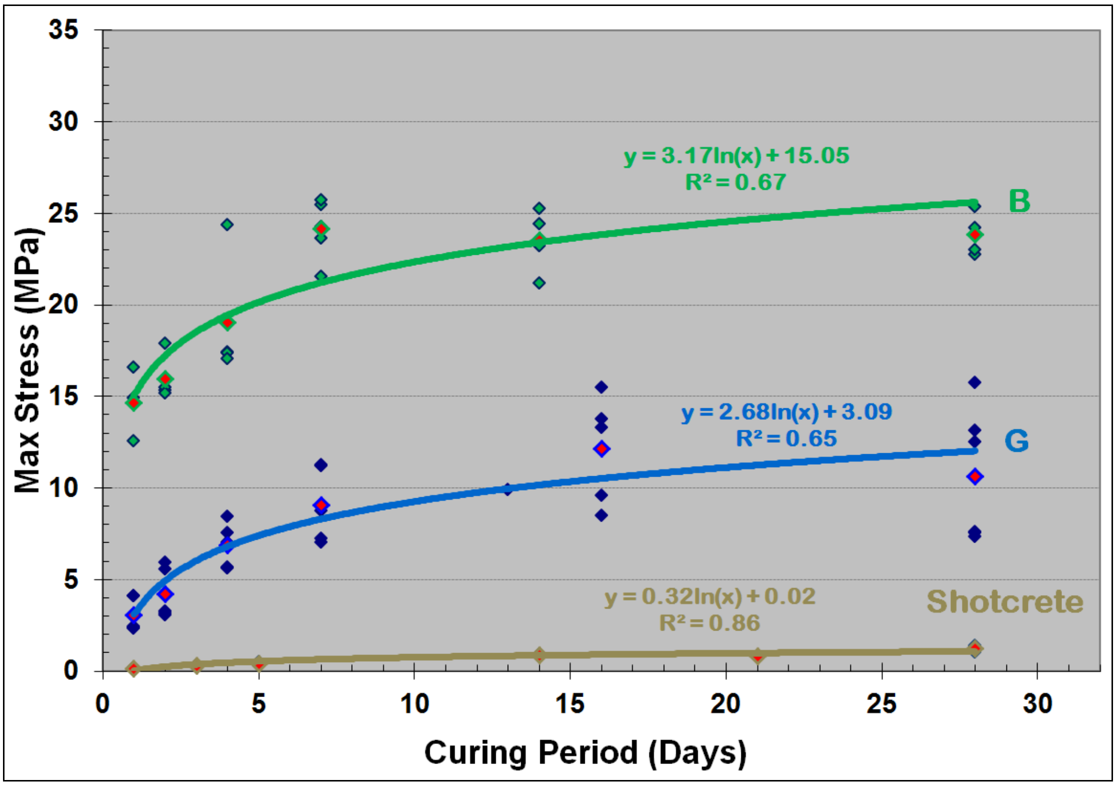


Figure 31. Example curves in the material-shear strength range

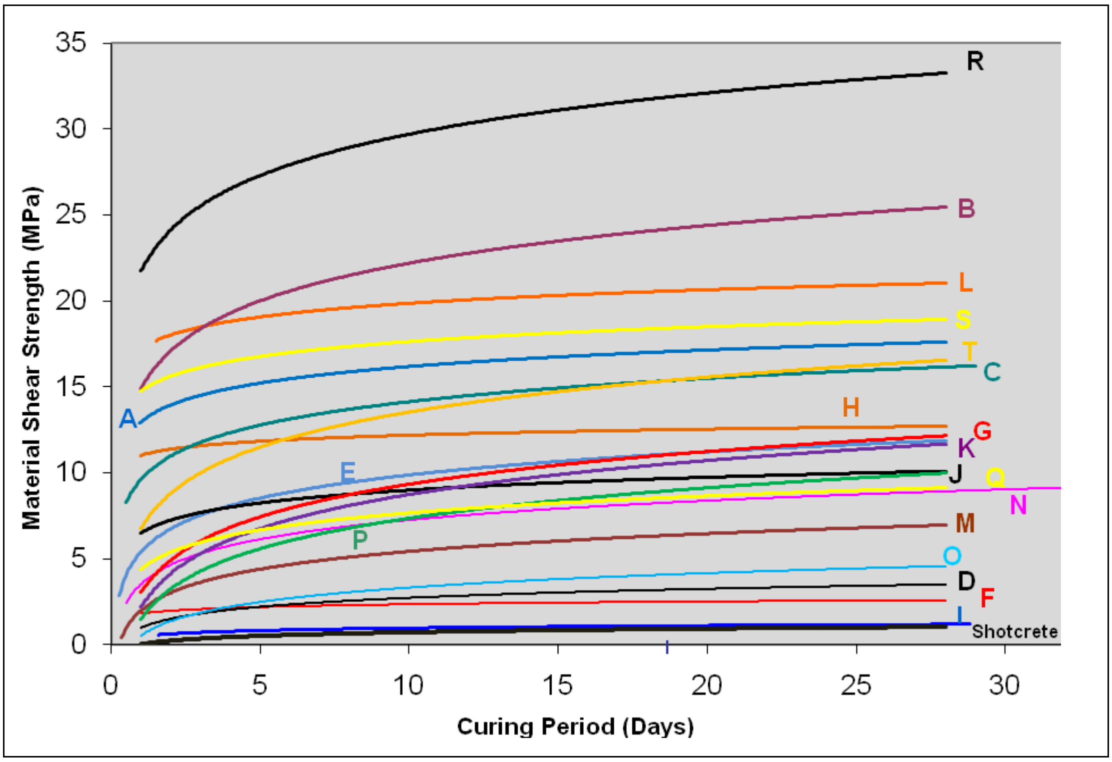


Figure 32. Material shear strength results

The categorisation of material shear strengths is made as illustrated in Figure 33 based on the information provided in Figure 32. The descriptions of weak, medium, strong and very strong material shear strength are given for the TSL materials in four strength categories. Shotcrete is one of the two weakest liner products and positioned in the category of weak material shear strength.

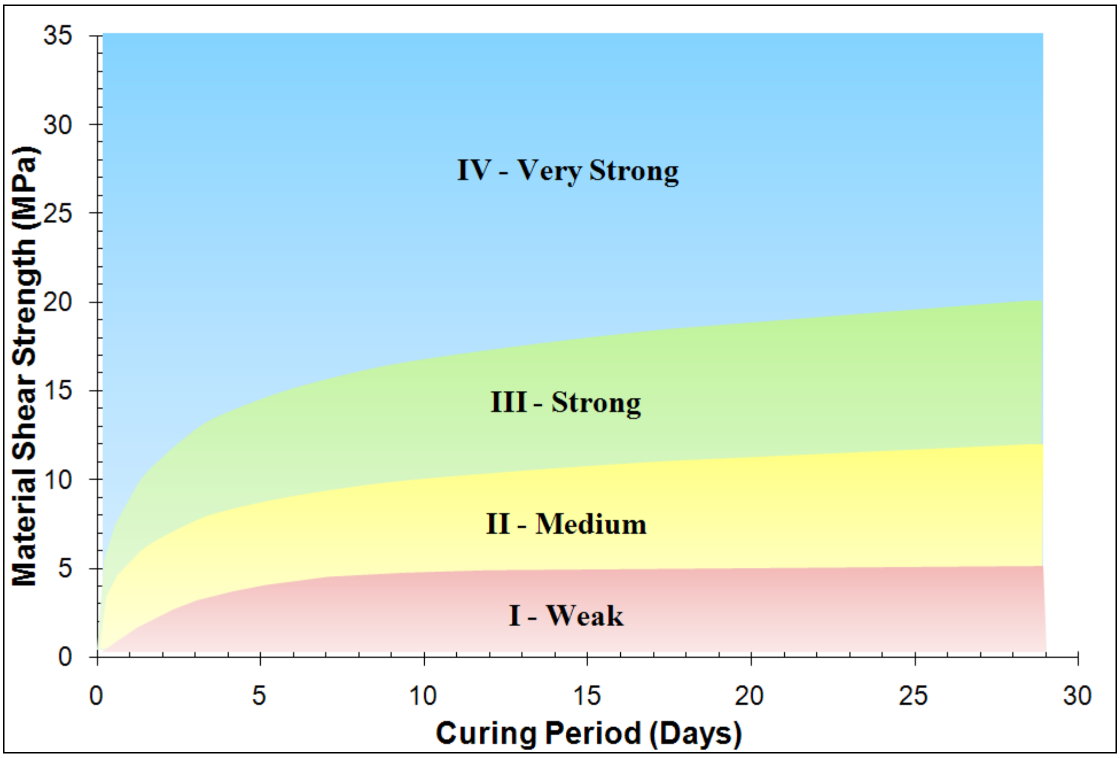


Figure 33. Material shear strength categories

Table 15 summarises the material shear strength equations, correlation coefficients (R^2) and strength ranking based on the 28 day strengths for all liner products. The correlation coefficients are found to be the highest of all the testing methods covered in this research. The values of correlation coefficients show a slight increase towards the weaker TSL materials. The water-based cementitious TSLs L and H display the lowest correlation coefficients.

Approximately 62% of TSL products tested are in the weak and medium strength categories. There seems to be an even spread of the number of liner products in the material shear strength categories.

Table 15. Material shear strength equation, correlation coefficients and ranking according to 28 day strength

TSL	Material Shear Strength Equation (MPa)	R^2	Rank	Strength Category
R	3.55ln(x) + 22.20	0.67	1	IV - Very Strong
B	3.17ln(x) + 15.05	0.67	2	
L	1.14ln(x) + 17.24	0.16	3	
S	1.24ln(x) + 14.82	0.62	4	III - Strong
A	1.30ln(x) + 13.20	0.76	5	
T	2.93ln(x) + 6.78	0.93	6	
C	1.96ln(x) + 9.62	0.95	7	
E	1.94ln(x) + 5.33	0.69	8	
G	2.68ln(x) + 3.09	0.65	9	II - Medium
H	0.73ln(x) + 10.44	0.09	10	
K	2.85ln(x) + 2.18	0.85	11	
J	1.09ln(x) + 6.51	0.53	12	
Q	1.42ln(x) + 4.40	0.97	13	
P	2.55ln(x) + 1.49	0.77	14	
N	1.69ln(x) + 3.40	0.82	15	
M	1.64ln(x) + 1.63	0.77	16	
O	1.21ln(x) + 0.54	0.97	17	I - Weak
D	0.76ln(x) + 0.99	0.96	18	
F	0.23ln(x) + 1.82	0.44	19	
Shotcrete	0.32ln(x) + 0.02	0.86	20	
I	0.20ln(x) + 0.53	0.74	21	

x: curing period in days

Detailed statistics on the material shear strength test results for all the TSLs in terms of mean strengths, standard deviations and coefficient of variations corresponding with each testing day can be found in Appendix V. Standard deviations generally increase over the curing period. High strength TSLs characteristically have higher standard deviations. There is no definite trend in the spread of CV% over the testing period and between the TSL products in different strength groups as can be seen in Figure 34. TSLs C, G and T, for example, are different versions of the same product. The CV of TSL G is much higher than the other two. In addition, TSL T demonstrates decreasing CV over the curing period, while TSLs C and G show an opposite trend as can be seen in Appendix V.

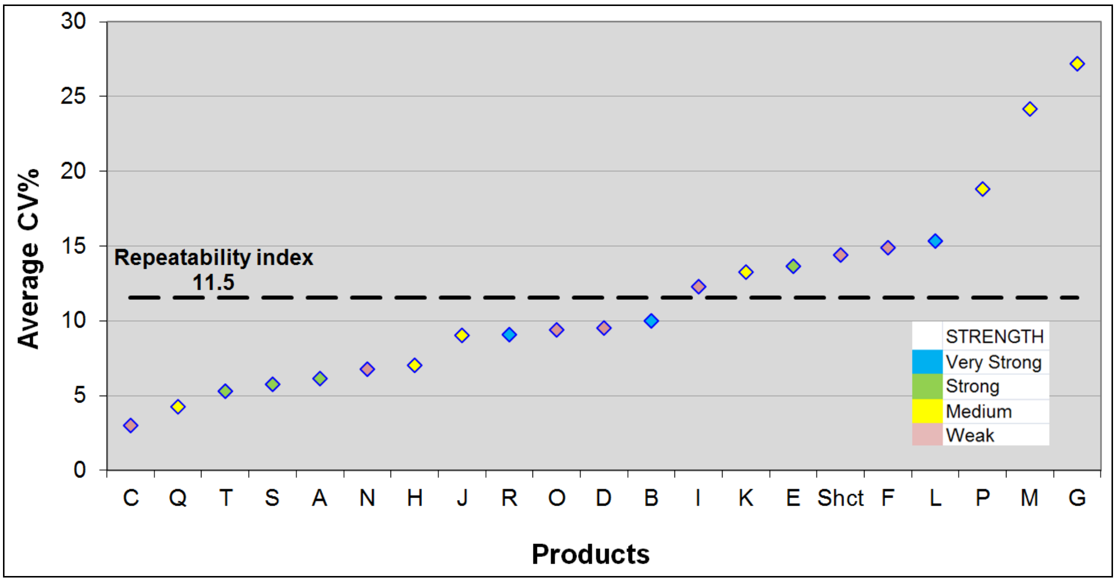


Figure 34. Distribution of average CV% for the TSL products in material shear strength testing

5.3.1 **Repeatability index**

The repeatability index for the material shear strength testing is calculated as 11.5. The calculation is done using the Equation 3 and based on the 103 curing times at which testing took place and the total CV% of 1187.3. A total of 484 individual material shear strength tests are included in the analysis. The small value of the repeatability index points out to the higher repeatability of this testing method.

5.4 Summary and conclusions

The movement of rock blocks from excavation walls may cause the shear loading of liner material provided that de-bonding does not take place. The measurement of material shear strength of a liner would be possible when the tensile-bond and shear-bond strengths are high. The main aim of the proposed testing method discussed in this chapter is the measurement of the shear strength across liner materials.

The rotation of the test specimen during shear testing may result in the complication of not attaining pure shear stress state in the TSL material. The circumferential continuity provided on the plane of TSL using a steel ring inhibited the rotation of the test specimen.

The aggregate content of a liner is important and should be considered when the material shear test fixture is designed. The clearance between the steel punch and plate holes in the clamping fixture should be in such an amount that shearing of liner aggregates will not take place. For this reason, the test set up had to be modified for shotcrete due to the bigger aggregate sizes.

The proposed testing method has numerous advantages over the other testing methods covered in this thesis. The main advantages are:

- Specimen preparation is simpler, easier and quicker.
- Testing method is more repeatable.
- The test set-up and the components used are small and easily manageable.
- Complications of using a substrate do not exist.
- No use of consumables makes this testing to be cost effective. The steel ring is easily cleaned for re-use.

The number of tests and the variety of TSL materials tested make the overall comparison of the material shear strength of TSLs possible. Time dependent material shear strength increase is observed on both TSLs and shotcrete. Shotcrete is noted as the lowest shear strength material over the curing range. Therefore, shotcrete cannot match the shear strength levels of TSLs.

The test results could be sensitive to many parameters. The curing time is used as the main tests parameter for the material shear strength testing. TSL material thickness is considered to be another important parameter that may influence the test results. The curing of thinner specimens may take shorter time than thicker ones. Although the TSL thickness of 20 mm is adopted in this research, the influence of 10 mm and 5 mm thicknesses on the shear strength should be investigated in the future.

TSLs with high shear strength are found to be stiffer than the low strength TSLs. Therefore, stronger TSL materials will require smaller displacement rates than the weaker materials. The influence of loading rate on the test results requires further research in the future.

The next chapter discusses the third testing method carried out in the testing programme that is the tensile strength testing method.

CHAPTER 6 TENSILE STRENGTH TESTING

The preceding two chapters discussed the newly developed shear property testing methods that are the shear-bond and material shear strengths. The discussion in this chapter is made on the tensile strength testing in a similar structure with the previous two chapters.

Tensile strength testing has been one of the most common physical property testing methods of TSL products by a number of researchers and manufacturers worldwide. However, the number of publications on the subject has been limited. Determination of tensile strength is included in the testing methods in order to assist in the comparison of various TSL products.

The American Society for Testing and Materials (ASTM) has a tensile test standard designed to determine the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell (dog-bone) shaped test specimens. “ASTM D638-Standard Test Method for Tensile Properties of Plastics” can be adapted to the testing of TSLs after some modifications since this test standard is not specifically designed for measuring the tensile strength of TSLs.

Researchers such as Tannant *et al* (1999), Archibald (2001) and Spearing and Gelson (2002) made reference to ASTM D638 and performed tensile tests on TSLs. The loading rate and specimen dimensions mentioned in the standard were used. The number of tests were adequate, on the other hand, only a few TSL products were available for testing. Tests were normally done at 7 days of curing and Tannant *et al* (1999) and Archibald (2001) recommended that in order to effectively assess material physical property behaviour, consistent and suitable interval times for testing must be established.

The suggested loading rates of 5 to 50 mm/minute in the ASTM D638 standard are intended for thin plastic sheets and cannot be applied for TSLs. Most TSLs have limited deformation range and failure occurs in less than 1 mm of deformation. The use of 5 mm/minute loading rate would imply that the testing would be completed in 12 seconds which fall short of the test duration recommendation of 60 to 180 seconds. Therefore, the loading rate should be flexible in such a way that the failure is achieved within the recommended time limit whether rigid or yielding TSLs are tested.

Preparation of specimens by a process of stamping using specially prepared die cutting moulds (Tannant *et al*, 1999; Archibald, 2001) is suitable for plastic materials and not for most TSLs. The cement based TSL could be damaged during the stamping process. The process of machining is time consuming, very difficult and can damage the specimen. The machining operation is also a significant cost addition to the specimen preparation

As an alternative, a much simpler method of preparing the specimens by making use of moulds made of perspex glass can be used. The TSL mixture is poured in the mould and the specimens are easily taken out after the setting of TSL without any damage to the specimens. In addition, moulding process ensures excellent thickness control on the prepared specimens.

6.1 Tensile strength test considerations

The general purpose of the test is to determine the tensile strength of a TSL material or shotcrete. Tannant *et al* (1999) stated that the rate at which a membrane cures in the mining environment may dictate how soon people can resume work in a given heading or stope. It is further stated that tests to measure the gain in tensile strength versus age under temperature and humidity conditions representative of the underground environment may be required. Therefore, the curing period is selected to be the main parameter for the tensile strength testing as well as the other three testing methods.

The specimen preparation and testing requires caution due to the dimensions and especially the small thickness of the specimen. Rough handling and misalignment of the testing machine can easily damage the specimen before the actual strength is obtained. Therefore, this section will discuss other sensitive issues that need to be taken into account in the procedures of the tensile strength testing.

6.1.1 **In-situ loading mechanism**

The crack formation through an intact rock could be attributed to reasons such as highly stressed ground, stress relieved ground, blasting, and seismicity. Crack dilations and movements along cracks towards the mining voids play an important role in tensioning TSL as seen in Figure 35. Crack dilations may be experienced at many locations in a mine such as pillars, bullnose (sharp corner) positions, hangingwall or roof where excessive sagging occurs.

When a crack joins with an adjacent one or pre-existing weakness planes, wedges or blocks would be formed. Depending on the orientation of cracks and the shear strength characteristics of the weakness planes, rock blocks may become potentially loose and drop from the roof and sidewalls of the excavation. Bond failure followed by plastic yield would cause the tensioning of the liner material on such blocks. TSLs with high bond strength and rigid behaviour would fail in shear rather than tension.

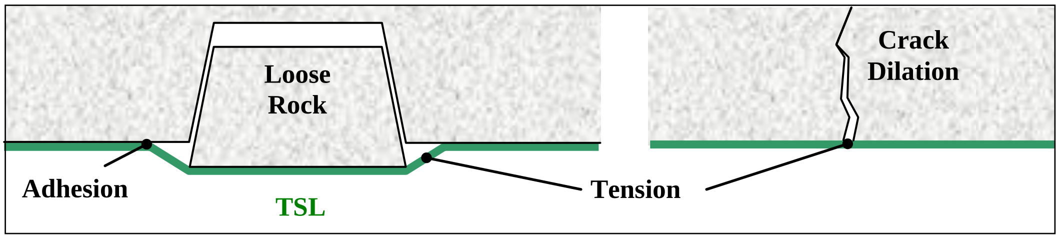


Figure 35. In-situ loading mechanism of TSL relevant to tensile strength testing

6.1.2 **Specimen dimensions**

TSL

The shape and dimensions of an ASTM D638 Type I test specimen, as seen in Figure 36, are suitable for testing rigid TSLs. The shape and dimensions of Type IV specimen mentioned in the same standard are considered to be more suitable for testing TSLs with high elongation capacities.

Testing equipment exhibit extension or stroke length limitation and in the case of the MTS machine used this limit is 100 mm. The distance of 115 mm between the grips for Type I specimen necessitates 200% elongation for yielding TSLs to reach the machine extension limit of 100 mm. Otherwise, tensile strength at break will not be obtained by the use of Type I specimen. Type IV specimen as seen in Figure 36, on the other hand, is smaller and most of the deformation would take place at the 33 mm long narrow section. Therefore the failure would be possible before the extension limit of the testing machine is reached. However, the use of Type IV specimen was not needed during the testing programme since none of the TSL materials used exhibited high yield capacity.

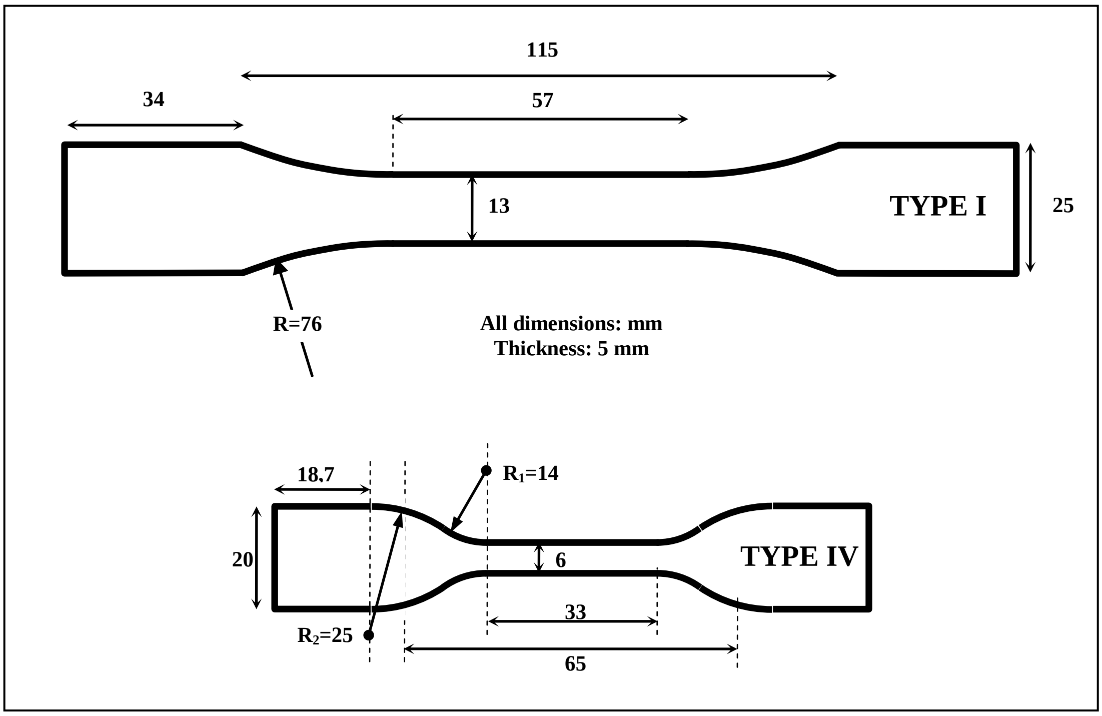


Figure 36. Type I and Type IV specimen shapes and dimensions of ASTM D638

The thickness of the TSL specimens is determined by taking the field applications as a reference. This thickness is generally accepted to be around 5 mm.

Shotcrete

Shotcrete dog-bone dimensions are, similarly, chosen to reflect the in-situ applied thickness. An average thickness of 50 mm is selected and the remaining dimensions are seen in Figure 37. The width of the narrow section of the specimen is kept at 50 mm and the remaining dimensions were increased by a factor of two as compared to Type I specimen for TSLs.

The increase in the size of the shotcrete specimen is necessary firstly due to the reason that shotcrete contains aggregates that may be larger than the 5 mm thickness of the Type I specimen. Secondly, the fibre length for the fibre reinforced shotcrete can be as much as 50 mm that exceeds the width of the narrow section on the dog-bone specimen. During the specimen preparation process these fibres would be forced to fit into the narrow section making their alignment along the long axis of the dog-bone specimen. In practice, of course, fibres are randomly orientated and the prepared specimen should simulate the actual shotcrete texture as much as possible.

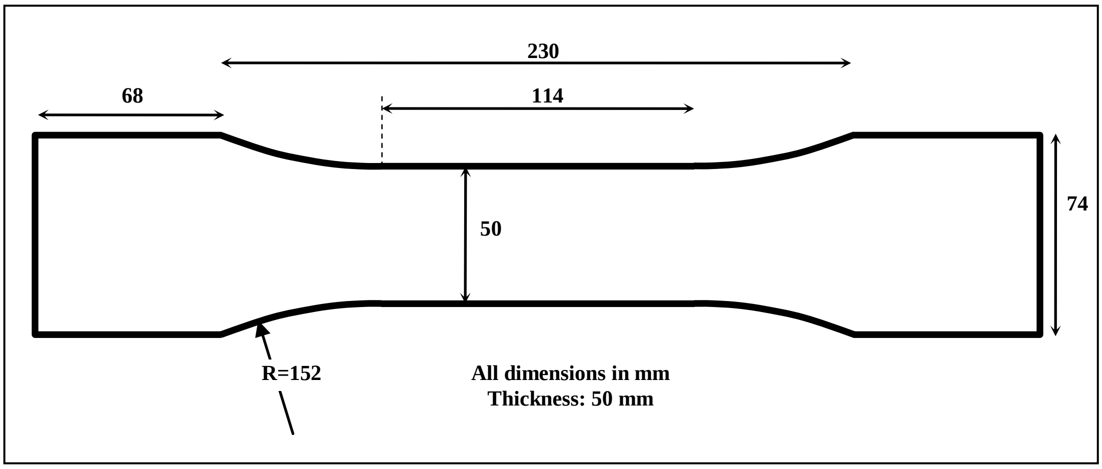


Figure 37. The shape and dimensions of dog-bone specimen for shotcrete testing

As an alternative, a sheet of shotcrete material could be prepared and then machined to size. However, the process of machining is quite difficult on brittle materials due to the damage potential for the specimen. In addition, the fibres of the prepared specimens would be trimmed. The yield performance of shotcrete depends on the pull resistance along its fibre length. The shorter fibres will result in a lower yield range that is a negative reflection on the yield performance of shotcrete.

The best solution to the problem caused by long fibres would be to increase the width of the specimen to accommodate the fibre length. This would mean a deviation from the standard specimen size already established for TSLs, however, a necessary adjustment for shotcrete considering its special characteristics.

6.1.3 **Thickness control**

The uniformity on the thickness of the dog-bone specimen is important for uniform stress distribution in the narrow section. Uneven shape at the grip positions may cause premature failure due to high stress concentrations during clamping of the specimen. A flat perspex glass is laser cut with the desired contours of the dog-bone specimens. Specimen thickness is governed by the depth of the perspex. Pouring of the prepared TSL mixture in the perspex mould and then levelling done by the help of a spatula against the surface of the perspex mould ensures uniform thickness throughout the specimen. Self-levelling of the less viscous TSLs gives rise to reasonably uniform specimen thickness.

6.1.4 **Eccentric loading**

Eccentric loading is the consequence of difference between the direction of pull and the axis of the specimen as illustrated in Figure 38. Eccentricity may also take place along the direction that is perpendicular to the plane of the specimen. The rigid attachment of the devices, used for gripping the specimen ends, to the loading machine is the primary reason for eccentric loading. Therefore the ends of the specimen should have the freedom to move and self-align with the direction of the pull. Universal joints or steel rope attachments could be used to impart freedom to the specimen ends in an attempt to prevent eccentric loading.

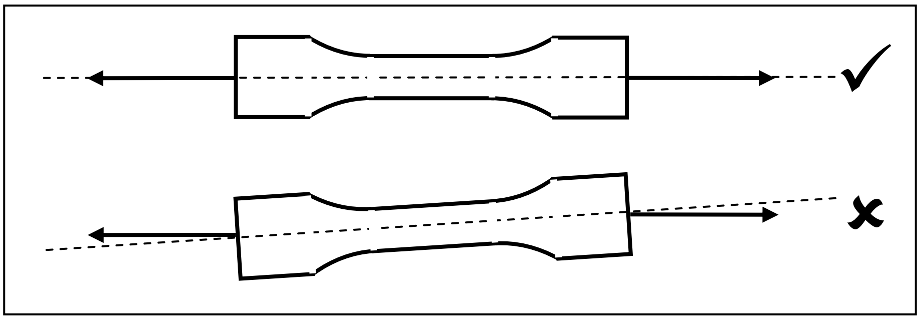


Figure 38. The importance of alignment between the specimen axis and pull direction

6.1.5 **Loading rate**

The loading in tensile strength testing is done under load control mode. The initial rate of loading is 2,5 N/s up to 100 N (40 seconds) and then tensioning at a constant loading rate of 5 N/s up to failure. The initial stage of loading may be skipped for stronger TSLs for which the failure would take place between 2 to 3 minutes. The loading rate for shotcrete is doubled due to the increased specimen dimensions in the narrow section that necessitate higher failure load.

6.1.6 **Failure mode**

The tensile loading of the dog-bone specimen induces the highest stresses in the narrow section in the middle as shown in Figure 39. The failure should take place anywhere in this part of the specimen for testing to be valid. The failure of TSL material occurs either due to tension or tear mechanism.

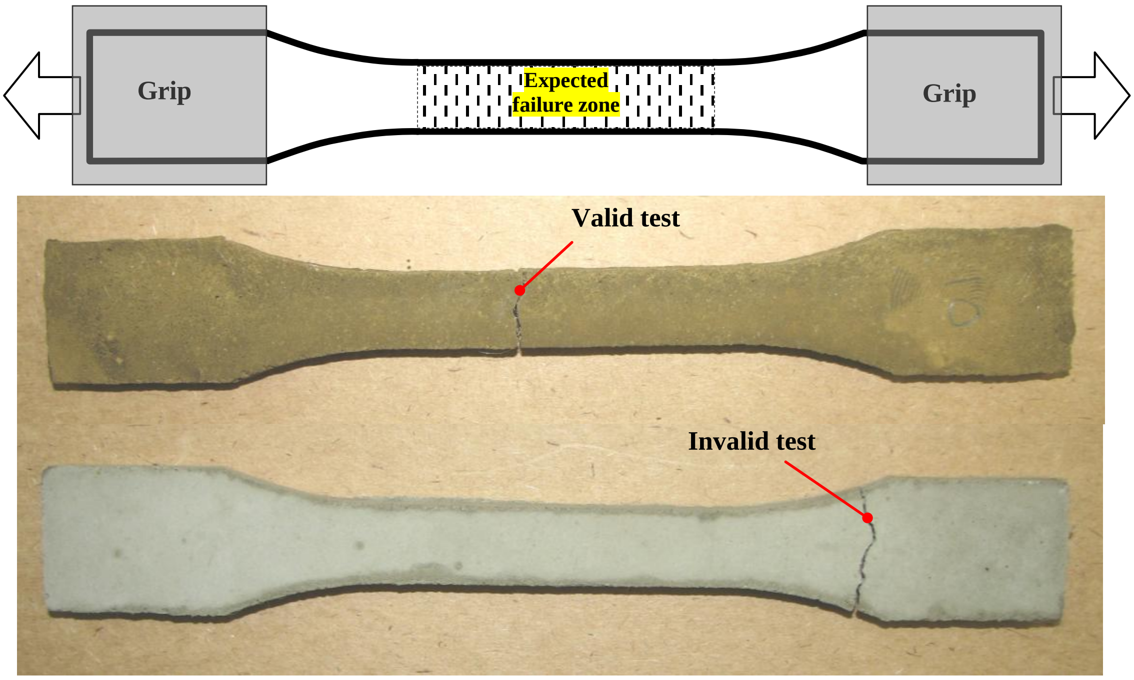


Figure 39. Failure location for valid tensile strength testing

Figure 39 also shows an example to both valid and invalid tensile strength testing. The strong TSL materials characteristically do not suffer from test invalidity due to failure taking place in the expected failure zone of the specimen.

Excessive tightening of grips could cause the weakening of the grip positions that would fail prematurely during testing. Weak tightening, on the other hand, would result in the slipping of grips. The level on the correct amount of gripping would be acquired after some experience.

Invalid testing may also result from uneven shape and thickness of the specimen at the clamping position, and air bubbles outside the narrow section of the specimen. The problem of test rejection due to invalid tests can be alleviated by careful specimen preparation and clamping at the time of testing.

6.1.7 **Calculations**

The calculation of tensile stress takes into account the original cross sectional area of the narrow section of the specimen. The following formula is used for calculating the tensile strength (σ_t):

Equation 6; $$\sigma_t = \frac{F}{A} \quad \text{(Pa)}$$

where F = load at failure in N
A = original cross-sectional area of the specimen (in m^2) at the narrow section

The area can be calculated before the test or after the test (for rigid TSLs) by measuring the width and the thickness of the specimen at the expected failure zone.

6.2 Description of specimen preparation, test apparatus, and procedures

6.2.1 **Specimen preparation**

The preparation of specimens is the most important stage of any testing method. The acquisition of quality experimental data depends on the preparation of quality test specimens. The procedures followed during specimen preparation are described in detail as follows:

- Preparation of the perspex mould (Figure 40a)
  - Apply a suitable releasing agent (machine oil, grease or any commercially available release agent) on the perspex glass to avoid the sticking of TSL. The application of releasing agent should not be excessive to prevent interference with the composition of TSL.

- Arrange a flat working surface for placing the perspex mould. In case of irregularities on the working surface, 8 or 10 mm thick plain perspex sheets may be used as the working surface. Note that the thickness of the base perspex sheet is different to the perspex used for moulding purposes (5 mm).
- Place overhead transparency films or plastic sheets on the working surface. The TSL specimens are easily removed from such flexible plastic sheets.
- Set and secure the perspex mould on the working surface so that the mould does not move during the pouring of TSL mixture.

- Mix the TSL according to manufacturer's recommended mix ratio by the help of a kitchen food mixer.
- Pouring of the TSL (Figure 40b)
  - Carefully pour the TSL mixture into the cavities on the perspex mould.
  - Viscous TSLs are difficult to pour therefore they should be taken from the TSL container and applied on the mould by a putty knife.
  - Clear the excessive spills away using a spatula.
  - Place another plastic sheet on top of the perspex mould. Swipe the spatula on the plastic sheet against the mould to level and to ensure uniform thickness of the TSL specimens (Figure 40c).
- Removal of the specimens from the perspex mould
  - Wait until the TSL mixture sets. Depending on the product, the setting time may vary from a few hours to a day.
  - Remove the plastic sheets from the top and bottom of the perspex mould.
  - Take the dog-bone specimens out of the perspex mould. It is important that the perspex mould is made up of detachable pieces to minimise the damage on the specimens. (Figure 40a)
  - Clean the unwanted extensions on the contour the specimen. These extensions are thin and easily broken with fingers without damaging the specimen. Scraping with a spatula leaves a good finish on the final contour of the specimen.

a) b) c)

Figure 40. Steps in the preparation of dog-bone specimens: a) Mould set up, b) Pouring of TSL, c) Levelling of TSL

Complete set of specimens are prepared from a single mix using approximately 1,5 to 2 kg of TSL material. Each mould unit generates five specimens that are used for testing at a curing time.

6.2.2 **Test set-up and execution**

Due to the unavailability of a tensile load frame, the set up illustrated in Figure 41 is designed for use in compressive testing machines. The set up for shotcrete testing is proportionately bigger.

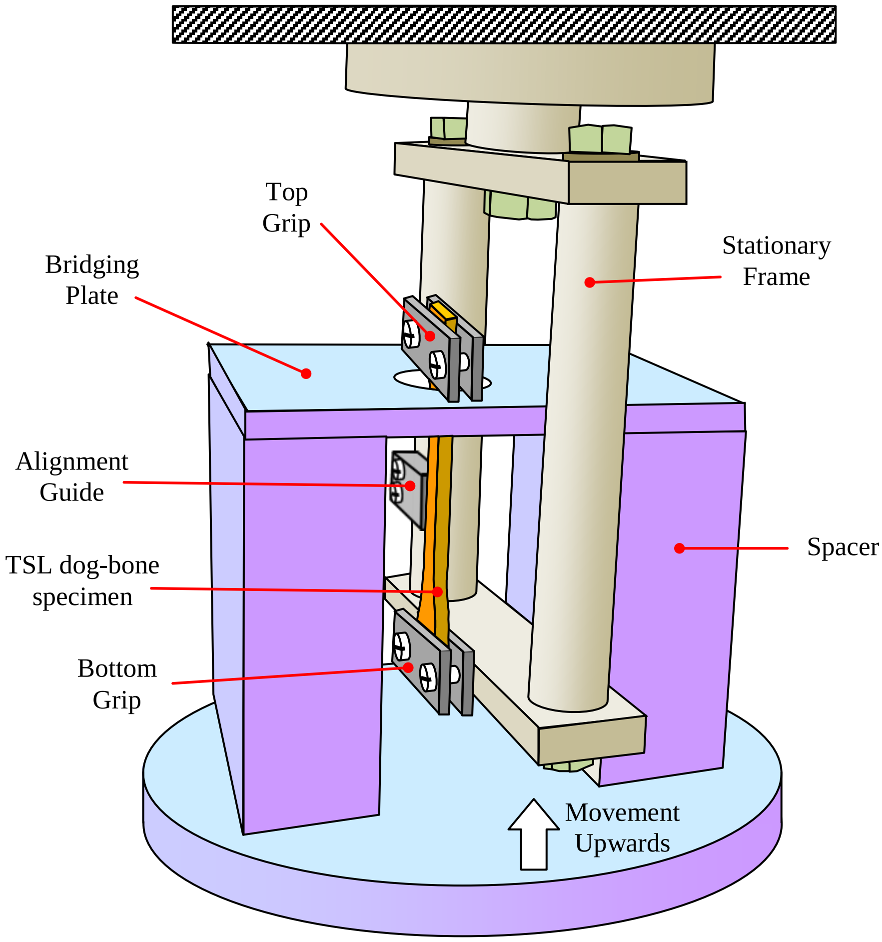


Figure 41. Configuration of the tensile strength test assembly to be used in compressive machines

Dog-bone shaped TSL specimens are prepared by pouring into perspex moulds as described earlier. The specimens cure until the predetermined curing period is completed under normal laboratory conditions. Five specimens are randomly selected out of the complete set of specimens. The specimen is placed in the bottom grip, as shown in Figure 41, and tightened while observing the alignment of the long axis of the specimen with the direction of the pull by the help of alignment guide affixed to the stationary frame to prevent any misalignment. Then, the top grip is attached and tightened carefully. Since the bottom grip is fixed, tightening of the top grip should not to impose any bending that could result in the failure of the specimen.

The specimen is loaded in tension at a constant loading rate of 5 N/sec until failure. The failure load is recorded and then the position of failure is inspected for test validity. The dimensions of the failed section are measured with a vernier to calculate the failure area. This measurement can be taken before the test at the narrow section of the specimen. The failure area should also be examined for any anomalous condition such as air bubbles or unmixed TSL lumps to understand the reason for test results that are unexpectedly lower.

6.3 Results and analysis

Typical load-displacement behaviours of plain and polypropylene fibre reinforced TSLs can be seen in Figure 42. Plain TSLs do not exhibit the post failure behavior due to the destructive nature of tensile strength testing. On the other hand, fibre reinforced TSLs yield and offer a significant advantage in terms of energy absorption capacity in spite of the lower ultimate strength level.

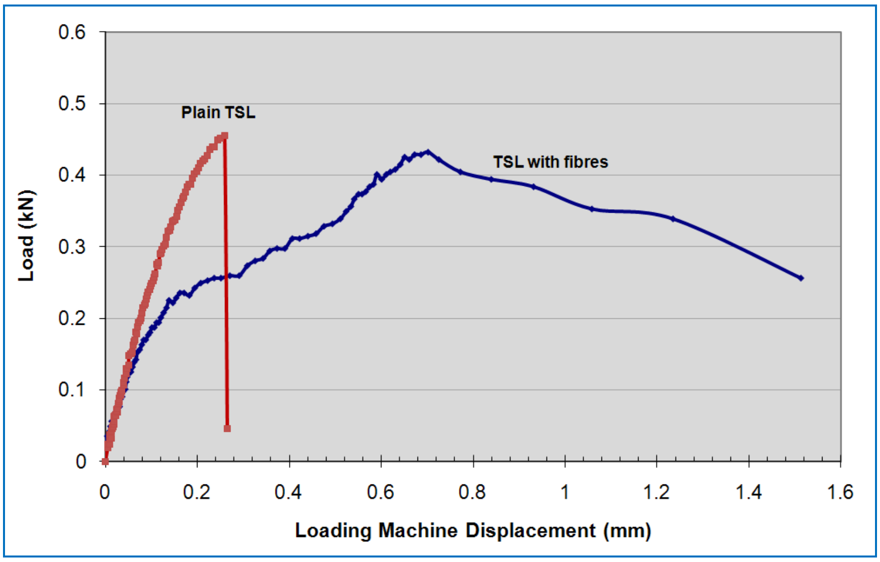


Figure 42. A typical example of the load-displacement behavior during material tensile strength testing for plain and fibre reinforced TSLs

The tensile strength curves over the curing period for three liner products T, E and shotcrete are shown as examples in Figure 43. The averages of tensile strengths at each curing time are indicated as red markers on the curves. Strength equations and correlation coefficients (R^2) for the best fit curves can also be seen in Figure 43.

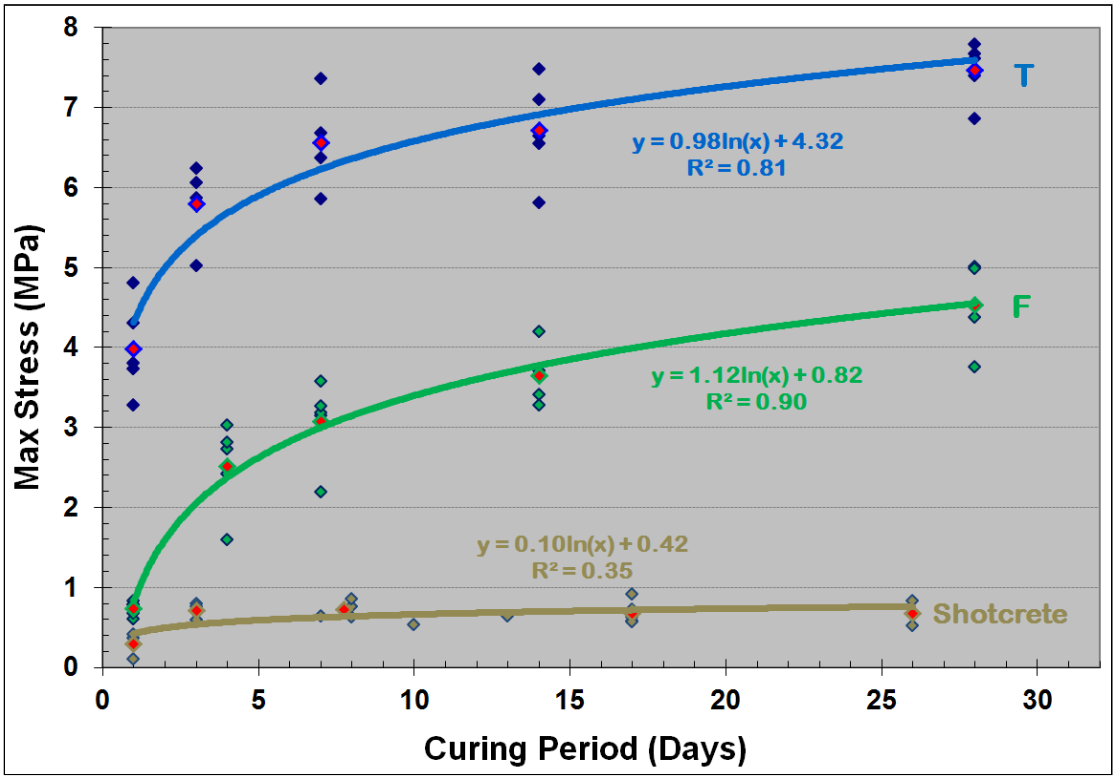


Figure 43. Example curves in the material tensile strength range

Summary graphs of tensile strength against the full curing period are provided in Appendix VI for all of the TSL brands and shotcrete. The scales on these graphs are kept the same for easy comparison.

Figure 44 shows the summary of the best fit curves in Appendix VI. The tensile strength development over the curing period for shotcrete and 20 letter-coded TSL products is notable. Tensile strength, in general, tends to increase with increasing curing period. Product R (polyurethane type) displays an exceptional behaviour in that tensile strength marginally decreases. This is partly due to the lack of number of tests required at some curing periods (see the graph of TSL R in the Figure 44). The strength improvement for the low strength TSL products and shotcrete is negligible.

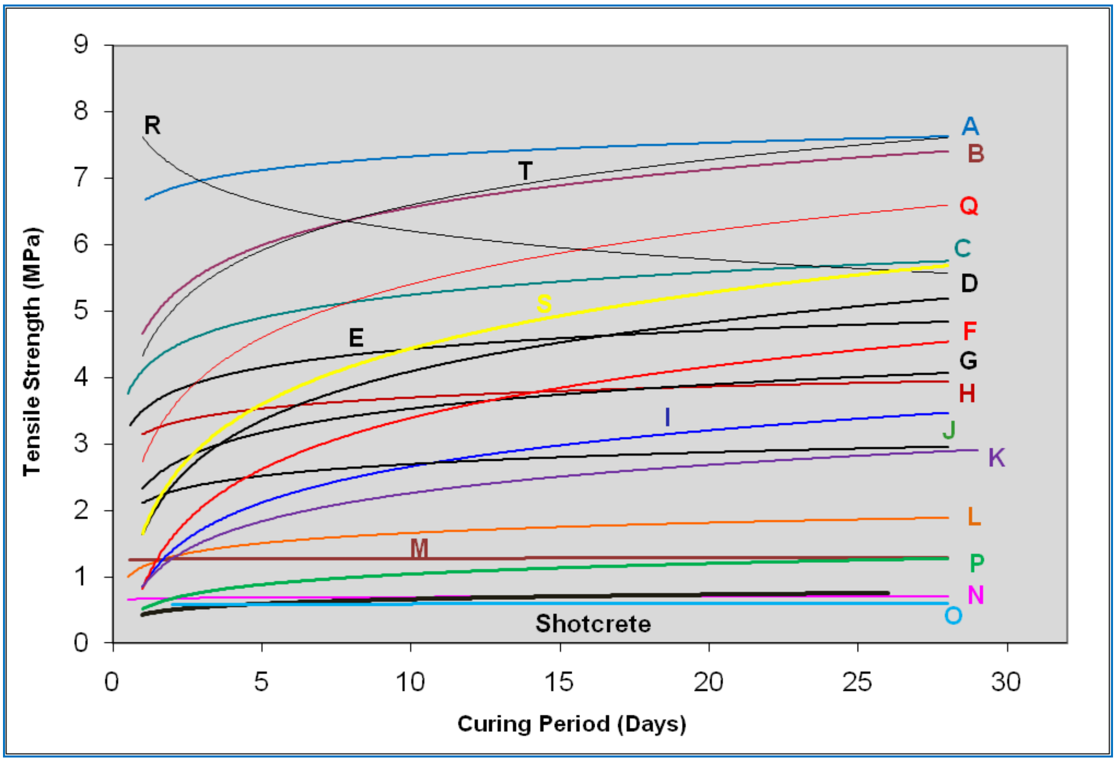


Figure 44. Tensile strength results for shotcrete and TSL products

The categorisation of tensile strength taking the strength development over 28 days into account is made and illustrated in Figure 45. The tensile strength of shotcrete is one of the lowest (0.68 MPa at 26 days), therefore, shotcrete is positioned in the weak tensile strength category.

The tensile strength equations, correlation coefficients (R^2) and strength ranking for all products are listed in Table 16. About 52,4% of the liner products displays strong and very strong tensile strength behaviour. The correlation coefficients tend to decrease with decreasing tensile strength. The products M, N and O in the weak tensile strength category, in fact, have zero correlation coefficients.

Polyurethane products A and R are also noticed to present lower correlation coefficients. However, the general trend with R^2 values point out to the strength improvement over the duration of 28 days.

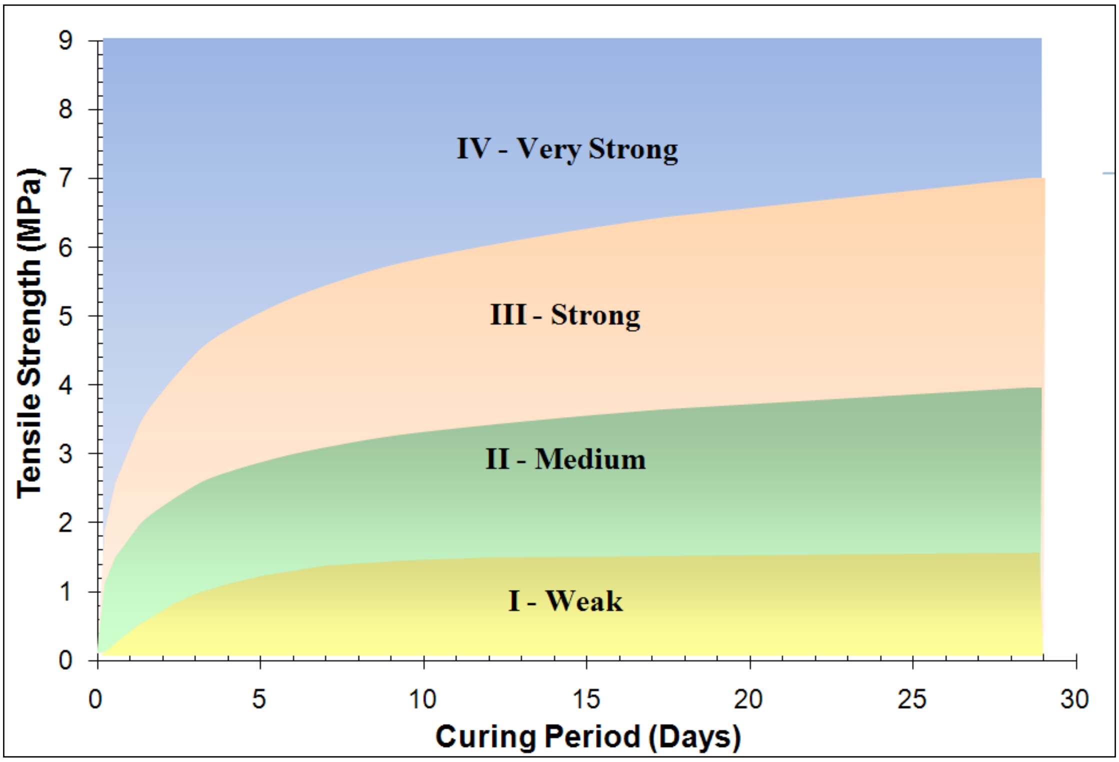


Figure 45. Tensile strength categories

Table 16. Tensile strength equation, correlation coefficients and ranking according to 28 day strength

TSL	Tensile Strength Equation (MPa)	R^2	Rank	Strength Category
TSL A	0.30ln(x) + 6.63	0.20	1	IV - Very Strong
TSL T	0.98ln(x) + 4.32	0.81	2	
TSL B	0.85ln(x) + 4.74	0.40	3	
TSL R	-0.52ln(x) + 7.93	0.15	4	III - Strong
TSL Q	1.16ln(x) + 2.73	0.84	5	
TSL C	0.50ln(x) + 4.11	0.32	6	
TSL S	1.21ln(x) + 1.62	0.77	7	
TSL D	1.06ln(x) + 1.65	0.93	8	
TSL F	1.12ln(x) + 0.82	0.90	9	
TSL E	0.44ln(x) + 3.37	0.38	10	
TSL G	0.54ln(x) + 2.34	0.41	11	
TSL I	0.78ln(x) + 0.86	0.91	12	II - Medium
TSL K	0.62ln(x) + 0.84	0.67	13	
TSL H	0.30ln(x) + 3.07	0.07	14	
TSL J	0.28ln(x) + 2.08	0.15	15	
TSL L	0.22ln(x) + 1.15	0.32	16	
TSL M	0.00ln(x) + 1.27	0.00	17	I - Weak
TSL P	0.23ln(x) + 0.51	0.70	18	
TSL N	0.00ln(x) + 0.68	0.00	19	
Shotcrete	0.10ln(x) + 0.42	0.35	20	
TSL O	0.01ln(x) + 0.57	0.00	21	

x: curing period in days

Detailed statistics on the test results in terms of mean strengths, standard deviations and coefficient of variations (CV) corresponding with each testing day are summarised in Appendix VII for all the tensile strength tests. Strong and very strong materials generally have lower CVs than the weak and medium strength TSLs. Standard deviations; on the other hand, demonstrate the opposite behaviour in that strong and very strong materials have higher standard deviations than the weak and medium strength TSLs. Standard deviations are also found to increase for the weaker TSLs as the curing period increases. There is no definite trend in the spread of CV over the testing period. Some materials (A, D, E, F, G, H, J, K, N, Q, S and T) show decreasing CV, while the remaining ones show increasing CV over 28 days.

6.3.1 **Repeatability index**

Repeatability index for the tensile strength testing is calculated using the Equation 3 (page 66) and its value is 17,1. The total number of curing times at which testing took place is 103 and the sum of CV% is 1763.5. Results included 491 individual tests in the analysis.

The distribution of average CV% for all tensile strength tests is shown in Figure 46. The data presented in Figure 46, indicates lower average CV% for TSLs in the high strength categories. One can, therefore say that, tensile strength testing is more stable and repeatable for stronger TSLs.

6.4 Summary and conclusions

Tensile strength is one of the most important TSL material properties that needs to be tested. ASTM D638 “Tensile Properties of Plastics” is the most relevant standard for measuring the tensile strength of TSLs. Previously; a number of researchers (Tannant *et al*, 1999; Archibald, 2001; Spearing and Gelson, 2002) took this standard as a reference and performed tensile strength testing. However, a few minor modifications in the preparation of the specimens and test execution were done for the ASTM D638 standard to be applicable on TSLs and shotcrete.

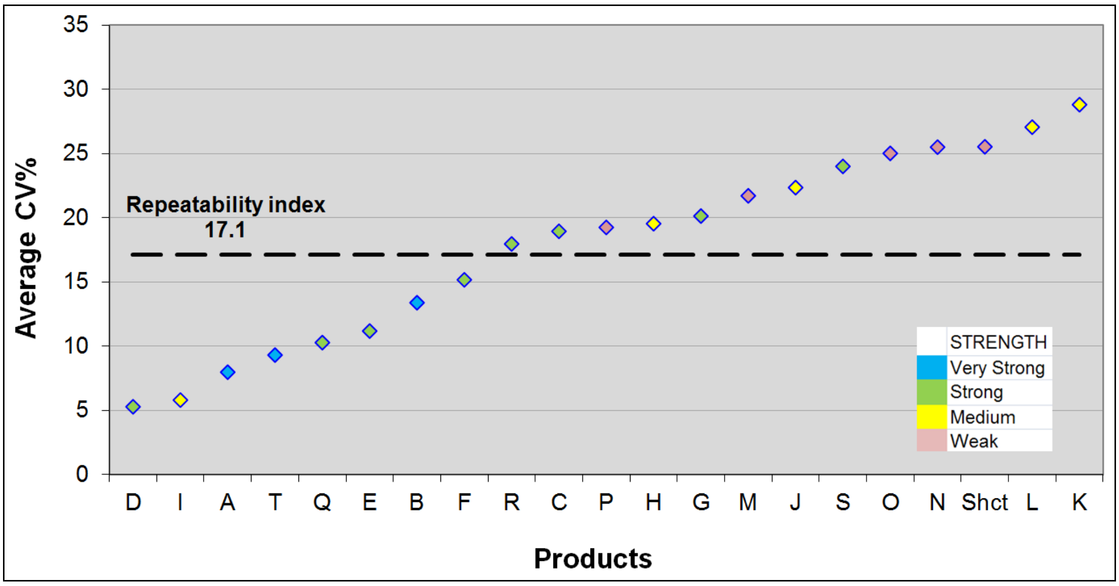


Figure 46. Distribution of average CV% for tensile strength testing for all liner products

The derivation of acceptable test results depends on the proper preparation of the specimens. The modifications adapted during the specimen preparation aimed to simplify and ease the specimen preparation process. Special attention was given to moulding procedures to ensure uniform specimen thickness, and to prevent damage on the specimens.

Tensile strength testing is applicable on shotcrete after increasing the size of the dog-bone specimen to suit for the shotcrete's structural composition and applied field thickness. The tensile strength of plain shotcrete is measured to be 0,72 MPa at 8 days and found to compare well with the values found in the literature. Lacerda and Rispin (2002) stated that shotcrete tensile strength was less than 1 MPa at 12 hours while Hahn and Holmgren (1979) quoted 0,5 to 1,0 MPa at 7 days.

The parameters necessary to establish standard testing methodology, such as the loading rate, dog-bone dimensions and thickness, number of tests, curing time, and environmental conditions are emphasised. The testing should be performed at set values on these parameters to obtain comparable results. Curing time is chosen as the main parameter and testing is done over a period of 28 days.

Sufficient amount of tensile strength testing was carried out on a variety of TSL products and shotcrete. The test results show that the comparison of tensile strength for liner products is possible. Strength improvement over the curing period is also noticeable on product basis.

The next chapter discusses the fourth and the last testing method, that is tensile-bond strength, included in the comparative assessment of liner products.

CHAPTER 7 TENSILE-BOND STRENGTH TESTING

Tannant (2001) considers the tensile-bond strength to be one of the important TSL properties to be tested. Tannant (2001) claims that the mass of loose rock, that needs to be safely held in place, depends on the TSL adhesion to the rock and TSL's tensile or shear strength. On the other hand, Stacey and Yu (2004) conducted finite element stress analyses to investigate the influence of the bond strength between liner and rock on the support capacity provided by thin liners. They found that the bond strength between the liner and the rock has no significant influence on the support capacity provided by the liner. The views expressed by these researchers on the importance of adhesion of TSL on the support capacity are contradictory. Therefore, additional research in the quantification of the effectiveness of tensile-bond strength on the support capacity is required.

Tensile-bond strength testing is the second most common physical property testing performed on TSL products worldwide. Tannant *et al* (1999), Archibald (2001), Lewis (2001), Ozturk and Tannant (2003), Tannant and Ozturk (2003) in particular, carried out comprehensive tensile-bond strength testing. The effect of the liner thickness, substrate conditions (fracture/joint roughness, oil or dust), rock type and properties (tensile/compressive strength, mineralogy, grain size), environmental conditions (temperature and humidity) and loading rates on adhesive strength were taken into account by Ozturk and Tannant (2003 and 2010).

The number of tests and the variety of TSL products in the testing programmes were often insufficient. Testing of only one TSL brand may not reflect the desired outcome from testing as the results may be product sensitive. The adhesion of a product may be affected by the presence of dust or moisture on the rock surface, while another product may be affected minimally. For example, Archibald, (2001) mentioned that Polyurea-based coatings and polyurethane-polyurea hybrids are less affected by the presence of free water. Kuijpers (2001) stated that Evermine adhered well to wet/or slightly dusty rock.

The method of tensile-bond strength testing, as practiced by the previous researchers, is adopted after a few modifications in the specimen preparation and test set-up. The modifications are intended to bring ease and simplification to the test procedures. The most notable difference is the use of perspex moulds in the specimen preparation where over-coring of TSL is eliminated. Perspex moulds also assisted in maintaining uniform TSL thickness. Secondly, substrate type and surface finish is standardised to avoid problems associated with variable surface roughness. The design of the testing frame incorporates differences in the way the steel dolly-specimen assembly is attached to the testing machine.

Espley *et al* (2001) stated that cure rate is one of the most important parameters for good adhesive strength. The cure rate is closely associated with the rate of strength development over time Therefore; tensile-bond strength testing is carried out over a period of 28 days at suitable curing times to see the effect of ageing on the strength.

7.1 Tensile-bond strength test considerations

A few important parameters of tensile-bond strength testing may influence the results. The understanding and addressing of these aspects is necessary to design a testing method that produces repeatable and comparable results.

7.1.1 **In-situ loading mechanism**

The adhesion loss of TSL on excavation surfaces may take place due to the influence of tensile forces as illustrated in Figure 47. The adhesion loss resulting from shear forces is covered in Chapter 4. Figure 47a shows the case of a loose rock moving away from the excavation surface and causing the TSL to de-bond progressively (peeling off). This mechanism is possible if the TSL is flexible or yielding type. The extent of de-bonding for stiffer and weak-bond TSLs would be greater. In both cases the tensile forces are the main reason for the ultimate failure of TSL. A stiff TSL with higher tensile-bond strength would ultimately fail in shear.

Some of the adhesion testing methods performed previously by researchers as well as the one discussed in this chapter addressed the measurement of the tensile-bond strength in the manner shown in Figure 47b. TSL, in this case, penetrates into a crack that subsequently dilates.

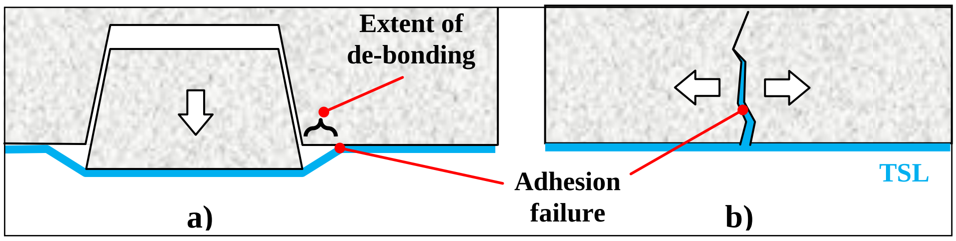


Figure 47. The de-bonding of TSL due to a) Loose rock, b) Crack dilation

7.1.2 Eccentric loading

A number of factors, such as specimen clamping, uneven substrate and TSL thickness, may contribute towards eccentric loading. If the rock surface is not smooth, as seen in Figure 48, the eccentric loading will be the consequence. Uneven TSL thickness, even if the substrate is smooth, would also cause eccentric loading. In both cases, the direction of pull deviates from the direction of the substrate or TSL axis. The TSL surface can be ground to become parallel with the rock substrate to prevent eccentricity. Care should also be taken in attaching the steel dolly perpendicular to the rock substrate.

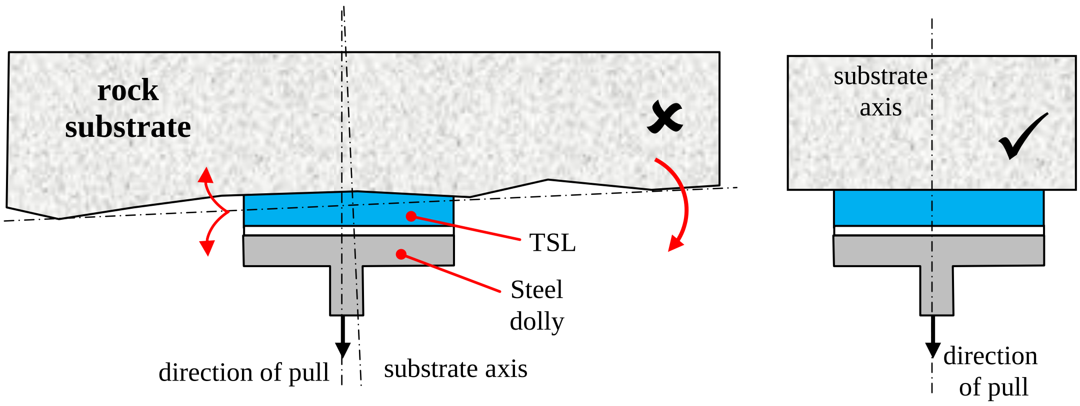


Figure 48. Eccentric loading due to irregular substrate

7.1.3 Thickness control

Ozturk and Tannant (2010) observed that increasing liner thickness reduced the adhesive strength of the liner they tested. The preservation of uniform liner thickness becomes important for obtaining comparable results. The TSL thickness of 5 mm is aimed for the prepared specimens.

7.1.4 Loading rate

The loading in tensile-bond strength testing is done similar to tensile strength testing that is under load control mode. The initial rate of loading is 2,5 N/s up to 100 N (40 seconds) and then pulling at a constant loading rate of 5 N/s up to failure. The failure would take place between 1 and 3 minutes for most TSLs.

7.1.5 Substrate rock type and surface condition

Norite is selected to be used as the substrate amongst available rock types. The primary reasons for using norite are its high uniaxial tensile strength (> 15 MPa), more competent surface conditions, and availability. The possibility of cohesive failure of the substrate is therefore minimised when TSLs with high bond strengths are tested. The variations in the surface roughness, and conditions are avoided by using the same surface finish for all specimens that are free dust, oil and moisture.

7.1.6 Shotcrete

No modifications in the tensile-bond strength test set up were necessary for shotcrete. Shotcrete applied thickness and aggregates were considered to have minimal interference with the bonding process. However, in order to maintain humidity levels and to prevent the rapid drying of shotcrete, the specimens were kept in a water-desiccator soon after preparation and only taken out at the time of testing.

7.1.7 The epoxy type and timing of the epoxy application

The type of epoxy used should be able to withstand the stress levels experienced by the TSLs bonding strongly. The epoxy failure would result in the test invalidity. The timing of the epoxy application is important since the entire surface of TSL is covered with epoxy that eventually interferes with the curing process. In order to prevent the possible variations in the test results, the practice of applying the epoxy 24 hours before testing is observed. The testing of TSL specimens at 1 day curing is not possible due to the requirement of the setting of the epoxy. Quick setting epoxies may be used if the testing is required in shorter (24 hrs or less) curing periods.

7.1.8 Calculations

The loading of TSL is in tension and the failure is caused due to tensile de-bonding. Therefore this test measures the interface bond strength between a liner material and a rock or similar surface. The tensile-bond strength (σ_{tb}) was calculated by dividing the load at failure F (in N) by the TSL surface area A (in m^2) i.e.;

Equation 7; $$\sigma_{tb} = \frac{F}{A} = \frac{F}{\pi \times r^2} \qquad \text{(Pa)}$$

where r = TSL radius that is approximately 0,0175 m.

7.2 Description of specimen preparation, test apparatus, and procedures

7.2.1 Specimen components and dimensions

Steel-dolly

The steel dolly serves the purpose of connecting the TSL-rock substrate and the testing machine (Figure 49a). Attachment of steel dolly to TSL is done by the help of an epoxy. The most important dimension is the diameter of the area on the cap of the steel dolly used for pulling the TSL. This area should not be less than the area of the poured TSL that has a diameter of 35 mm. The choice of this particular size firstly reduces the specimen dimensions to a manageable size. Secondly, the recording of force at failure in kN is approximately the same as the tensile-bond strength in MPa. A quick estimation of strength can be done without calculation.

The remaining dimensions of dolly length, cap thickness and column diameter can be selected in such a way to suit with the testing frame. These dimensions are provided in Figure 49a.

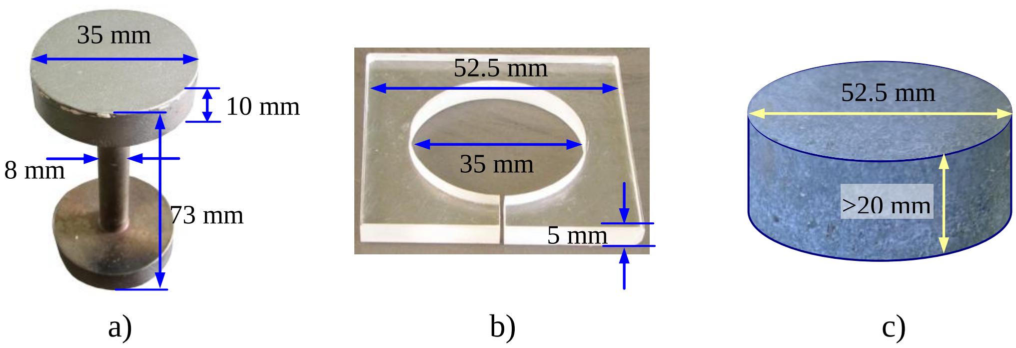


Figure 49. Dimensions of a) Steel dolly b) Perspex mould and c) Rock core

Perspex mould

Figure 49b shows the 5 mm thick perspex glass, with 35 mm diameter cavity, used as a mould for ensuring uniform TSL diameter and thickness. The biggest advantage of using perspex mould is the elimination of overcoring process as practiced by the previous researchers. Overcoring may damage and weaken the substrate. Higher failure loads in tension would be experienced when the substrate is not affected by overcoring. The second advantage of using perspex mould is the attainment of uniform TSL thickness that facilitates the attachment of the steel dolly to be at right angles. The risk of eccentric loading is reduced if the steel dolly is glued normal to the TSL surface. The cavity area on the perspex mould should be the same as the steel dolly cap area.

Rock substrate

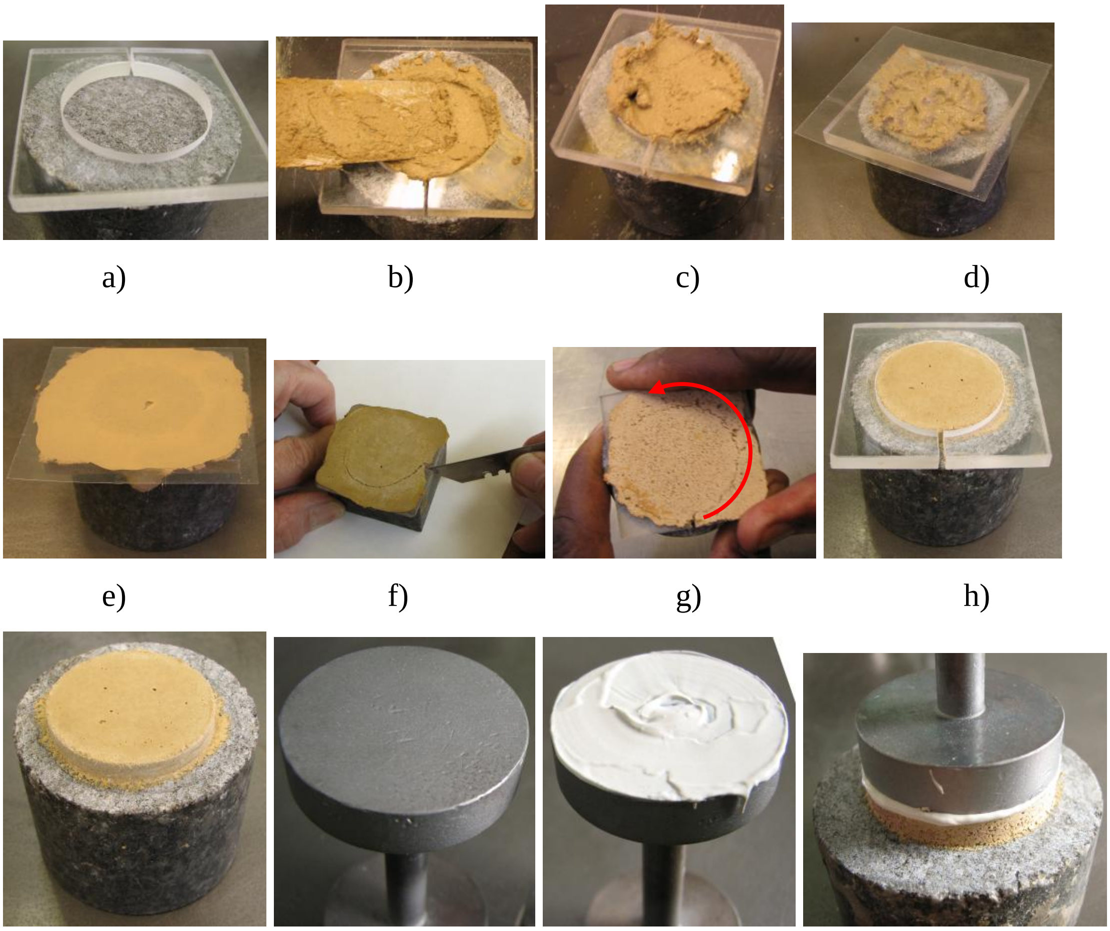
The option of using rock cores with the dimensions shown in Figure 49c is exercised for substrate purposes. As mentioned previously, norite is used as the rock substrate. The 52,5 mm norite cores were drilled and both ends are cut with a diamond saw disc to a smooth surface finish. The shape of the substrate may be circular, rectangular or any other shape provided that the substrate surface, on which TSL is applied, is smooth. This surface is cut with a diamond saw machine to a smooth finish with no additional processing. The preparation of cylindrical rock specimens is much easier than the preparation of cubic specimens. The area of substrate should be sufficiently large to accommodate the perspex mould into which the TSL is poured.

7.2.2 Specimen preparation

The procedures followed during specimen preparation are as following:

- Perspex mould is placed on the flat rock substrate (Figure 50a).
- TSL is mixed with a kitchen food mixer and poured manually into the cavity of the perspex mould by the help of a putty knife (Figure 50b and c).
- A piece of plastic film is positioned on top of the TSL which is then flattened by pressing against the plastic film with a flat surface of a suitable material (such as rock, wood, and metal). The excess TSL squeezes out during this process and TSL thickness becomes uniform (Figure 50d and e).
- Plastic film is removed after the setting of TSL.

- The perspex mould is released from TSL by pushing and levering a knife or a thin metal at the perspex grove (Figure 50f). The perspex mould can be freed from TSL by turning as shown in Figure 50g depending on the side TSL is released by levering. The TSL spills are cleaned from the perspex mould easily.
- The perspex mould is totally removed, leaving behind uniform TSL thickness (Figure 50i). Overcoring process is eliminated.
- The surface on the cap of the steel dolly is cleaned with acetone. The Pratley white epoxy or any strong epoxy resin that is commercially available is applied on the steel dolly. (Figure 50j and k).
- The steel dolly with epoxy is pressed against the TSL surface (Figure 50l). The epoxy gains its maximum strength in 24 hours, therefore the timing of the application of the epoxy should be 24 hours before the actual testing.



a) b) c) d)

e) f) g) h)

i) j) k) l)

Figure 50. Steps in the preparation of the tensile-bond strength specimens

7.2.3 Test set-up and execution

The Figure 51 shows the specimen used in tensile-bond strength testing where the strength is measured by pulling the steel dolly away from the rock substrate. The failure is expected to take place at the rock-TSL contact for valid testing.

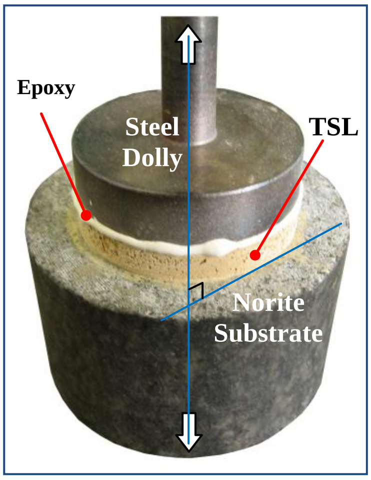


Figure 51. Configuration of the specimen in tensile-bond strength testing

The fixture used in tensile-bond strength testing is shown in Figure 52. The cured specimen is placed on the bridging plate so that the rock substrate remains on the top as shown in Figure 52. The bridging plate has a hole greater than 35 mm in diameter in order to facilitate the passing of the steel dolly. The other end of the dolly is hooked into the groove of the stationary frame that is bolted to the testing machine. None of the ends of the specimen requires clamping. The design of the test setup allows the TSL to be loaded in tension by the upward movement of the bottom platen of the testing machine. The loading direction is perpendicular to the plane of the TSL or substrate. Misalignment of the specimen axis from the direction of pull is prevented by the preparation of flat substrate surfaces and uniform TSL thickness. Then, the steel dolly becomes in line with the axis of the TSL-substrate component after attachment with an epoxy.

The loading of TSL is done by load control method and the rate was the same as the one used in tensile strength testing that is 5 N/s. The test continues until the TSL material is detached from the rock substrate while load and testing machine displacement are recorded. The failure load and the diameter of the failure area are noted for calculating the tensile-bond strength using the Equation 7. The position of failure is also recorded to explain any anomalous test results.

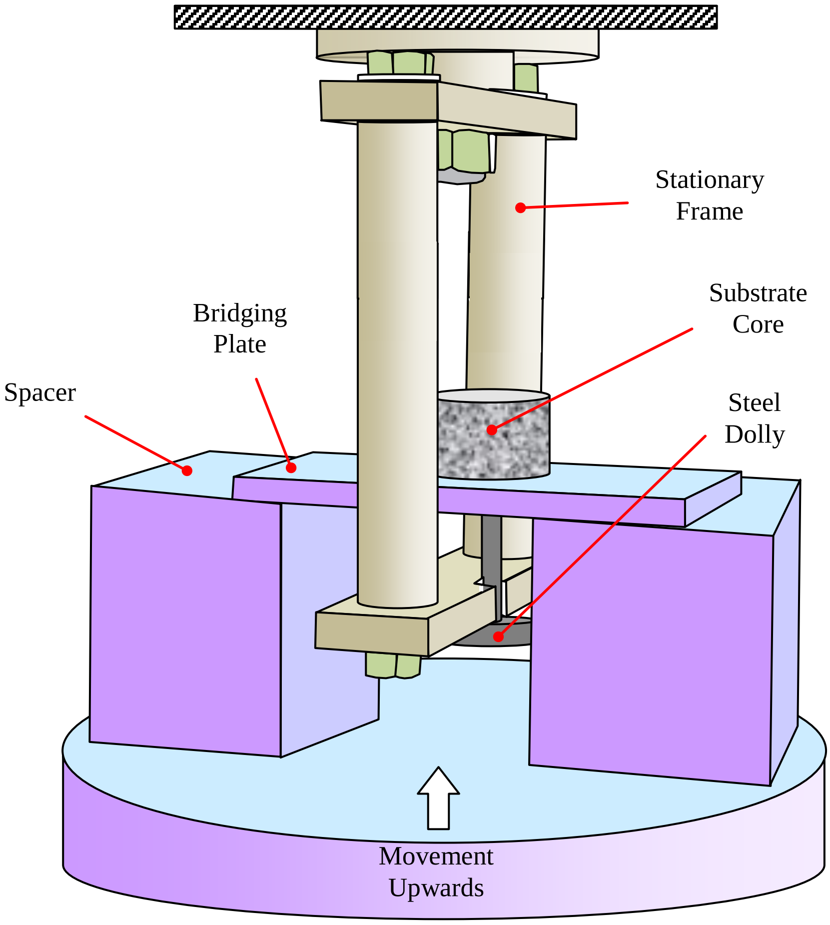


Figure 52. Configuration of the tensile-bond strength test assembly to be used in compressive machines

7.2.4 **Failure mode**

The loading of TSL takes place in tension and the failure is caused due to tensile de-bonding. Therefore this test measures the interface bond strength between a liner material and a rock or similar surface.

As mentioned in the previous section, the location of failure after testing needs to be noted to correlate with any anomalous test result. The failure would possibly occur in four locations as shown in Figure 53.

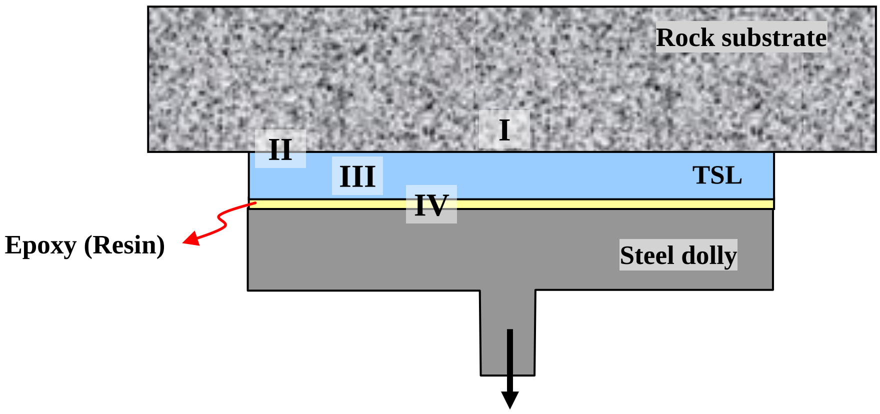


Figure 53. Possible failure locations in tensile-bond strength testing

Photographs corresponding with each of the failure locations in Figure 53 were taken and provided in Figure 54. The four failure types can be described as following:

- **Type I failure**: The photograph in Figure 54a demonstrates the failure of substrate resulting from very strong bonding of a liner that is also very strong in tensile strength. The substrate tensile strength is exceeded and an amount of rock material is plugged out by TSL. If the amount of failed substrate is more than 50 % of the pull area, then the test result is indicative of a lower bound value for the TSL material's bonding to the substrate as the failure mainly involves the rock material. Type I failure mode is a rare case and only TSL product R failed in this manner.
- **Type II failure**: De-bonding occurs between the rock substrate and TSL with minimal TSL material left on the substrate as shown in Figure 54b. This failure mode is ideally what is required from this testing as a true reflection of the tensile-bond strength.
- **Type III failure**: Failure takes place within the TSL material. Implication is that TSL's tensile strength is lower than its tensile-bond strength (Figure 54c).
- **Type IV failure**: De-bonding is between TSL/epoxy (resin) or epoxy/steel dolly interface as depicted in Figure 54d. This case indicates that epoxy bonding both to TSL and metal plug is weaker than TSL's tensile-bonding to substrate. This failure necessitates the rejection of the test result. A stronger epoxy should be used to resolve the problem. Incorrect mixing and application of strong epoxies may also cause type IV failure. The cleaning of the steel dolly cap and the TSL surface with acetone is found to enhance the bonding of the epoxy.

There may be a combination of failure types I and II, or II and III. In both cases, the amount of rock fragments plugged out by TSL or the amount of TSL material left on the substrate should be noted.

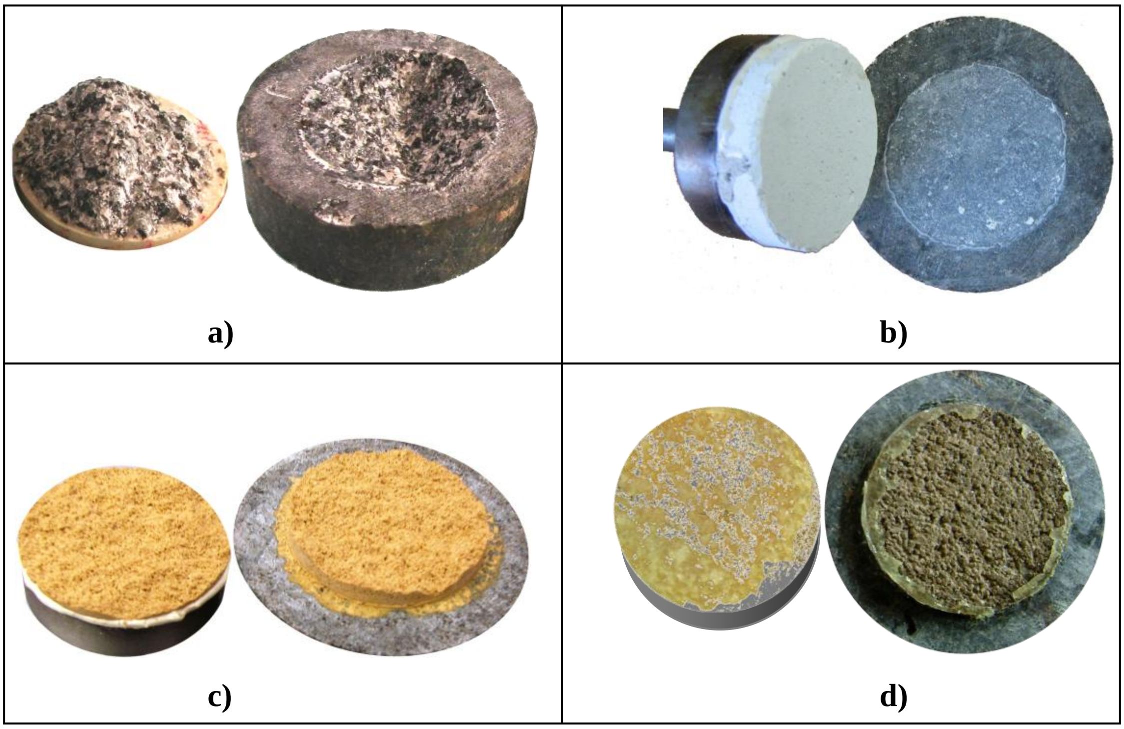


Figure 54. Failure types: a) Type I, b) Type II, c) Type III, d) Type IV

7.3 Results and analysis

Figure 55 shows a typical example of the load-displacement behavior during tensile-bond strength testing. The total loss of load carrying capability at failure is the characteristics of this testing.

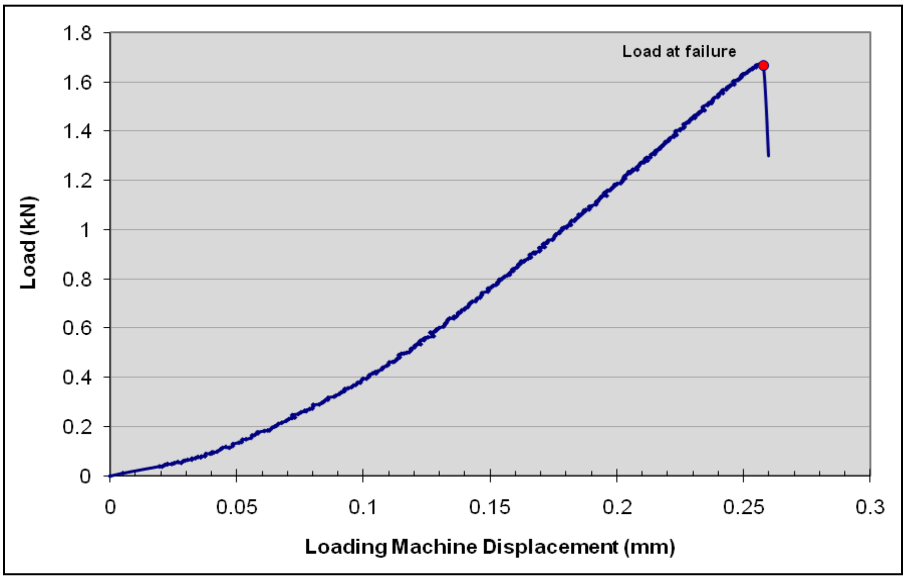


Figure 55. A typical example of the load-displacement behavior during tensile-bond strength testing

Appendix VIII summarises all the graphs of tensile-bond strength tests for TSLs and shotcrete. Three of these graphs for products A, D and shotcrete are reproduced in Figure 56. The averages of tensile-bond strengths, the equations and correlation coefficients (R^2) for the best fit curves at each curing time are shown in Figure 56. The best fit curve is logarithmic and it is applied for all data points on the graph of a particular liner. Note that the scales of the graphs Appendix VIII are the same except TSL R which has exceptionally high tensile-bond strength.

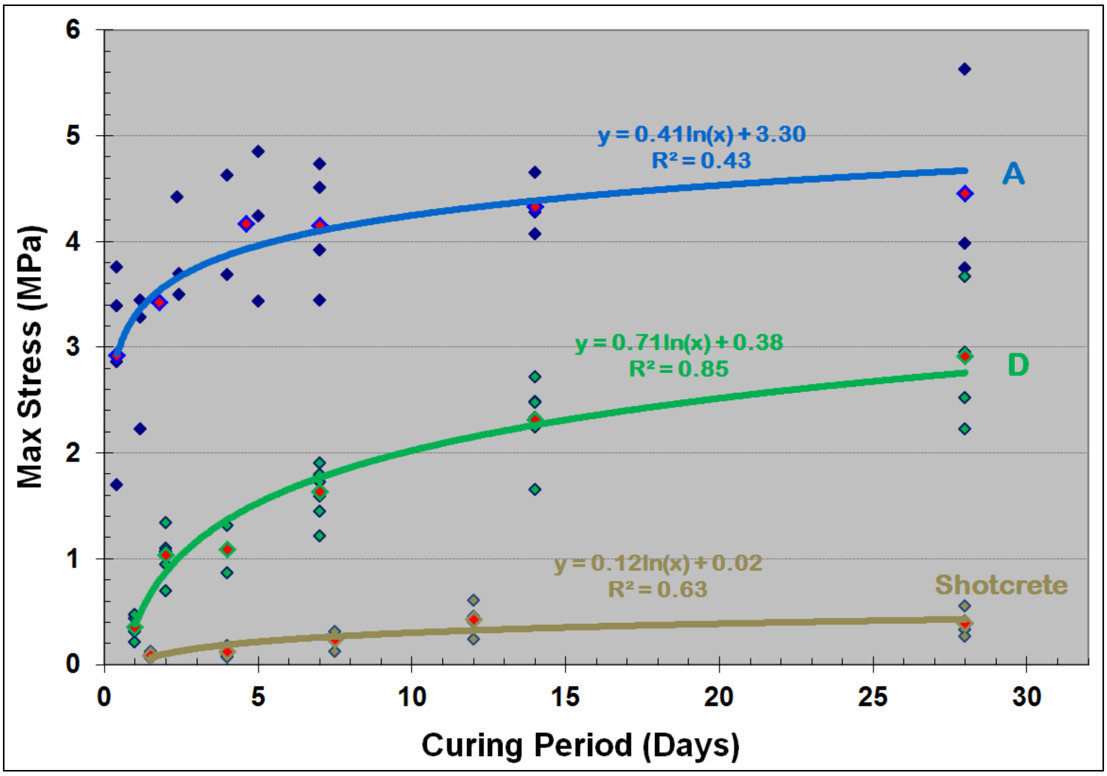


Figure 56. Example curves in the tensile-bond strength range

Figure 57 is the overall summary of the results, presented in Appendix VIII, in terms of the best fit curves for each liner product. Tensile-bond strength for most liner products in the lower strength section (<0.5 MPa at 28 days) does not show any remarkable change over 28 days of curing. A few products (TSLs G, J and L), in fact, demonstrate decreasing tensile-bond strengths. These products are all cementitious and characteristically display shrinkage behaviour. The remaining TSLs, especially the ones with higher tensile-bond strengths, show an increasing trend with the increasing curing period. The tensile-bond strength of TSL R (polyurethane type) is exceptionally higher than the rest of the TSLs. The second best performing TSL in terms of tensile-bond strength is also found to be polyurethane based (TSL A). It can, therefore, be said that polyurethane based TSLs have superior tensile-bond strength characteristics over the cementitious or polymer based TSLs.

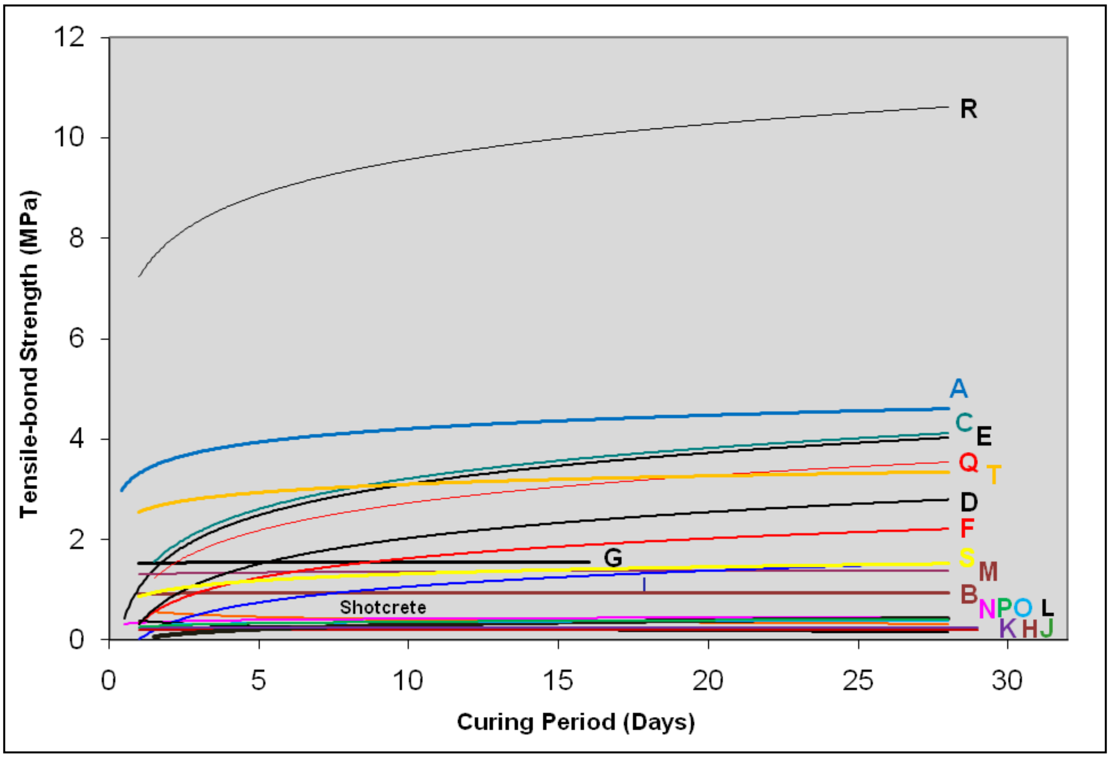


Figure 57. Tensile-bond strength results for shotcrete and TSL products

The categorisation of tensile-bond strength is made taking the strength development over 28 days into account as can be seen in Figure 58. Clustering of a number of weak TSLs can be noticed. A total of 38% of the liner products are in the weak strength category and shotcrete is one of them. Two TSL products within the very strong category are both polyurethane based.

The tensile-bond strength equations, correlation coefficients (R^2) and strength ranking for all products are listed in Table 17. Strong and very strong tensile-bond strength behaviour were displayed by the 38.1% of the liner products. The correlation coefficients tend to decrease with decreasing tensile-bond strength. Three and two products in the medium and weak tensile-bond strength category respectively have zero correlation coefficients. Polyurethane products A and R present above average correlation coefficients.

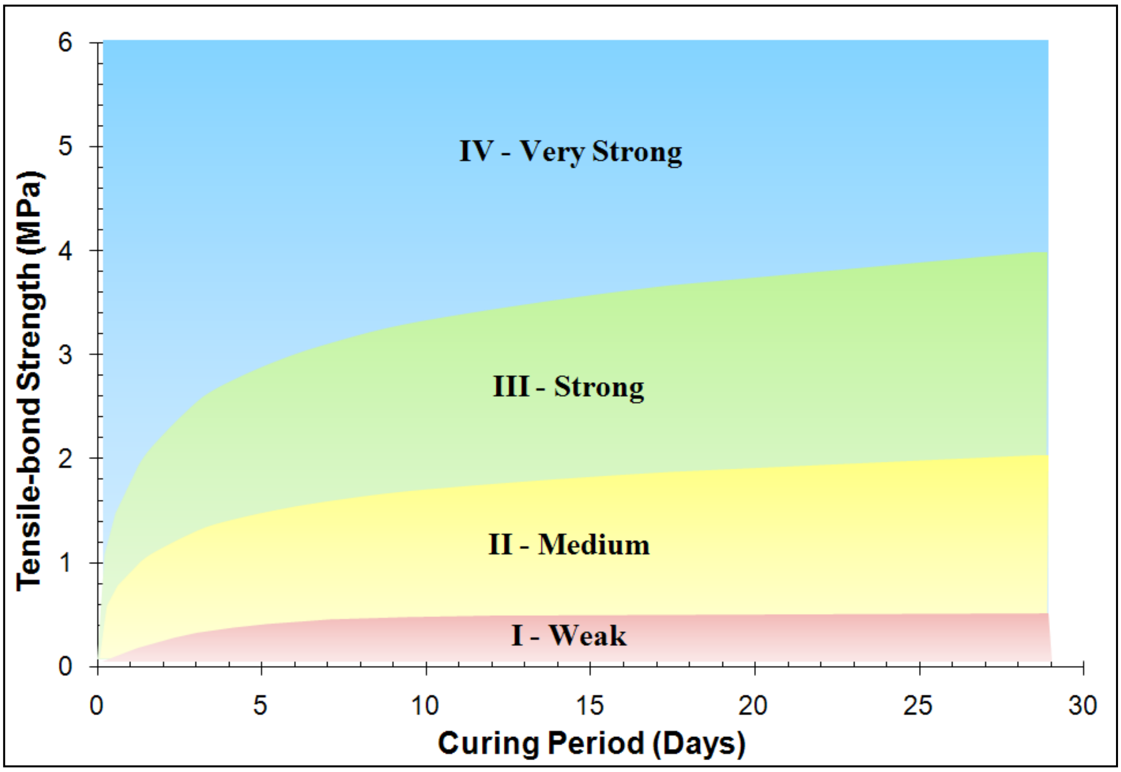


Figure 58. Tensile-bond strength categories.

Detailed statistics on the tensile-bond test results in terms of mean strengths, standard deviations and coefficient of variations (CV) corresponding with each curing day are summarised in Appendix IX. Very strong materials have lower CVs, otherwise there is no definite trend in the CV values for the remaining TSLs. Standard deviations increase with the TSLs in the higher strength categories.

Figure 59 shows the distribution of average CV% for all tensile-bond strength tests. The two polyurethane products R and A, being in the very strong category, have lower average CV%. Tensile-bond strength testing of polyurethane products is more repeatable than the other products. The distribution of average CV% for the other strength categories is rather inconclusive.

Table 17. Tensile-bond strength equation, correlation coefficients and ranking according to 28 day strength

TSL	Tensile-Bond Strength Equation (MPa)	R^2	Rank	Strength Category
TSL R	0.94ln(x) + 7.36	0.41	1	IV - Very Strong
TSL A	0.41ln(x) + 3.30	0.43	2	
TSL C	0.88ln(x) + 1.20	0.61	3	III - Strong
TSL E	0.97ln(x) + 0.99	0.76	4	
TSL Q	0.78ln(x) + 0.91	0.78	5	
TSL D	0.73ln(x) + 0.36	0.86	6	
TSL T	0.27ln(x) + 2.50	0.22	7	
TSL F	0.56ln(x) + 0.34	0.39	8	
TSL S	0.19ln(x) + 0.91	0.21	9	II - Medium
TSL B	0.03ln(x) + 1.28	0.00	10	
TSL I	0.45ln(x) + 0.02	0.77	11	
TSL G	-0.10ln(x) + 1.76	0.04	12	
TSL M	0.01ln(x) + 0.92	0.00	13	
TSL N	0.04ln(x) + 0.34	0.15	14	I - Weak
TSL P	0.05ln(x) + 0.26	0.22	15	
Shotcrete	0.12ln(x) + 0.02	0.63	16	
TSL O	0.03ln(x) + 0.28	0.15	17	
TSL L	-0.08ln(x) + 0.59	0.47	18	
TSL J	-0.07ln(x) + 0.40	0.29	19	
TSL K	0.00ln(x) + 0.25	0.01	20	
TSL H	0.00ln(x) + 0.21	0.00	21	

x: curing period in days

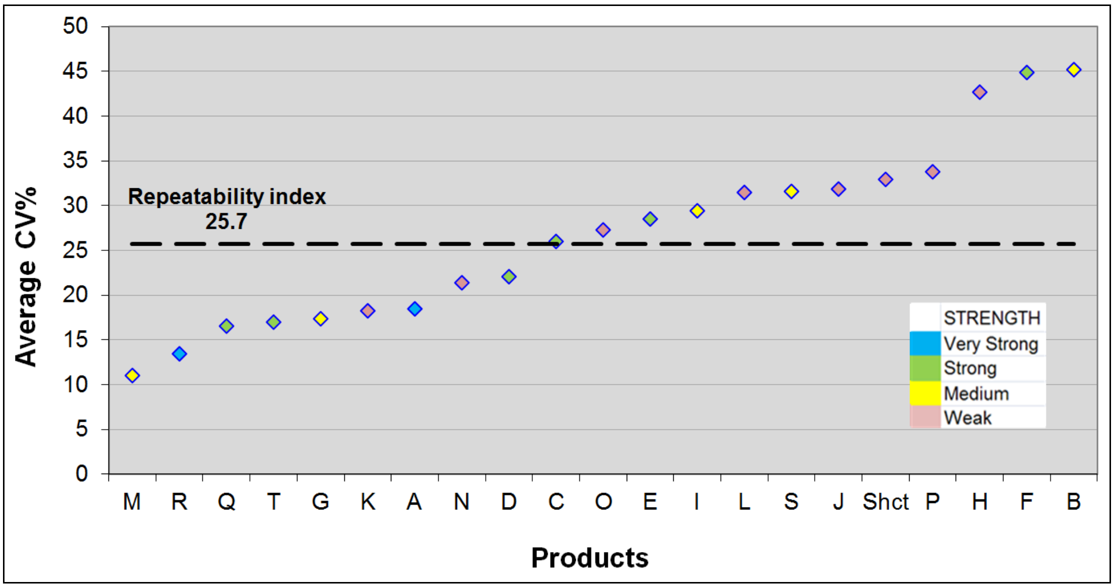


Figure 59. Distribution of average CV% for tensile-bond strength testing

7.3.1 **Repeatability index**

Repeatability index for the tensile-bond strength testing is calculated to as 25,7. The total number of curing times at which testing took place is 99 and the total CV% at these curing times is 2548.3. Results included 442 individual tests in the analysis. This index, being the highest for the testing methods discussed from Chapter 4 to Chapter 7, indicates the lower repeatability of tensile-bond strength testing.

7.4 Summary and conclusions

Tensile-bond strength testing is more difficult and time-consuming as compared to the other testing methods. The need to use a rock substrate, steel dolly and epoxy in the testing method brings more complications that must be dealt with. The major complication is the eccentric loading which can be handled by preparing smooth substrate surface and uniform TSL thickness.

The major difference between the tensile-bond strength testing carried out previously by other researchers and the one discussed in this chapter is the use of perspex moulds in the preparation of specimens. The perspex mould eliminates the overcoring process and ensures excellent thickness control. Overcoring of substrate was previously practiced by Ozturk and Tannant (2003) to free the TSL pull area from the remaining extent of TSL. Overcoring, if not done carefully, may cause the detachment of TSLs with weak tensile-bond strength. The overcoring progresses a small distance into the substrate and may reduce rock's pull or tensile strength.

The tensile-bond strength testing is applied to shotcrete with no alterations in the test setup. However, the curing of shotcrete is done in a water desiccator to protect shotcrete against evaporation and to maintain humidity level. The tensile-bond strength of shotcrete is typically low and the values are similar to the 25 mm thick wet and dry shotcrete test results obtained by Reynolds and Leach (2002) on dolomite substrate.

The tensile-bond strength testing is capable of reflecting the TSL bond characteristics on a substrate when subjected to tensile loading. Time dependency of tensile-bond strength in weak TSLs was negligible; however, there was a remarkable strength increase with increasing curing period in the other groups of TSLs.

The location of the failure is important and should be noted to validate the test results. Shotcrete and TSLs are only as strong as their weakest link in tensile loading. A specimen should not fail at the steel dolly and epoxy contact since this is an indication of the weak epoxy strength. Ideally the failure should take place at the substrate-TSL contact as a true reflection of the tensile-bond strength. Theoretically, the tensile-bond strength cannot be greater than the tensile strength since the TSL material would fail in tension before the attainment of its tensile-bond strength.

The test results obtained so far from the four testing methods, discussed in the previous four chapters, are analysed for comparison purposes in the next chapter.

CHAPTER 8 GENERAL ANALYSIS OF RESULTS FOR THE COMPARISON OF TSL MECHANICAL PROPERTIES AND DISCUSSIONS

The results of testing methods are discussed individually in Chapters 4 to 7. Some of the tests were performed at 14 days curing time while others were performed after 15 days. The testing program in a few cases coincided with public holidays or unforeseen circumstances prevented the execution of testing on the scheduled time. Differences in the curing time had negligible impact on the comparability of test results. Some TSLs had only a few tests done compared to others (i.e. shear-bond strength test on TSLs L, O, P and R) due to insufficient amount of material provided by the suppliers. Insufficient amount of test specimens in a few cases caused anomalies in the comparison of test results. Nevertheless, in general, it was seen that the TSLs could successfully be compared by looking at their performance for each testing method. The collective analysis of test results and comparison of TSLs is presented in this chapter.

8.1 Specimen preparation and testing time

Comparison of the times involved for various activities on a specimen in the testing of TSLs by various methods is provided in Table 18.

Table 18. Time analysis for the preparation of a single specimen

Test Activities (min)	Tensile-Bond	Shear-Bond	Tensile	Shear
Substrate preparation	1½	2	-	-
Specimen preparation	1½	2	1	½
Test setup and execution	3	3	4	3
Clean up for re-use	1½	1½	1	½
TOTAL	7½	8½	6	4

Tests involving the use of substrate take longer to prepare and execute. The simpler testing methods require shorter times. Shear-bond strength testing demands the longest time followed by the tensile-bond strength testing.

8.2 Ease of testing method

Every testing method involves the performance of a variety of tasks, from specimen preparation to the testing of the specimen. The performance of these tasks is associated with a degree of difficulty. The tests requiring the use of a substrate necessitates the additional handling of such material and related complications. The following Table 19 summarises the tasks for the testing methods with the assignment of a rating for the level of difficulty experienced.

Table 19. The difficulty rating for the tasks involved in the testing methods

Tests / Activities	Tensile	Tensile-bond	Shear-bond	Shear
Mould set up preparation	4	2	4	1
Substrate preparation	-	3	4	-
Cleaning of apparatus after testing	3	4	3	1
Complexity of apparatus	2	2	2	1
Handling of testing fixture	4	3	1	2
Interpretation of test results	3	3	1	1
TSL pouring into the moulds	4	2	5	1
Work for the completion of specimen preparation	3	2	3	1
Extraction of specimen from moulds	2	2	1	1
Contouring (cleaning) of specimen	3	3	3	1
TOTAL	28	26	27	10
Rating: 1. Very Easy, 2. Easy, 3. Medium, 4. Difficult, 5. Very Difficult				

Material shear testing method stands out as the easiest and the other three methods do not significantly differ in terms of difficulty.

8.3 Repeatability analysis

The repeatability of each testing method was calculated in Chapters 4 to 7. The analysis will be done taking the testing methods and the products as the basis.

8.3.1 Test methods

The values of the repeatability index for the four testing methods are summarised in Figure 60. There is a significant difference between the repeatability indexes of shear strength testing compared to the other three test methods. The reason for the difference could be explained as follows:

- Shear and tensile strength tests are material only tests. The influence of substrate seems to be affecting the results of shear-bond and tensile-bond tests. If TSL material, for example, has shrinkage problems, the bonding of TSL on a substrate would certainly be influenced.
- The complications in loading may add to the variances in the test results. Tensile strength testing requires the clamping of the specimen. Tensile and tensile-bond strength testing, in addition, necessitate the alignment of the long axis of the specimen with the loading direction. Misalignment would result in eccentric loading and the rejection of the test result. However, the test results would incorporate the influence of minor misalignments that are difficult to detect.

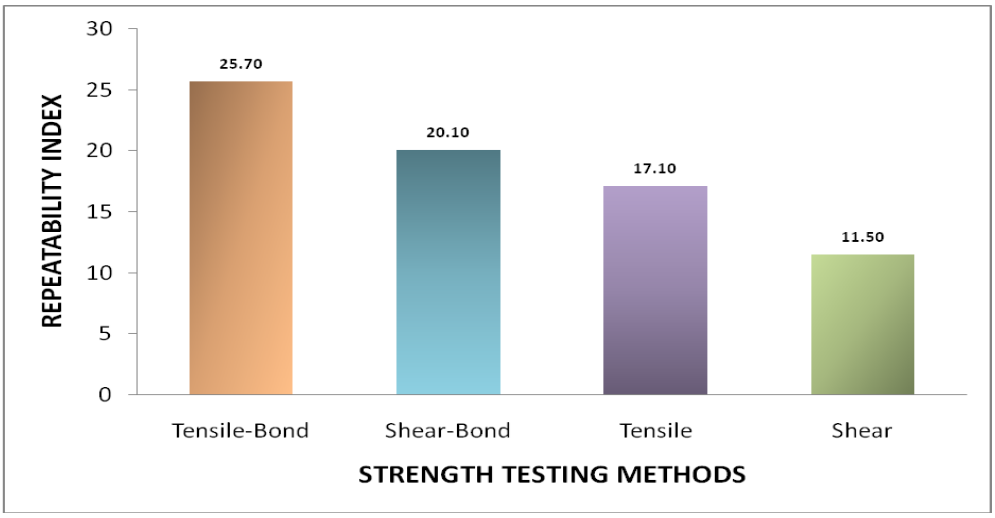


Figure 60. Summary of the repeatability indexes for the testing methods

- The specimens used in tensile and tensile-bond strength tests are susceptible to failure at the weakest point within the liner material. The failure plane may be located anywhere, depending on the position of the material weakness, and there is no control over this location. Therefore, inconsistencies on these test results are experienced. While extreme care is taken to avoid the inclusion of air bubbles in the TSL mixture, unfortunately, complete elimination of the bubbles is not possible. The occurrence of a bubble in the narrow section of the dog-bone specimen will certainly cause the failure to take place at the location of the bubble. The influence of a similar bubble in the other three types of test would be minimal on the test results since the size of the bubble would be small compared to the size of the failure.
- A factor of influence for tensile-bond strength testing is that failure does not always take place at the ideally intended position i.e. the TSL- rock interface. Weak liners may fail within the liner, leaving an amount of liner material on the substrate. TSLs with strong bonding characteristics may plug out rock material or alternatively fail within the liner material, leaving a significant amount of TSL material on the substrate. A TSL product may demonstrate more than one failure

mode during tests at a particular curing time. This will cause variation in the test results to a certain degree and cannot be avoided.

8.3.2 TSLs and shotcrete

The repeatability indexes and their averages on a product basis for all the test methods are presented in Figure 61. The powder products that required mixing with water are particularly difficult to prepare. Their curing, shotcrete inclusive, necessitated the use of a water dessiccator to prevent the adverse effects of rapid drying on the test result. In spite of this case, these products produced less repeatable test results. The strong TSLs (T, A, Q and C) and the ones with high yield capabilities (D and I), on the other hand, are found to result in the higher repeatabilities in the tests. Thus, it is reasonable to conclude that the test repeatability is also sensitive to the product type used. However, the good repeatable nature of a product in a particular test does not necessarily imply similar repeatabilities in the other tests. Product C, for example, has the best repeatability in shear testing, but not for the other tests.

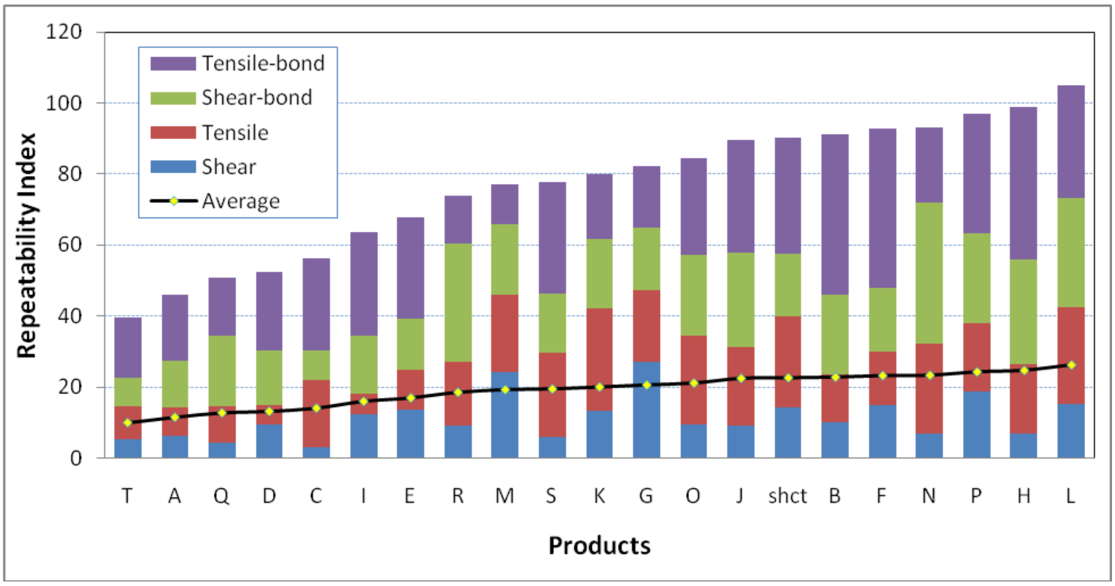


Figure 61. Summary of the repeatability indexes for the liner products tested

8.4 Correlation coefficients (R^2)

The correlation coefficient of a liner product for a testing method is determined from the logarithmic regression curve obtained on the test data over the curing period. The correlation coefficients for all liner products tested are shown in Figure 62 on a cumulative scale for the four test methods employed in this thesis. The averages of these correlation coefficients are also indicated on the same graph. This average is calculated by adding the R^2 values for a liner product from each test and then dividing this sum with the number of testing methods that is four. It is interesting to note that two high-yield TSL products I and D generated the highest R^2 values while the water-based cementitious TSLs generated the lowest ones. High correlation coefficients could be a reflection of the homogeneity of the TSL material or the stability of its chemical composition. Material shear strength in general resulted in the higher correlation coefficients followed by tensile, shear-bond, and tensile-bond strengths.

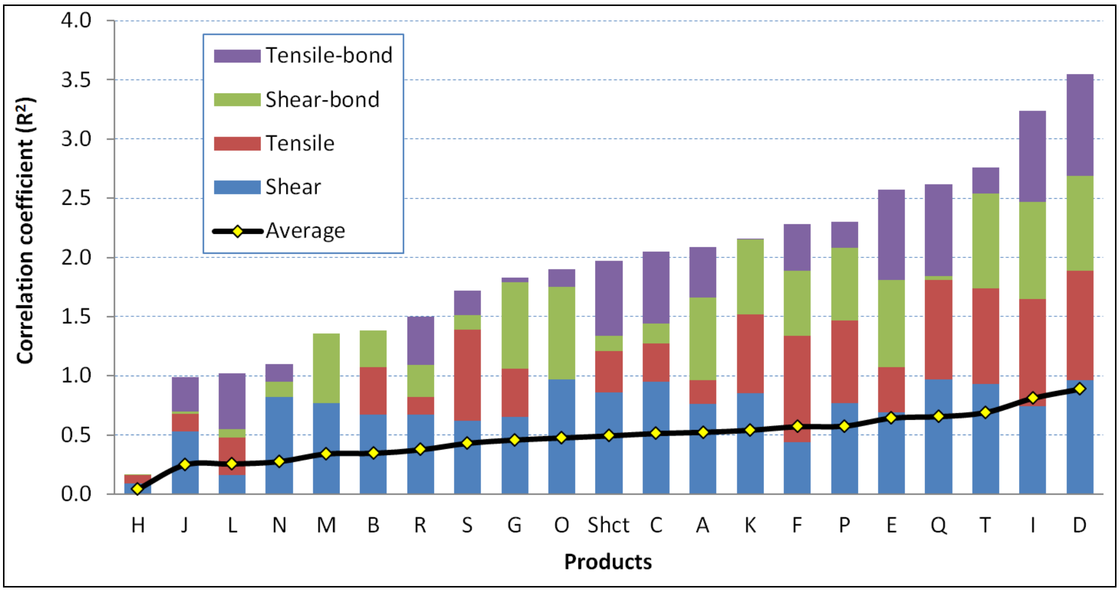


Figure 62. The correlation coefficients for the products tested in all test methods

Figure 63 displays the average correlation coefficients taking the strength categories of testing methods as the basis. The average, in this case, is calculated by adding the R^2 values for all liner products used in a testing method in each strength category and then dividing this sum again with the number of testing methods. Figure 63 indicates that weak and medium strength TSLs normally have lower average R^2 values than strong and very strong TSLs for the test methods. Shear strength testing, similar to the finding from Figure 62, in general produced higher average R^2 values in strength categories.

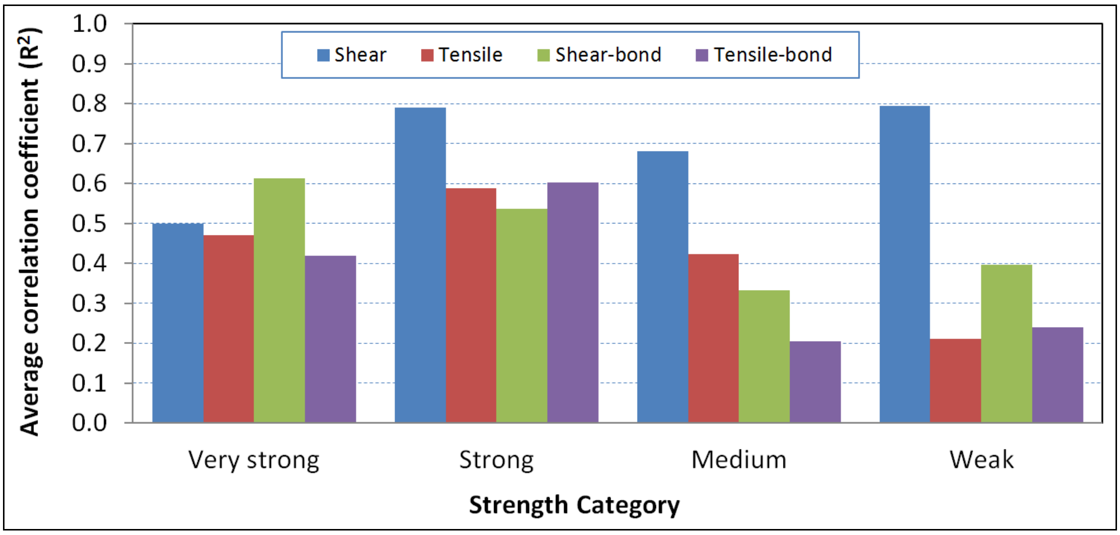


Figure 63. The average correlation coefficients for the strength categories for each test method

8.5 Comparison of TSL mechanical properties

The results of four testing methods display different magnitudes of strengths at 28 days as shown in Table 20. In general, the average shear strength was the highest and the average tensile-bond strength was the lowest. The averages of the tensile and material shear strengths (all products inclusive) are approximately twice and six times the tensile-bond strength respectively. The average magnitude of the material shear strength is the highest, followed by the tensile strength. The strength measurements involving the use of a substrate occupy the lower average magnitudes. The average shear-bond strength is approximately 50% higher than the tensile-bond strength.

Table 20. The averages, maximum and minimum values of the test results inclusive of all the TSLs for the testing methods based on the 28 days curing time

	Tensile	Shear	Shear-bond	Tensile-bond
Average (MPa)	3.94	11.79	2.89	2.05
Max (MPa)	8.13	33.99	6.85	9.91
Min (MPa)	0.60	1.13	0.73	0.20

Figure 64, on the other hand, shows the results of testing methods at 28 days for each TSL. The graph displays the liners in decreasing order in view of the sum of all strengths. Unfortunately, there is no currently available method of reducing the four strength values into a single strength parameter for quick and simple comparison of mechanical properties of the TSLs and shotcrete. The assignment of equal importance to each testing method is possible by taking their average. However, the method of averaging is not recommended since this average would be sensitive to high and low strength values. For example, two high results in two tests combined with two low results in the other two tests would have the same average as four medium test results. In addition, the mechanical properties of the two products would be very different.

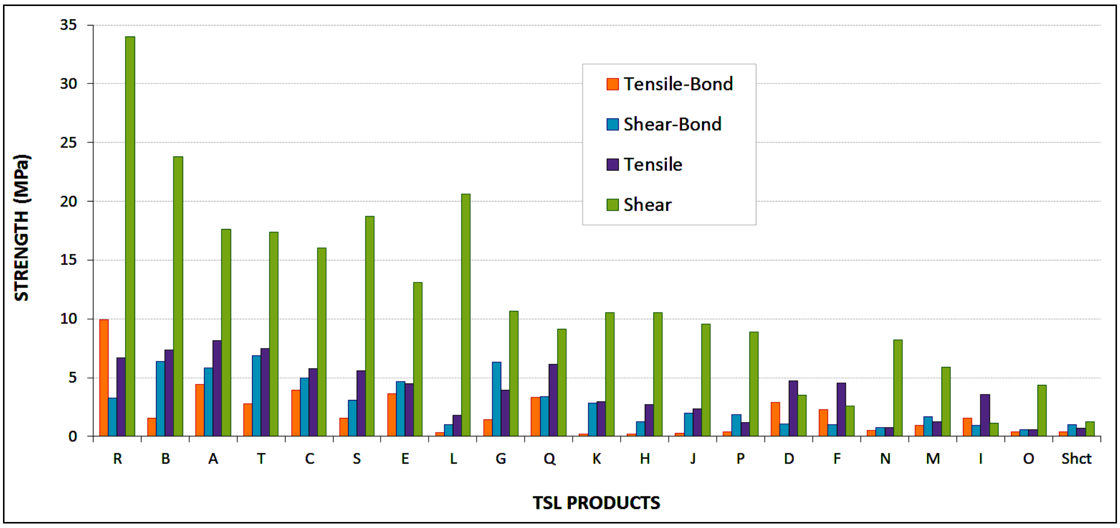


Figure 64. Magnitudes of strengths for each testing method and their averages at 28 days on a product basis

If a single value is desired for comparison purposes, the more appropriate approach would be the assignment of an importance rating for each testing method. The adoption of these ratings cannot simply be based on “thumb-suck” figures. Different test methods, similar to the one performed by Stacey and Kasangula (2003) that involves a combination of mechanisms and several of the TSL properties, should be designed. Such combination tests could provide guidance in establishing the importance ratings. In addition, having the basic properties measured from the already established testing methods may be useful in overcoming the interpretation difficulties of the results of combination tests.

Opinions may differ on the issue of the assignment of importance rating on each strength property. As mentioned in Chapter 7, Stacey and Yu (2004) considered that tensile-bond strength has minimal importance due to the insignificant influence on the support capacity provided by the TSL, while Tannant (2001) considered the tensile-bond strength to be one of the important TSL properties. Collaboration and consensus between the TSL manufacturers, researchers and experienced end-users would be required if the importance rating approach is implemented in the future.

Numerical modelling would also provide valuable insight into the support capabilities of liners in the light of laboratory determined properties. Typical laboratory results are required to create a simple model of the liner material for some numerical modelling programs (Tannant and Wang, 2004). The importance of any mechanical property could be well established by conducting proper numerical modelling. Unfortunately, both the combination tests and the numerical modelling are beyond the scope of the research in this thesis.

Nevertheless, the sequencing in Figure 64 demonstrates that the polyurethane based TSL R is the top performing product in tensile bond and material shear strengths while cementitious TSLs occupy the lower positions on the strength scale. Figure 65 further demonstrates that the polyurethane based TSLs outperform the cementitious ones. It must be emphasised that shotcrete is ranked the lowest amongst all liners in both Figure 64 and Figure 65.

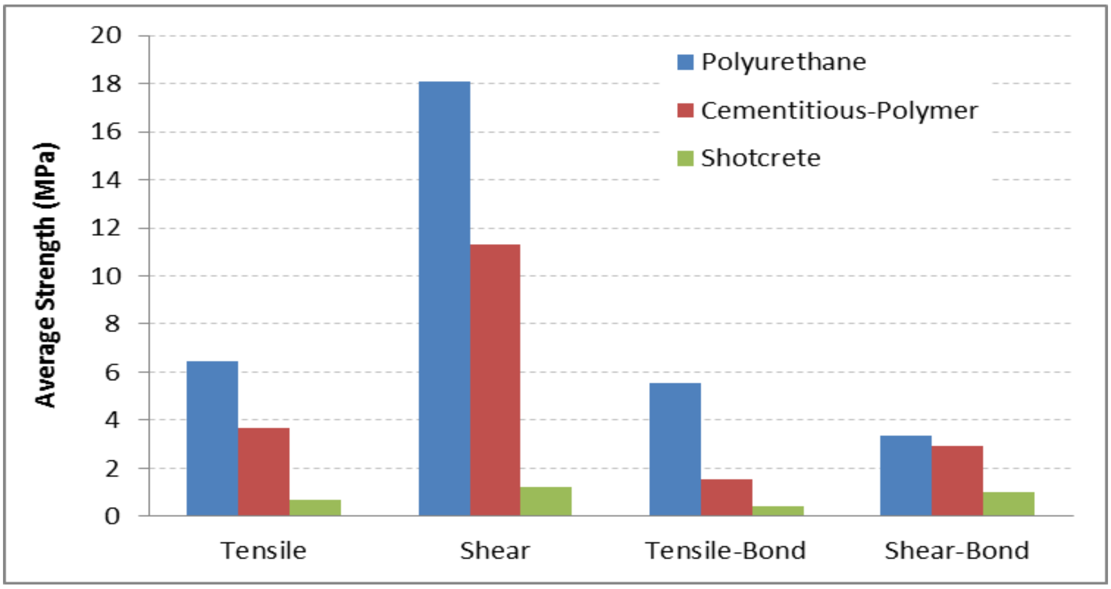


Figure 65. Average strengths at 28 days for different types of TSL

8.5.1 Comparison of tensile-bond and tensile strengths

The comparison of the two testing methods subjected to tension is shown in Figure 66. The graph shows that the tensile-bond strength is on average 56% smaller than the tensile strength. Theoretically, the tensile-bond strength could be greater than the tensile strength; however, it is interesting to note in Figure 66 that the magnitude of the measured tensile-bond strength is always smaller than the tensile strength. This means that a measurement of the tensile-bond strength that is greater than the tensile strength is practically (and theoretically) not possible. The TSL material would firstly fail due to the lower tensile strength. Such cases are always associated with some amount of TSL material left on the substrate as indicated with failure type III in Figure 54 c. The second possibility is the failure of rock in tension if the tensile-bond and tensile strengths of the TSL are greater than the tensile strength of the rock as indicated with failure type I in Figure 54 a. The rock fragments would then be plugged out on the TSL material. In both cases the true tensile-bond strength of the TSL material would not be realised.

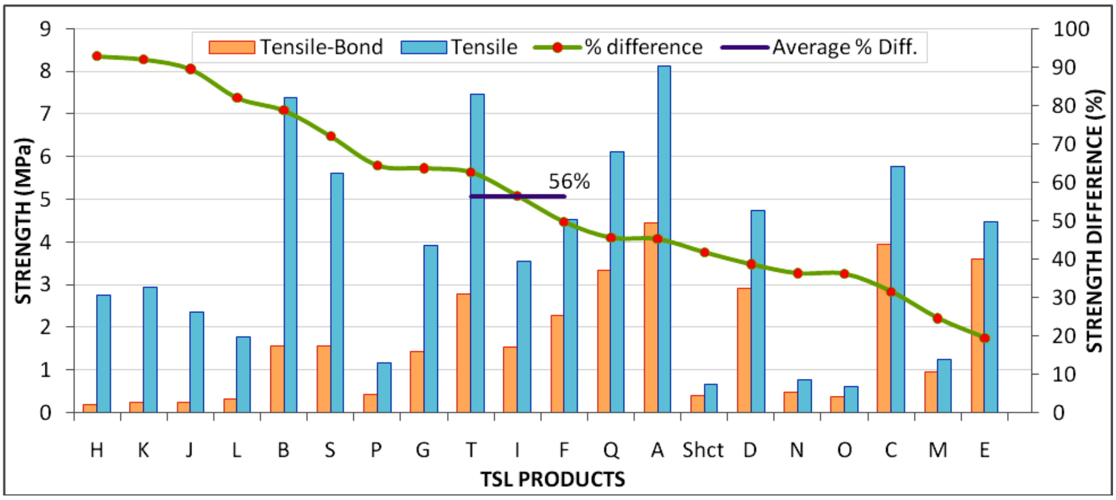


Figure 66. Tensile-bond strength and tensile strength comparison at 28 days

Note that TSL R is not included in the above analysis due to the different mixtures tried for both tests. The texture of TSL R used for tensile strength testing contained fibres and was influenced by bubbles while the specimen for the tensile-bond strength testing was more compact and contained no bubbles and fibres.

8.5.2 Comparison of tensile-bond and shear-bond strengths

Figure 67 compares the tensile-bond and shear-bond strengths based on the results at 28 days of curing. The majority of products tested are of cementitious origin and the tensile-bond strength is on average 54% smaller than the shear-bond strength. Two polyurethane and two high-yield single component TSL products on the other hand display the opposite trend in that tensile-bond strength is greater.

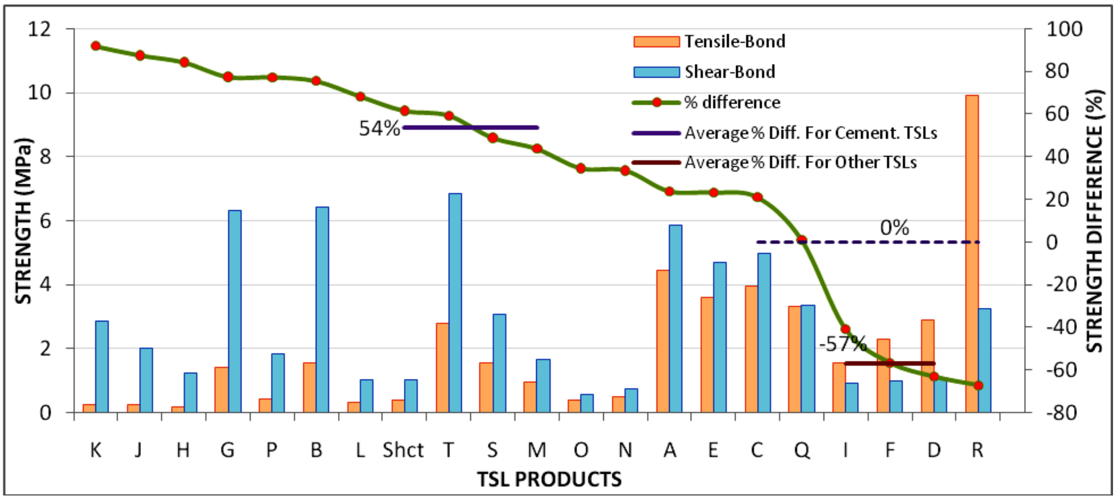


Figure 67. Tensile-bond and shear-bond strength comparison at 28 days curing

8.5.3 Comparison of material tensile and shear strengths

The comparison of the two testing methods that do not require the use of a substrate (tensile and shear strengths at 28 days) is shown in Figure 68. The liners are listed in the order of decreasing percentage difference between the two properties. The relationship is similar to that observed for the tensile-bond and shear-bond strengths in the previous Figure 67. The tensile strength is, on average, 70% smaller than the shear strength. Only three products out of 21 show the opposite behaviour where shear strength is smaller than the tensile strength. Two of these products are the high-yield single-component TSLs (D and I). TSL F is a polyurethane type that was influenced by bubble formation in the texture. Keep in mind that this comparison is only applicable between the tensile strength results on a 5 mm thick dog bone sample with the shear strength on a 20 mm thick circular sample. If comparison other than these thicknesses is desired then further testing would be required.

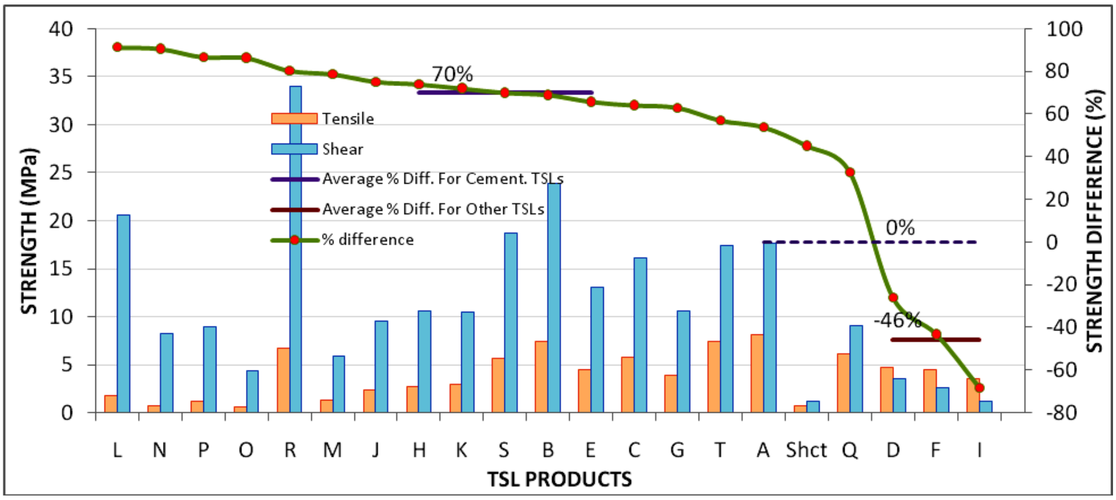


Figure 68. Material tensile and shear strength comparison at 28 days curing

High tensile strength does not necessarily imply high shear strength as seen in Figure 69 where the tensile strength is plotted in decreasing order. The percentage difference displays no correlation between tensile and shear strengths on this graph. Therefore a specific test is developed to determine shear strength as it is a unique characteristic.

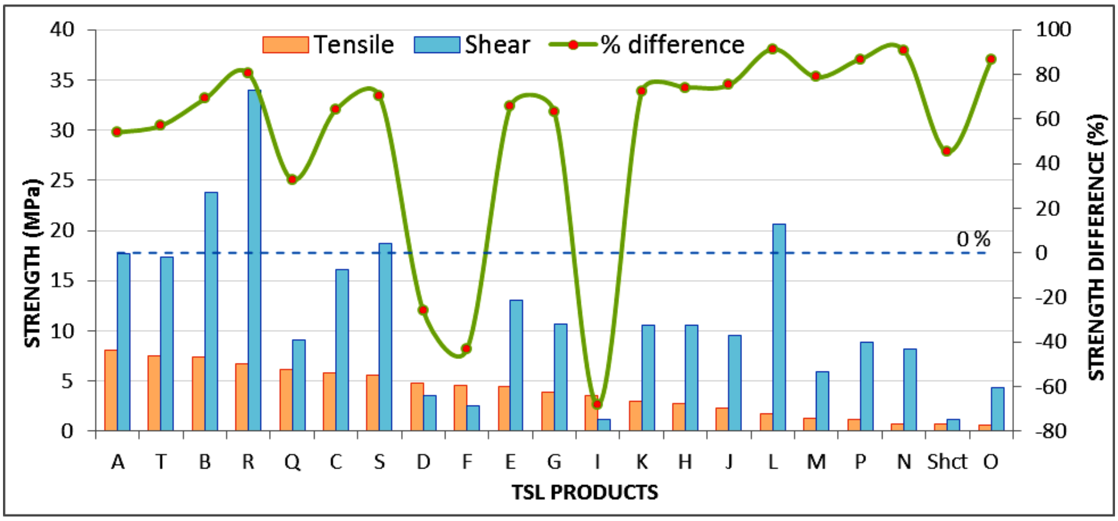


Figure 69. Material tensile and shear strength correlation at 28 days curing

Note that the TSLs C, G, T are the different versions of the same cement polymer based product. In the manufacturer's opinion, the tensile strength was the most important parameter; therefore a number of versions were developed in an attempt to increase the tensile strength. However, it was not known whether increasing the tensile strength would cause increase in all the other strengths. The graph in Figure 70, with an additional version of the same brand, shows the effect of increase in tensile strength on the other three properties. The behaviour in Figure 70 seems to suggest that increasing the tensile strength also increases the material shear strength, while both shear and tensile bond strengths decrease. One should, therefore, be prepared to accept that strength increase in one of the properties may cause degradation in some other properties. This observation, however, could be liner sensitive and its validity needs to be checked on the other types of TSLs. The correlation coefficients in Figure 70 confirm the findings made in Section 8.4 that material shear and tensile strengths have higher correlation coefficients. Having lower correlation coefficients on shear and tensile bond strengths necessitate further investigation on the influence of a change in a particular strength on the other strengths.

8.6 Liner availability in strength categories

The percentages of the TSL products as shown in Figure 71 point out the higher availability of the weak and medium strength TSLs. The high percentage of TSLs with strong tensile strength is indicative of the importance given to tensile strength by the manufacturers. Unfortunately, there is no product that unites all the tested properties in the very strong category. Having a strong TSL in one strength property could cause the weakening of other properties as indicated in Figure 70.

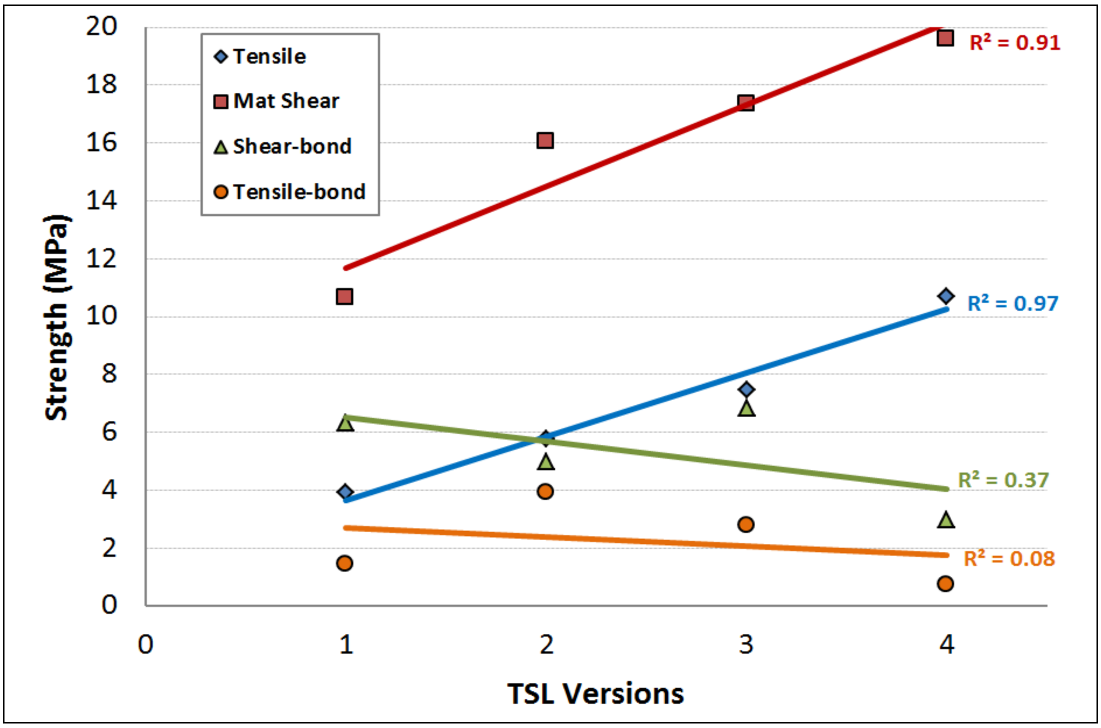


Figure 70. The effect of tensile strength increase on the other properties for a TSL brand based on the strength at 28 days

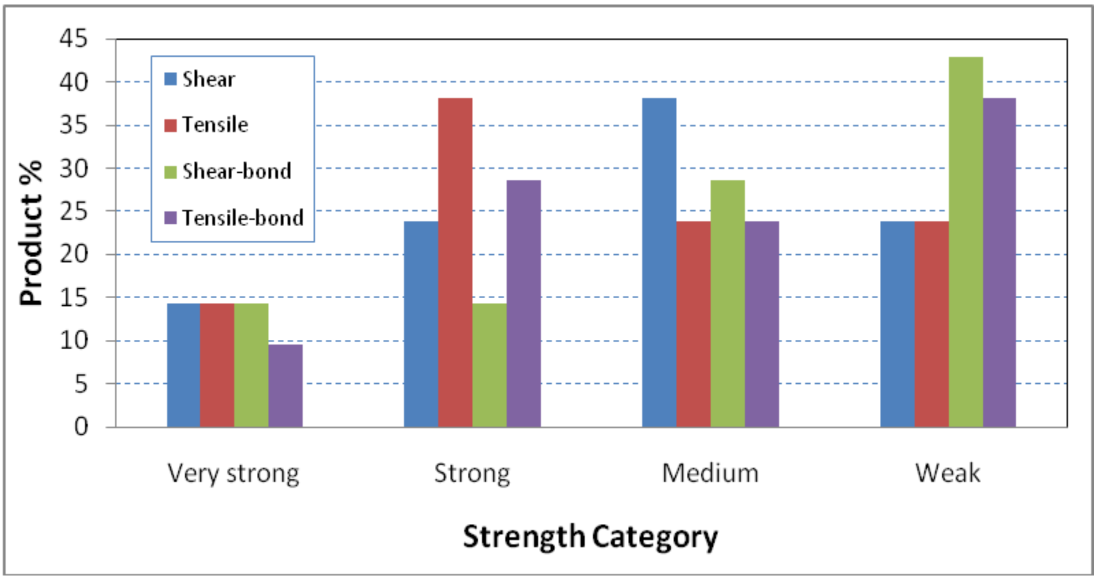


Figure 71. Availability of liners in different strength categories for the test methods

8.7 Summary and conclusions

The selection of the best performing TSL in a particular mechanical property is possible from the test results. However, no single TSL has the capability to perform the best in all the properties. A liner may well be the best in one property while it may suffer low strength values in the other properties. A more rigorous approach is needed to the selection of the best performing TSL, possibly with the incorporation of deformation measurements and the assignment of importance ratings for the tested properties.

The tests requiring the use of a substrate take more time to prepare and execute. The difficulty of testing, however, tended to increase for the tests necessitating the use tensile forces. Shear strength testing stands out as the quickest, easiest and simplest of all tests performed. The repeatability of shear testing is also found to be the highest. Therefore, the possibility of the acceptance of material shear testing as the standard testing method is high.

The repeatability of testing methods could be established by making use of the Equation 3. In addition, the repeatability and correlation coefficients are shown to be sensitive to the type of TSL used. The measured strengths for the water-based cementitious TSLs are generally low. Their repeatability and correlation coefficients are also the lowest. However, the availability of these products in the market is the highest.

The measured strengths tend to increase with curing period for all the test methods. The strength increase is more noticeable in the tests involving TSL material only, that is, the material tensile and shear strength tests.

The next chapter is the final chapter which discusses the findings, conclusions and recommendations arising from the previous chapters.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

The research described in this thesis has focused on the laboratory testing of thin spray-on liner materials. These materials are being increasingly used for structural support of rock excavations, but as yet no satisfactory standard tests, nor testing regimes, have been defined. The data provided by such testing is important for support design purposes, and also for quality control purposes. The research carried out, involving more than 4000 tests, has addressed these issues. The research has concentrated on the development two new test methods, the shear-bond strength test and the material shear strength test. Two other test methods, tensile-bond strength and tensile strength, were also adapted with minor adjustments and implemented in the testing programme. The data generated from these four tests proved to be useful in many respects and the major outcomes of the research are summarised in the following points:

- The lack of knowledge regarding the mechanical properties of TSLs has been addressed:
  - Tests substantially involving shear stresses have been carried out in the past, however, no direct shear testing of TSL *materials* have been performed (Potvin *et al*, 2004). In particular, no attention has been given to testing for the shear-bond strength. Therefore, the determination of shear strength properties was prioritised in this thesis. Two unique testing methods for measuring the shear-bond and the material shear strengths were developed and applied on TSLs for the first time as part of this research programme. These tests are new and provide valuable information on shear properties that were poorly understood in the past. The development of these test methods has been challenging and required many modifications and trial tests before the full scale implementation of the finalised method. The intended testing methods were developed through trial and error attempts and continuous improvements. The test equipment was designed and produced in-house and any design alterations were promptly attended to until the final stages of test setup were achieved.

- One of the main aims of the research was to develop a test procedure to determine the shear bond and material shear strengths. The test results, as seen in Figure 21 and Figure 32 for shear bond and material shear strength respectively, shows the validity of these testing methods to differentiate between different TSL materials.
- Material tensile strength and tensile-bond strength tests were also performed, with slight modifications, in order to provide two additional important properties to establish a healthier database for the comparison of TSLs and shotcrete.

- Contributions have been made with regard to an improved method of preparing the tensile-bond strength specimens. Firstly over-coring is eliminated, and substrate roughness was standardised. In addition, a re-usable steel dolly to eliminate bending concerns was designed.
- Little published technical information currently exists concerning quantifiable and comparable physical properties for candidate TSL materials available (Archibald, 2001). The variety of TSL materials tested and the numbers of tests performed were substantial in this research. Of the 36 TSLs tested, 21 included material comparisons. Approximately 4000 tests, including the initial trial tests, have been performed to date, and testing is still on-going. Therefore, the availability of such extensive data, based on the results of tests performed in a standard manner, makes it possible to categorise and compare the four strength properties of TSLs.
- Strength increase with increasing curing period is common and easily distinguishable for all testing methods. The categorisation of products on a strength basis is also done for each test method. The manufacturers or the end users could easily establish the strength category of their TSL product by looking at the data generated from the tests. In some cases, the test results assisted the manufacturers to either discontinue some of the TSL products or to improve the properties by carrying out further research and development.
- A simple method of calculating the repeatability index was introduced. The two new test methods fall in the repeatability range of the currently practised tensile and tensile-bond strengths. The tensile-bond strength test is one of the most commonly practised test methods, but has the lowest repeatability of the four test methods. The fact that the repeatabilities of the shear-bond and material shear

strength tests are higher, and that these tests are much simpler and easier to carry out, increase the chances of acceptance of these tests as standard test methods.

- It was shown that the test methods developed for TSLs could also be applied successfully for shotcrete. This is quite different to the traditional methods of shotcrete testing such as round determinate panel, UCS-ASTM C39/C39M, flexural strength using simple beam with third-point loading-ASTM C78, adhesive strength, pull-out strength, and shear strength tests. Tensile and shear strength tests necessitated slight modifications for shotcrete, taking the applied field thickness and aggregate composition into account. No modification was necessary for tensile-bond and shear-bond strength testing.
- The absence of clearly applicable tests is an unsatisfactory situation that is likely to inhibit the further development and application of TSLs (Potvin *et al*, 2004). Manufacturers and end users indicated a high degree of confidence in the testing methods and the knowledge generated due to the large numbers of tests performed and the comparable nature of the test results. The field performance of TSLs and the data from laboratory testing have been found to correlate well. The feedback from the industry users has been supportive and confirmative in that the TSL materials having high strength values generally performed well in the field. As a result, one of the major gold producing companies, Anglogold Ashanti, has initiated the drafting of its TSL specifications based on the results of these tests. The qualification of suppliers and selection of TSLs are done by the scrutiny and comparison of the test results. It is hoped that the practice of establishing TSL specifications will be spread to the other mining houses. This would mean a potentially increased use of TSLs in the near future.
- Numerical modelling carried out for the purposes of establishing the influence of TSL parameters on the support capacity (e.g., Stacey and Yu, 2004) and TSL load capacity calculations (e.g., Tannant, 2001) require published values for the basic TSL and shotcrete strength parameters. Some modelling programs, such as PFC2D, require the calibration of input parameters in such a way that the rupture load and elongation at rupture are similar to the laboratory test data (Tannant and Wang, 2004). In the absence of reliable test data, researchers are often forced to make assumptions regarding the mechanical properties of TSLs (Malan and Napier, 2008). Tannant (2001) assumed the shear strength to be equal to the tensile strength in his analysis. One of the results of this research has shown that

the tensile strength of cementitious TSLs is on average 70% less than the shear strength (Figure 68). Therefore, the results of testing, such as described in this thesis, would be a sound source of information covering most of the liner types and providing a range of values for the four important properties of TSLs in future modelling exercises. The researchers would not run into the risk of assuming inappropriate values in these measured properties.

- A structured and orderly manner of performing TSL testing, by way of standardisation of various test parameters, was developed:
  - A variation in the TSL thickness cannot be tolerated for comparability reasons and therefore thickness control should be exercised in the tests.
  - The number of tests should be sufficient (at least 5 tests are recommended per curing time) for statistical correctness.
  - It was found that the testing of TSLs cannot be carried out under constant rates of displacement or load due to the variation in the yieldability and the strength of TSLs. The emergence of even stronger or more flexible TSLs necessitates revision in the loading rates used in this research bearing in mind that a test should not last more than three minutes and less than a minute. Otherwise, the implication is that, with the existing loading rates, the duration of testing would extend to hours for high-yield or strong TSLs. The best approach would be the adoption of a loading rate that aims to fail the TSL within 60 to 180 seconds from the start of loading.
- The successful integration of new support tools in the support design process implies that we have a good grasp on material properties (Hadjigeorgiou and Grenon, 2002). Design methodologies for TSLs and evaluation of the in-situ support performance require reliable databases on their basic physical properties from laboratory tests and instrumented underground trials (Nagel and Joughin, 2002; Hadjigeorgiou and Grenon, 2002; Leach, 2002). The tests described in this thesis provide a wide spectrum of relevant results that can be integrated into the evaluations of support performance.
- The current use of shotcrete in the mining industry is extensive. However, superior strength characteristics of TSL products as compared to shotcrete indicate that TSLs have the potential to be applied successfully as a replacement for shotcrete. Availability of significant laboratory test data would encourage the mining industry to perform more TSL applications or trials at mining sites.

- At this stage, none of the tests performed within the scope of this thesis, including the commonly performed tensile and tensile-bond strength tests, are accepted as standardized tests. However, all of the tests performed within the scope of this thesis have the right qualities to satisfy the requirements for acceptance as standard tests. The tests incorporate the use of small test specimens that are simple, easy and quick to prepare. The simplicity is also reflected in the specimen preparation procedures and actual testing. The whole testing process is, as a result, inexpensive. These nontechnical factors often become dominant influences when any proposed testing method is being evaluated for the qualification of being a standard test (Adams, 2009). The fact that the tests produce repeatable results is an added advantage. Thus, it is reasonable to conclude that all the conditions required for a testing method to be accepted as a standard test method are satisfied in all four tests that were conducted.
- The acceptance and growth in the use of TSLs in underground and surface mining in the future requires the establishment of standard tests for TSLs.
- Data from standard tests enable mine rock engineers to select the appropriate TSLs for their needs and subsequently to implement quality controls.
- The availability of test data will provide assistance in the design of TSLs.

Owing to the current status of TSL technology, research efforts in this field have been limited. There are still many aspects of TSLs, such as the establishment of design criteria, field application trials and correlation of field performance with laboratory data, that remain to be studied further. The following recommendations are made for further research in the field of testing of liners:

- Further mechanical properties of TSLs, such as tear, bend, impact and compressive strengths, need to be determined, and this implies the development of suitable testing methods. Although UCS, for example, is one of the simplest parameters to determine in rock engineering, there is no available UCS test standard for TSLs. The importance and applicability of the UCS for TSLs may be questioned. However, the determination of strength and elastic properties under uniaxial compression as well as tension are necessary for numerical modelling since these properties become the input parameters required.
- Tests on other plain shotcrete types from different manufacturers are unlikely to produce results that would significantly affect the findings from the

abovementioned tests. Testing programmes, however, need to be implemented for high strength shotcrete and fibre reinforced shotcrete to provide better and more objective comparisons with TSLs.

- The effects on the test results of methods of mixing and application during specimen preparation of TSLs require further investigation. In particular, the difference in the test results between manually and spray prepared specimens needs to be quantified.
- Tensile-bond strength testing involves the use of a substrate, epoxy and test fixture that may significantly influence the repeatability of test results. Further investigation of these aspects is necessary to improve the repeatability and comparability of the results of this test method.
- The deformation behaviour of TSLs, particularly in tensile strength testing, is an important property and should also be taken into account in assessing the performance of TSLs. The determination of the yield capacity of any TSL is as important as the strength determination. These two parameters coupled together would provide a healthier platform for comparative assessment of TSLs.
- The testing of TSLs should account for any possible variation in TSLs' performance under extreme temperature and humidity conditions that may be experienced in mines. The tests should, therefore, be carried out for the full range of temperatures and relative humidity values experienced in mining.

More interaction between the research institutions and the mines is needed to draw up the requirements and specifications for TSLs. The building of confidence levels and then acceptance of TSLs require many field trials. Field observations and documentation of TSL performance are very important to establish the correlation between field and laboratory performance of TSLs. The mining industry is expected to make more use of trials of TSLs, and feedback from such trials will be an essential component in TSL research.

TSL quality control has been weak and remains a major issue that has to be addressed by end users. As is common with shotcrete quality control testing, TSL tests should, therefore, be performed at an independent laboratory.

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CHAPTER 11 APPENDICES

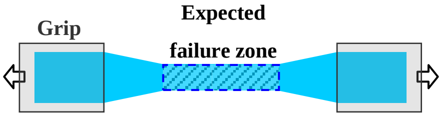
Appendix I– Data sheets on previous TSL testing methods

1 - Tensile strength and elongation testing

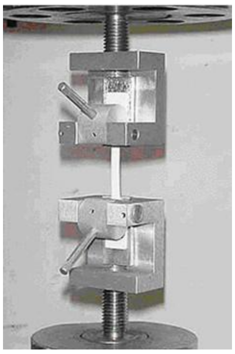
(Tannant *et al*, 1999; Archibald, 2001; Spearing and Gelson, 2002)

Description: Dog-bone shaped TSL specimens are prepared by machining, moulding or by a process of stamping. The specimen is clamped at each end into a tensile testing machine by fixed gripping platens or glueing or screw clamping and then tensioned at a constant displacement rate until the TSL has failed.

Illustration / photo



ASTM D638-Type 1 test specimen



Loading mechanism: Tension.
Failure mechanism: Tension, tear.

Material and substrate specifications:
Maximum TSL Thickness: 14 mm; displacement rate: 5 to 50 mm/min; maximum displacement limit: 50 mm; recommended curing time: 7 days.

Measures:

- Tensile strength. Elongation capacity. Deformation modulus in tension.

Applicable equations: $\sigma_t = \frac{F}{A}$ (Pa); $L\% = \frac{\delta\ell}{\ell_o} \times 100$

σ_t = tensile stress ; F: load (N); A: original specimen cross-sectional area at the expected failure zone (m^2); L%: percent elongation; $\delta\ell$: measured specimen extension; ℓ_o: original gauge length.

Advantages:

- The specimens may be sprayed or poured to the desired test thickness.
- Suitable for quality control testing of TSL materials.
- The loads and the displacement or elongation can be measured.
- Cost effective specimen preparation and testing.
- Specimen preparation is simple, easy and quick. The specimen size is small.
- Standard test specification available (ASTM D638, ASTM D412).

Disadvantages:

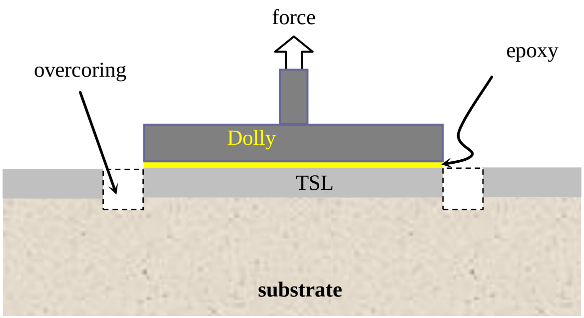
- Deviation between the specimen long axis and pull direction causes eccentricity and premature failure.
- Differences in specimen thickness results in considerable variability in load-deformation response between different TSL materials.
- Testing is valid if failure takes place at the specimen centre span only.
- No substrate interaction.
- Materials with significant elongation capacities may not fail at the extension limit of the test equipment.
- Tensile properties may vary with specimen preparation, speed of testing and test environment.

2 - Adhesive (bond) strength testing

(Tannant and Ozturk 2003; Lewis, 2001)

Description: TSL is applied to substrate and then over-cored at selected positions. A steel dolly is glued normal to the TSL surface with epoxy. After the epoxy has cured, the specimen is clamped into a tensile loading apparatus. The adhesion is measured by pulling the dolly gradually, away from the clamped specimen normal to the surface of the TSL, while load and displacement are recorded. The test continues until a plug of material is detached.

Illustration / photo



Loading mechanism: Tension.
Failure mechanism: Tensile de-bonding.

Material and substrate specifications:
Recommended dolly diameter: 32 mm; TSL Thickness: 2 to 4 mm; substrate: brick or rock; displacement rate: ± 1 to 2 mm/min.

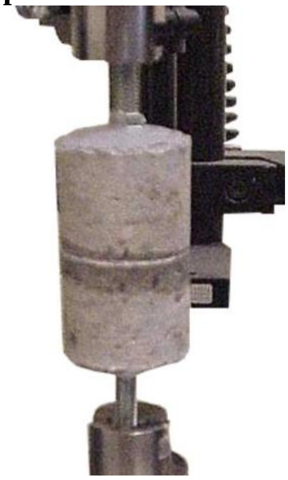
Measures:
- Interface bond strength between a liner material and a rock or similar surface.
- Force versus displacement.

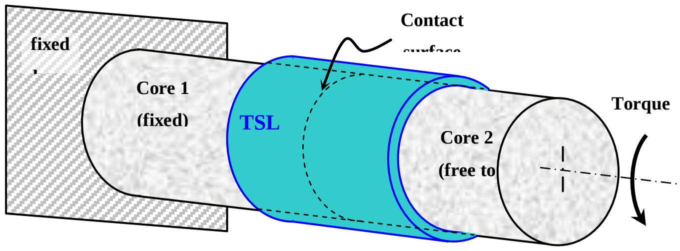
Applicable equations: $\sigma_a = \dfrac{F}{A}$

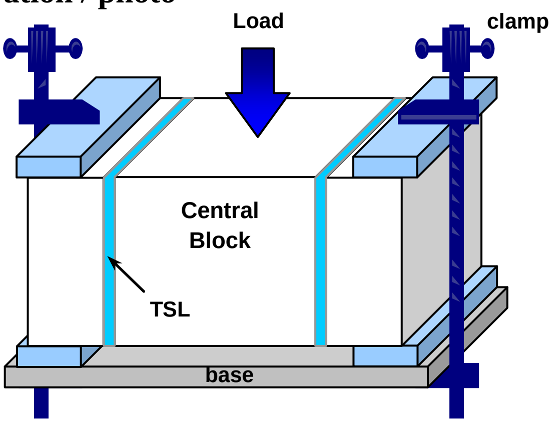
σ_a : Adhesive strength (Pa); F: maximum load (N); A: original surface area (m^2).

Advantages:
- Small scale and portable test set-up with small specimen size.
- Simple, easy and quick specimen preparation.
- Practical and cost effective specimen preparation and testing.
- Interaction between TSL and substrate is taken into account.
- Can be performed in the laboratory or the field.
- Repeatable test results.

Disadvantages:
- Eccentricity or bending may arise due to poor setting up of the test equipment or inaccurate coring thus resulting in uneven load distribution across the interface.
- Eccentric loading promotes progressive failure at the interface, causing underestimated adhesive strength.
- Large dolly diameter may cause progressive liner failure.
- Test results with small dolly diameter may not reflect inherent variations in surface texture and roughness of the substrate.
- The result is very dependent on the rock type, surface condition and the substrate preparation.
- Test is valid only if de-bonding occurs at the liner-substrate interface.
- Over-coring may damage the liner and liner-rock interface.

3 - Core to core adhesive (bond) strength testing (Spearing, 2001)	
Description: Two pieces of core are bonded together by TSL. Top and bottom halves are subjected to a uniaxial pull until failure takes place at the TSL rock interface. (*No references are available detailing the procedure*)	**Illustration / photo** 
Loading mechanism: Tension. **Failure mechanism:** Tensile de-bonding.	
Material and substrate specifications: TSL Thickness: not available; substrate: rock; core diameter: not available; displacement (load) rate: not available.	
Measures: • Interface bond strength between a liner material and a rock. • Force versus displacement.	
Applicable equations: $\sigma_a = \frac{F}{A}$ σ_a : Adhesive strength (Pa); F: maximum load (N); A: original surface area (m^2).	
Advantages: • Small specimen size. • Simple, practical and cost effective testing. • Substrate involvement during the test. • Repeatable results.	
Disadvantages: • Specimen preparation is an important issue in that both halves should lie along the same axis and in the direction of pull to prevent eccentric loading and premature failure. • TSL on the perimeter will cure faster than inner portion causing differential curing along the radius. The center may even contain un-cured TSL at the time of testing.	

4 - Torque testing method (Yilmaz *et al*, 2003)	
Description: Two pieces of core are placed along the same axis and are coated with TSL to the required thickness around the contact surface. One end of the prepared specimen is fixed while the other end is rotated on the core axis until the TSL has failed.	**Illustration / photo** 
Loading mechanism: torque type rotation on the core imposes shear loading on the TSL. **Failure mechanism:** shear, tensile tear.	
Material and substrate specifications: Core diameter: variable; core length: 2,5×core diameter; TSL Thickness: 4 mm; substrate: diamond-drill cored granite; loading rate: ± 0.4 N/sec; Curing time: 7 days	
Measures: • Rotational shear strength (τ_r). • The load-deformation behaviour of TSL. • Brittle and yielding TSL behaviours can easily be distinguished. • Provide an insight into the degree of bonding and mode of failure.	
Applicable equations: $\tau_r = \dfrac{T}{\pi\left((r+t)^2 - r^2\right)}$ (Pa.m) T: Torque (N·m); r: core radius (m); t : TSL thickness (m).	
Advantages: • The continuous nature of TSL on the applied rock surface is taken into account. • The effect of TSL boundary on the premature failure initiation is minimized. • TSL forms a component with the applied rock surface therefore their interaction is taken into account. • Test set-up is small and portable. • Re-using of the cores is possible after cleaning. • The testing is simple, repeatable, low cost and approximates one mechanism of the in-situ TSL behaviour. • Specimen preparation is easy and quick. The specimen size is small.	
Disadvantages: • Deviation from the core axis causes eccentricity and premature failure during loading. • Equation is not applicable in case of de-bonding which may result in uneven failure surface. • Opening of discontinuities and filling of open cracks by TSL are not represented. • Specimens are prepared by moulding and not by spraying.	

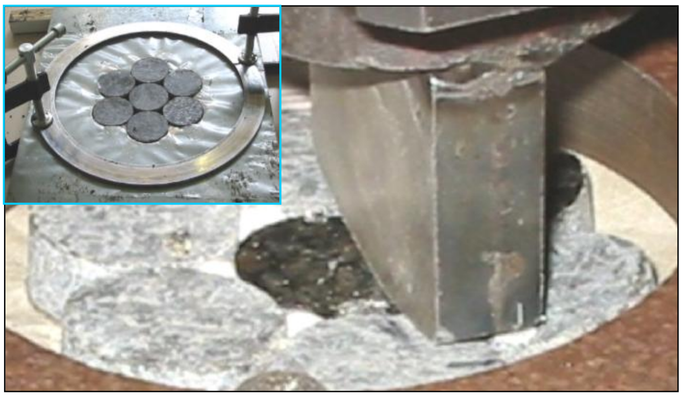
5 - Double-sided shear strength (DSS) test (Saydam *et al*, 2003)	
Description: Three rock blocks are bonded together at the adjoining surfaces by TSL. Two outer blocks are clamped and fixed in position. Load is applied on the central block and is measured together with displacement.	**Illustration / photo** 
Loading mechanism: Shear **Failure mechanism:** Shear and/or tensile de-bonding	
Material and substrate specifications: Block bond area: 10 cm×10 cm; TSL Thickness: 4 mm; substrate: granite; loading rate: ±0.5 kN/s; Curing time: 7 days.	
Measures: • Shear (bond) strength. • The load-deformation behaviour of TSL.	
Applicable equations: $\tau_{DSS} = \frac{F}{2 \times A}$ τ_{DSS}: Double-sided shear strength; F: Failure load; A: TSL area (one side only).	
Advantages: • Shear-bond strength and tensile adhesion characteristics are addressed. • Simple, easy and quick specimen preparation. • Small specimen size. • Cost effective specimen preparation and testing. • Representative of in-situ behaviour within fractured and cracked rock zones. • Interaction between TSL and substrate is taken into account.	
Disadvantages: • If the block sides are not clamped properly, premature failure due to bending takes place. • The surface contact areas between the adjacent blocks should be the same for a balanced load distribution. • Difficulty in interpreting results in terms of shear or tensile failure. • Spread of strength and displacement data for a particular TSL is statistically significant. • Specimens are prepared by moulding and not by spraying.	

6 - Asymmetric core punching of TSL by radiused plunger

(Stacey and Kasangula, 2003)

Description: TSL material is applied to the surface of a “simulated” rock mass made up of an assembly of seven short lengths of small diameter rock core (a central core and surrounding six cores). The test assembly is loaded using a radiused plunger which is located off-centre to ensure asymmetrical loading.

Illustration / photo



Loading and failure mechanism:

- Shear loading (in and out of plane) of the liner.
- Tensile loading of the liner.
- Tensile and shear loading of the bond.
- Tear loading of the liner.
- Failure is initially by “punching” of cores into the liner and subsequently there is a combination of shearing and tearing failure.

Dimensions:

Core diameter: 27 mm; core length: 13.5 mm (shorter recommended); TSL Thickness: 4 mm; displacement (load) rate: not available; curing time: not available.

Measures:

- Load and displacement.
- Tear strength.
- Extensibility and stiffness.

Applicable equations: not available.

Advantages:

- Liner material may be allowed to penetrate into cavities.
- Specimen preparation and testing are easy, quick and low cost.
- Repeatable test results.
- The test method is representative of real behaviour of a support liner.
- Test set-up is small, simple and portable.

Disadvantages:

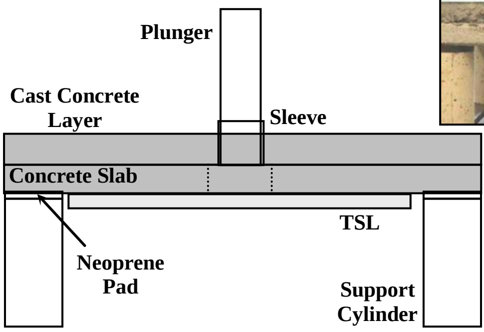
- A combination of failure mechanisms causes difficulties in data interpretation.
- Long cores inhibit the bending/basketing of the liner under load, producing a form of “punch” test.
- The results did not differentiate markedly between the two distinctly different types of liner.
- It is not possible from the test results to conclude that one liner will provide better rock support than the other.
- It is not possible to identify whether one support mechanism is contributing more than another.

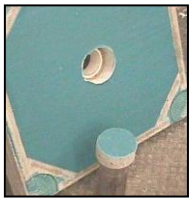
7 - Punch (TSL displacement) test

(Spearing *et al*, 2001; Kuijpers, 2001)

Description: A hole in the center of a pre-cast concrete slab or rock block is made and a concrete or rock core with the same or smaller diameter is fitted. TSL is applied on the surface of the slab and this assembly is supported on the corners. A plunger is centered on the core and pressed through a guiding sleeve which is held in position by another layer of cast concrete. Load displacement data are recorded.

Illustration / photo





Loading mechanism: Tension, shear.
Failure mechanism: Tension, de-bonding, tear/shear.

Material and substrate specifications:
Concrete slab size: 610×610×51 mm; support cylinder diameter and height: 102 mm and 204 mm; hole (core) diameter: 102 mm; plunger diameter: 76 mm; TSL Thickness: 4 mm; displacement rate: 2.5 mm/min; (Kuijper's: Rock block size: 200×200×100 mm; rock piston diameter: 51 mm; borehole diameter: 53 mm; curing time: 4 days)

Measures:
- Load and displacement.
- Load carrying capacity.
- Ductility factor (elongation capacity).
- Adhesive and tensile strength.

Applicable equations: not available.

Advantages:
- TSL may be sprayed or applied manually to the desired test thickness.
- Tensile, tear, shear and bond strengths together with elongation properties of TSLs are combined and therefore provide performance data for evaluating TSLs.
- Test is easy and inexpensive to execute. The results are repeatable.
- The loads and the displacement or elongation can be measured.
- Both short- and long-term tests may be performed to evaluate the effects of environmental factors on TSL performance.
- Comparison of the relative performance of different TSLs is possible.
- On site testing with a mobile test unit can be done.
- Substrate interaction during testing, therefore, test emulates in-situ behaviour.

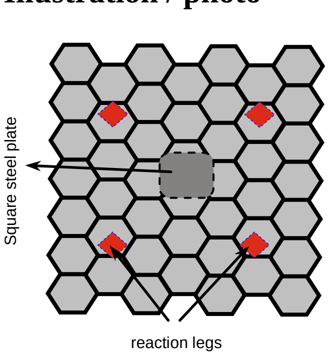
Disadvantages:
- Large area of liner application may cause difficulties in controlling material thickness.
- Specimen preparation is complicated and time consuming due to large scale involved.
- Specimen preparation is costly.
- TSL may flow into the space between the rock piston and the borehole causing an initial peak load.
- TSLs with stiff and high bond characteristics will not benefit from deformation capacity.
- Difficulties in data interpretation.

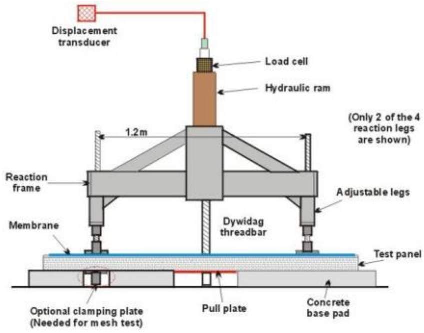
8 - Large scale plate pull testing

(Tannant, 1997; Espley *et al*, 1999)

Description: An interlocking series of hexagonal concrete paving blocks are coated by TSL from above and left to cure. A lifting-type loading is applied to a square steel plate located in the center and underneath the assembled paving blocks until the TSL has failed.

Illustration / photo





Loading mechanism: Tension.
Failure mechanism: Tension, de-bonding, tear/shear, flexural.

Material and substrate specifications:
Paving block thickness: 50 mm; Size of square steel plate: 300 mm; displacement rate: not available.

Measures:

- Load and displacement.
- Load carrying capacity.

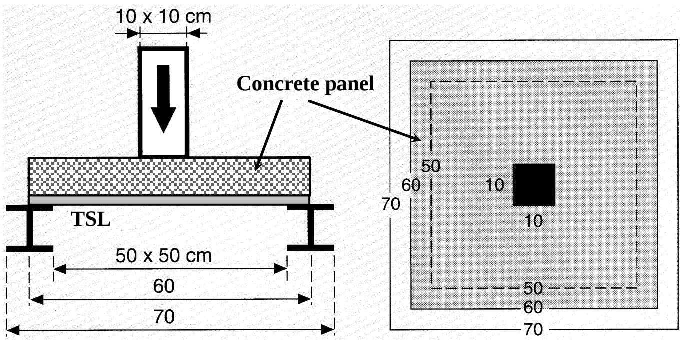
Applicable equations: not available.

Advantages:

- The TSL is sprayed to the desired test thickness.
- Test is easy to execute.
- Highly visual and therefore good for operator training and educational purposes.
- Substrate interaction during testing.
- Tests the interaction of the bond strength, tensile strength, elongation and tear strength of a TSL.
- The energy absorption capabilities of TSLs may be estimated from load-displacement data.
- Test emulates in-situ behaviour.
- Test can be used for other liners such as screen and thin shotcrete layers.

Disadvantages:

- Difficult to maintain uniform TSL thickness.
- Specimen preparation is complicated and time consuming due to large scale involved.
- Testing is costly.
- Significant portion of the supporting function arises from block-to-block interaction which results in difficulties in data interpretation.
- Repeatability of the results is poor.

9 - Coated panel test (Kuijpers, 2001; Naismith and Steward, 2002)	
Description: 600 mm square, 100 mm thick concrete panel or 50 mm thick paving stone is coated with TSL. The reverse side of the concrete slab is loaded on the center. This assembly is supported on the perimeter. Load and the deflection of the panel are measured.	**Illustration / photo** 

Loading mechanism: Tension, shear.
Failure mechanism: Tension, de-bonding, tear/shear.

Material and substrate specifications:
Concrete slab size: 600×600×100 mm; loading area: 100×100 mm; TSL Thickness: 3 to 6 mm; displacement (load) rate: not available; curing time: 1, 4, 7 and 8 days

Measures:
- Load and displacement.
- Load at fracture initiation.
- Elongation ability and energy absorption
- Load carrying capacity.

Applicable equations: not available.

Advantages:
- TSL may be sprayed or applied manually to the desired test thickness.
- The loads and the displacement can be measured.
- Test is easy and inexpensive to execute.
- Substrate interaction during testing.
- The effect of varying TSL thickness on energy absorption capabilities is measured.
- The possibility for dynamic loading exists.
- Test emulates in situ behaviour.
- Results obtained are repeatable.

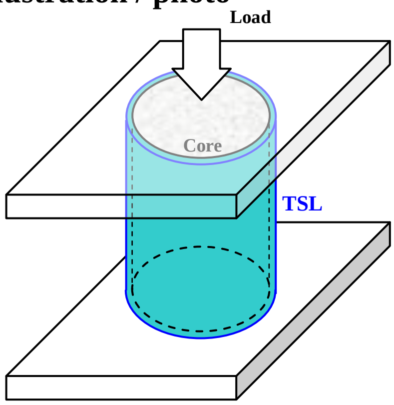
Disadvantages:
- Large area of liner application may cause difficulties in controlling material thickness.
- Large scale test.
- Specimen preparation is difficult, time consuming and may be costly.
- Concrete has to fail before measuring the performance of TSL.
- TSL performance may be overshadowed with that of the substrate.
- A number of uncoated panels need to be tested to determine the mean load at fracture initiation.
- Effect of point loading as opposed to perimeter loading is unknown.

10 - Coated-core compression tests

(Espley *et al*, 1999; Archibald and DeGagne, 2000; Kuijpers, 2001)

Description: Cylinders of concrete or rock were coated by TSL to uniform thickness and tested under uniaxial loading conditions between hard steel loading platens. Pillar models with different width to height ratios were also obtained and tested in the same way.

Illustration / photo



Loading mechanism: Tension.
Failure mechanism: Tension, de-bonding.

Material and substrate specifications:
Core diameter: 50 to 150 mm; TSL Thickness: 1 to 4 mm; load (displacement) rate: not available; curing time: not available.

Measures:

- Force and deformation.
- Peak and residual strength levels.
- Energy absorption capacity.

Applicable equations: not available.

Advantages:

- TSL's ability to contribute towards structural reinforcement of pillars by reducing the damage resulting from potential pillar-bursts by absorbing some of the stored strain energy is demonstrated.
- The results demonstrate that post failure behaviours of pillars change from violent and brittle manner to smooth and ductile manner.
- Simple test which is useful to demonstrate liner's ability to accommodate large strain ranges and generate continuous tensile support resistance.
- Test is good to demonstrate residual strength gain by increasing TSL thickness.

Disadvantages:

- Test is not relevant in deriving physical properties of TSLs.
- Application of uniform TSL thickness around curved cylinder surface is difficult.
- Yielding of loading platen may result due to high rock strength. Punching of core into the loading platen may affect the post failure behaviour.
- TSL's effect in increasing the pillar strength cannot be quantified due to interference from different width to height ratios.
- Results are not repeatable due to dependence on the core strength.
- Flexible TSL leads to more stable post failure behaviour than rigid TSL.
- The best test results are achieved when the TSL is totally de-bonded from the core and this is not the reality underground.
- A stiff loading system should be used to prevent unstable post peak failure.
- The effect of a coating may be insignificant when the response of rock pillar is ductile.

11 - Box of rocks (baggage load) test (Swan and Henderson, 2001)	
Description: An open-ended steel frame is loaded with slabs of unwashed–100mm rock debris. The "loose" surface is roughly levelled and a TSL is sprayed with a pre-determined thickness. TSL may penetrate into the discontinuous surface of rock debris. After curing the frame is flipped upside down and supported above the ground such that the sprayed face is downward. A large area hydraulic press applies a distributed compressive load to the centre of the upper surface at a controlled rate in order to simulate creep failure. LVDTs positioned at the TSL's face then record the vertical deformation at the centre and the periphery of the TSL.	**Illustration / photo**  

Loading mechanism: Tension, flexure, shear.
Failure mechanism: Tension, tear.

Material and substrate specifications:
Steel frame size: 1.1m ×1.1m and 0.3m deep; TSL thickness: 6mm on average; displacement (load) rate: not available; curing time: not available.

Measures:
- Rupture load.
- Deformation capacity.

Applicable equations: not available.

Advantages:
- The loose rock supporting (baggage) capacity of a deformable TSL is established.
- Test emulates in-situ behaviour.
- Substrate interaction.
- More conservative than one where a large intact or interlocking surface is used.

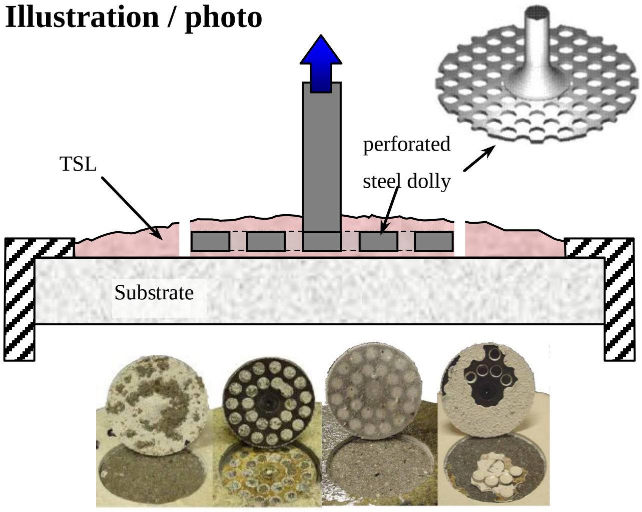
Disadvantages:
- Repeatability of this test is questionable since the distribution of rock debris varies for each test.
- Preparation for a test is difficult and time consuming due to the size involved.
- TSL thickness is not uniform.
- Specimen preparation and testing are costly.

12 - Perforated plate pull testing

(Tannant *et al*, 1999; Archibald, 2001)

Description: A TSL is sprayed onto a flat surface of a concrete paving stone or rock. A perforated steel test dolly is immediately placed on the fresh, uncured TSL that is still in its initial liquid state and permitted to seep through the holes of the dolly. Second coating is sprayed over the test dolly to fully embed it within the TSL. After curing, the embedded test dolly is overcored to isolate the test area from the rest of the TSL. The test dolly is pulled normal to the substrate with an attached central bolt until full release.

Illustration / photo



Loading mechanism: Tension.
Failure mechanism: De-bonding, tension.

Material and substrate specifications:
Test dolly diameter: 25 cm, 12,5 cm, 10 cm, 5,9 cm; Test dolly thickness: 3,2 to 6,0 mm; substrate size: 30,5 cm diameter by 3,8 cm thick; displacement rate: 1 mm/min; maximum displacement limit: 25 mm; curing period: minimum 2 days; initial TSL thickness: 1 mm; second coating TSL thickness: 2 mm.

Measures:
- Load and displacement.
- Adhesive strength (determined from the peak stress).

Applicable equations: $\sigma_p = \frac{F}{A}$ (Pa);

σ_p = pull stress; F: measured load (N); A: over-cored area (m^2).

Advantages:
- Small scale and simple test.
- Substrate interaction during testing.
- The loads and the displacement can be measured.
- Simple, easy, quick and cost effective specimen preparation and testing.

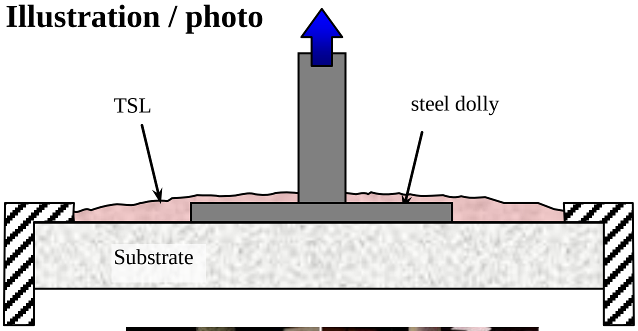
Disadvantages:
- Differences in rock type or surface conditions cause adhesion bond variation due to differences in substrate strength, surface roughness, porosity and degree of alteration.
- Pull-through of the plate from TSL occurs should excessively high adhesion bond forms at the substrate surface.
- Calculation of adhesive strength is questionable due to the influence of perforations.

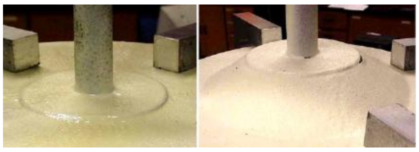
13 - Material plate pull testing

(Tannant *et al*, 1999; Archibald, 2001; Finn, 2001)

Description: A solid circular or rectangular plate of steel is placed on a concrete or rock surface and then sprayed over with a uniformly thick TSL including the area surrounding the plate. No TSL is permitted to be placed between the substrate and plate. After curing, the plate is pulled perpendicular and away from the substrate with an attached central bolt while measuring loads and displacements. The test is completed when the load begins to drop or when the plate is pulled free of the substrate.

Illustration / photo





Loading mechanism: Tension.
Failure mechanism: De-bonding, tension, shear.

Material and substrate specifications:
Dolly diameter and thickness: 10 cm and 3,2 mm; substrate size: 30,5 cm diameter by 3,8 cm thick; pulling collar diameter: 19 mm; displacement rate: 5 to 50 mm/min; displacement limit: 50 mm; curing period: minimum 2 days; TSL thickness: 2 to 8 mm.

Measures:
- Load and displacement.
- Adhesive strength (determined from the peak stress).
- Tensile capacity.

Applicable equations: $\sigma_p = \frac{F}{A}$ (Pa); $A = C \times t$

σ_p = pull strength; F: peak pull force (N); A: TSL area about the perimeter of the pull plate at the start of the test (m^2); C: plate perimeter length (m); t: TSL thickness at the plate perimeter.

Advantages:
- Small scale and simple laboratory test.
- Substrate interaction during testing, therefore testing relates to in situ behaviour.
- The relative performance of the TSLs under load can be assessed.
- Simple, easy, quick and cost effective specimen preparation and testing.
- The test can be performed, either in the laboratory or in-situ where the plate is placed on the wall of a drift.

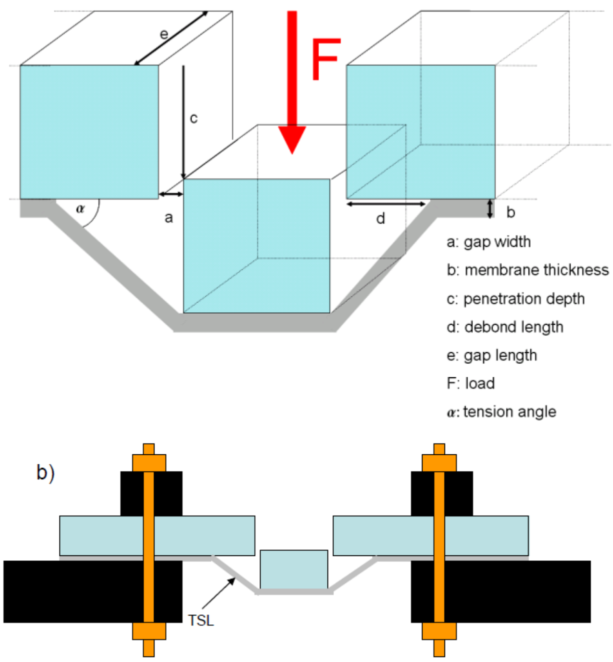
Disadvantages:
- Pull-through of the plate from TSL occurs should excessively high adhesion bond forms at the substrate surface.
- The contributions from adhesion, tensile strength cannot be individually gauged.
- The desired mode of failure is a combination of adhesion loss and tensile rupture and should not involve shear through the TSL.
- TSL performance is sensitive to its applied thickness and continuity over the substrate.
- Tensile stress within the TSL may create localized zones of tensile failure if sufficient extension develops.

14 - Linear block support test

(EFNARC, 2008)

Description: Aluminium plates and concrete specimens are placed in the formwork. To avoid later adhesion of the TSL to the aluminium plates they are pre-treated with a mould release agent (spray). Two aluminium spacers of a defined thickness are placed and fixed on top of the formwork for thickness control of the TSL. The mixed TSL is applied by hand, (it can also be sprayed) onto the framework. Immediately after preparation the specimens are stored in a climate chamber until testing. Shortly before testing the specimens are cut from the formwork. The test specimen is screwed tight to the test device taking care not to compress the TSL. The loading is done under displacement control while load displacement curve is measured until failure.

Illustration / photo



Loading mechanism: Tension, shear.
Failure mechanism: Tension, de-bonding, tear/shear.

Material and substrate specifications:
Concrete substrate size: two of 8x4x3 cm, one of 4x4x3 cm; displacement rate: 16mm/min; curing period: n.a.; TSL thickness: 3 mm is recommended.

Measures:

- Load and displacement.

Applicable equations: $LLC = \frac{F_{max}}{2e}$

LLC: The linear load capacity (N/cm); F_{max}: maximum load (N); e: gap length (cm)

Advantages:

- Small scale and simple laboratory test.
- Substrate interaction during testing, therefore testing relates to in situ behaviour.
- Simple, easy, quick and cost effective specimen preparation and testing.
- Good TSL thickness control.
- TSL can be applied by hand or sprayed.

Disadvantages:

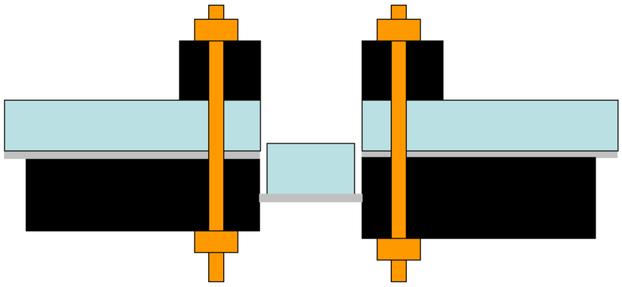
- The contributions from adhesion, tensile strength cannot be individually gauged.
- The desired mode of failure is a combination of adhesion loss and tensile rupture and should not involve shear through the TSL.
- TSL performance is sensitive to its applied thickness.
- Tensile stress within the TSL may create localized zones of tensile failure if sufficient extension develops.
- Test is only applicable to yielding TSLs.

15 - Gap shear load test

(EFNARC, 2008)

Description: The same as “Linear Block Support Test”. The only difference is the test configuration during testing (see the illustration). In this case the de–bond of the TSL is avoided so that the pure intrinsic bearing capacity is measured as a shear stress.

Illustration / photo



Loading mechanism: Shear.
Failure mechanism: Shear.

Material and substrate specifications:
Concrete substrate size: two of 8x4x3 cm, one of 4x4x3 cm; displacement rate: 16mm/min; curing period: n.a.; TSL thickness: 3 mm is recommended.

Measures:

- Load and displacement.

Applicable equations: $LLC = \frac{F_{max}}{2e}$

LLC: The linear load capacity (N/cm); F_{max}: maximum load (N); e: gap length (cm)

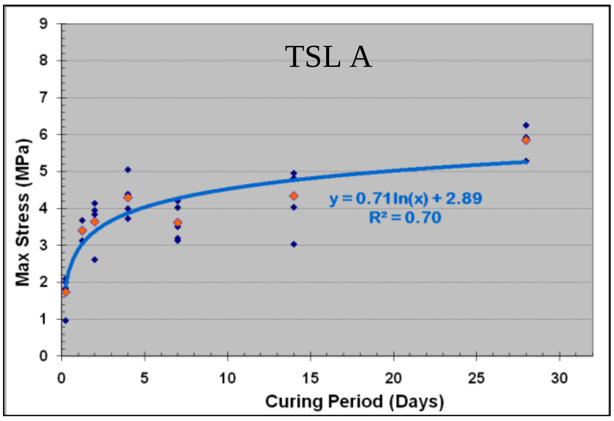
Advantages:

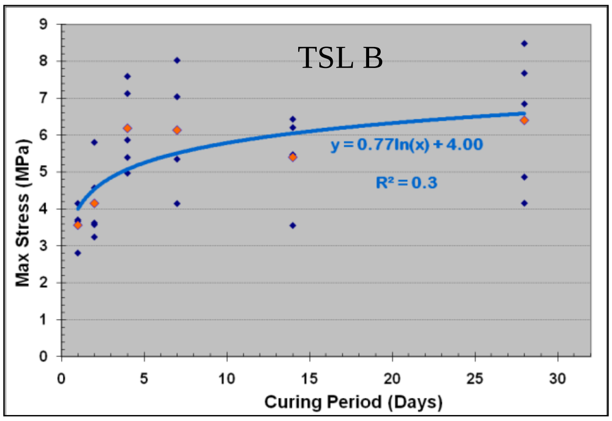
- Small scale and simple laboratory test.
- Substrate interaction during testing, therefore testing relates to in situ behaviour.
- Simple, easy, quick and cost effective specimen preparation and testing.
- Good TSL thickness control.
- TSL can be applied by hand or sprayed.

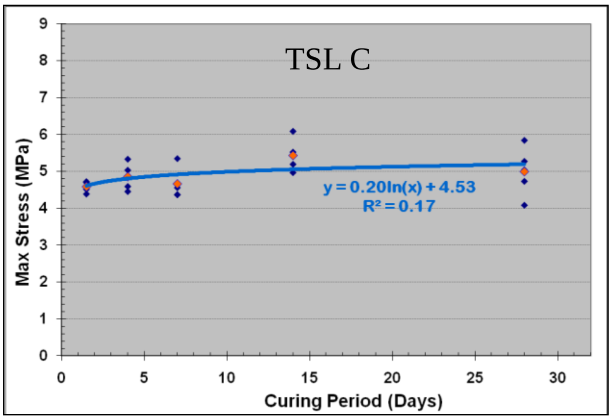
Disadvantages:

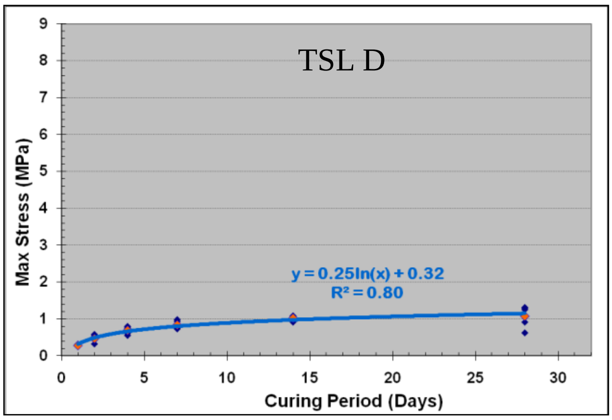
- TSL performance is sensitive to its applied thickness.
- Clamping should be done carefully to avoid TSL damage and rotation of the test assembly.

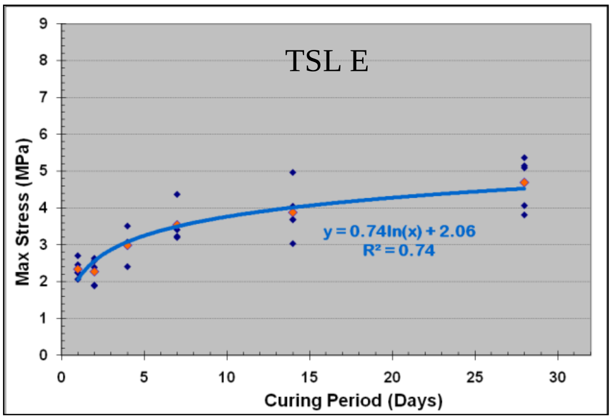
Appendix II– Shear-bond strength test results

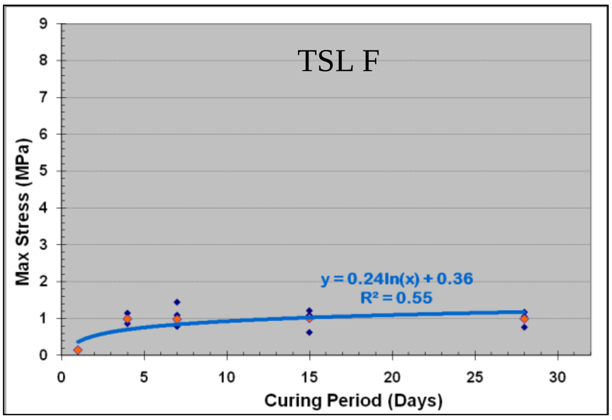


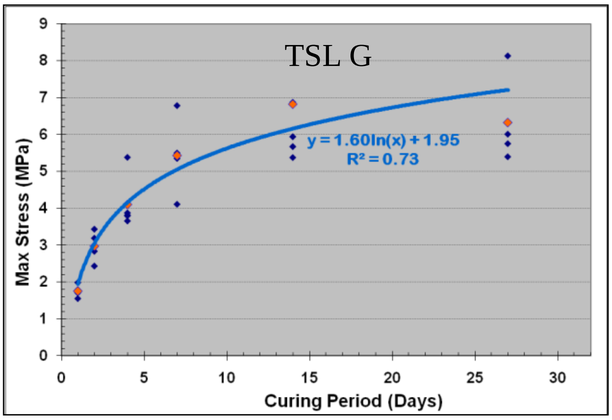


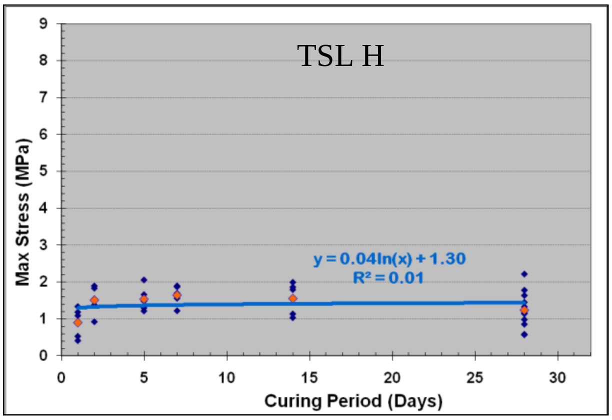


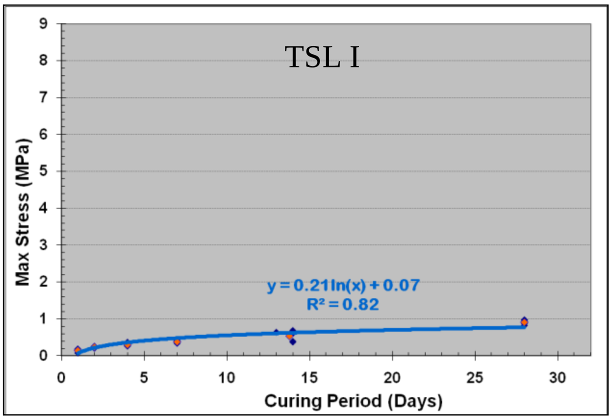


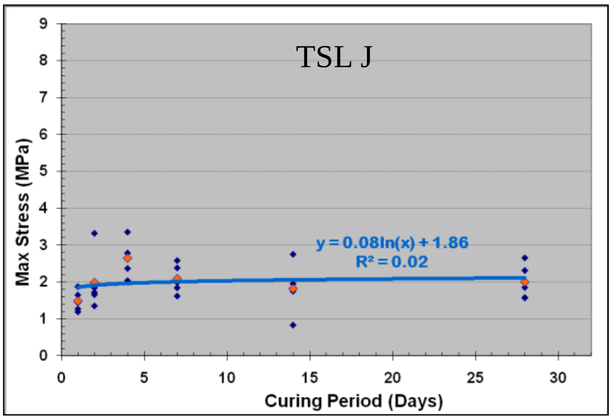


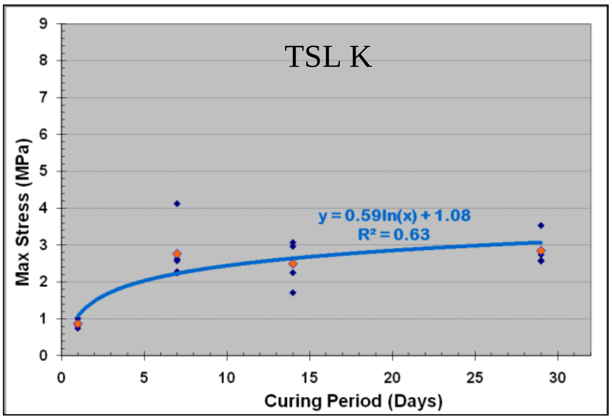


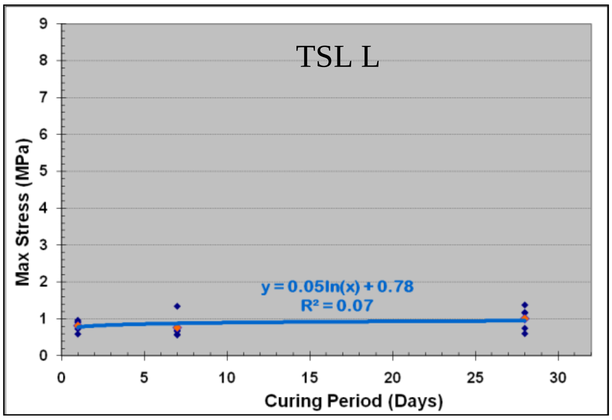

TSL G
y = 1.60ln(x) + 1.95
R² = 0.73
Max Stress (MPa)
Curing Period (Days)

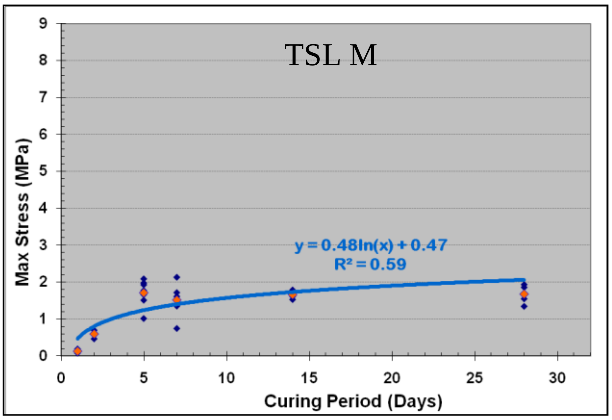

TSL H
y = 0.04ln(x) + 1.30
R² = 0.01
Max Stress (MPa)
Curing Period (Days)

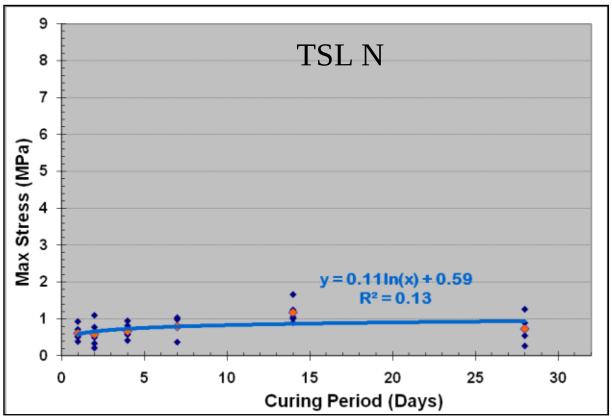

TSL I
y = 0.21ln(x) + 0.07
R² = 0.82
Max Stress (MPa)
Curing Period (Days)

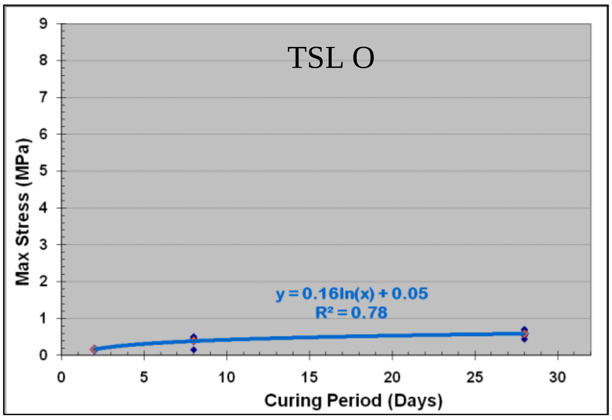

TSL J
y = 0.08ln(x) + 1.86
R² = 0.02
Max Stress (MPa)
Curing Period (Days)

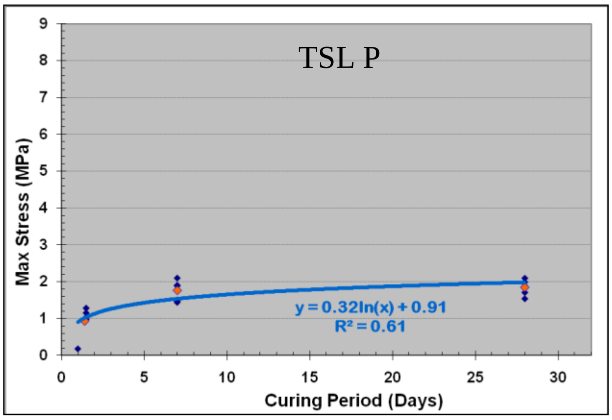

TSL K
y = 0.59ln(x) + 1.08
R² = 0.63
Max Stress (MPa)
Curing Period (Days)

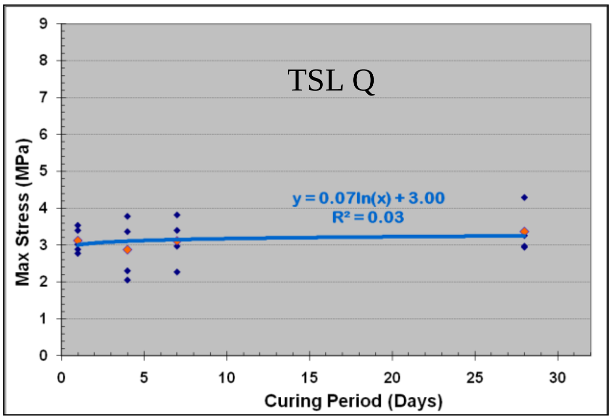

TSL L
y = 0.05ln(x) + 0.78
R² = 0.07
Max Stress (MPa)
Curing Period (Days)

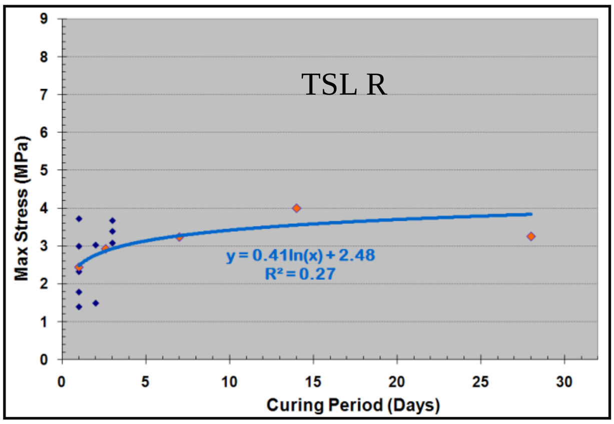

TSL M
y = 0.48ln(x) + 0.47
R² = 0.59
Max Stress (MPa)
Curing Period (Days)

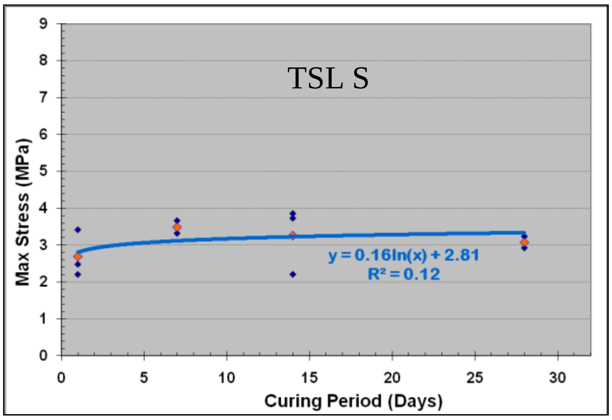

TSL N
y = 0.11ln(x) + 0.59
R² = 0.13
Max Stress (MPa)
Curing Period (Days)

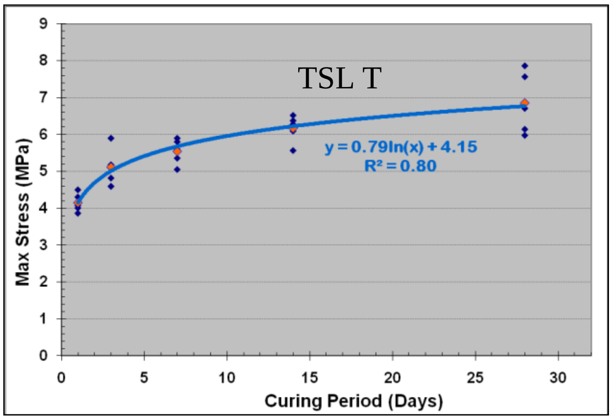

TSL O
y = 0.16ln(x) + 0.05
R² = 0.78
Max Stress (MPa)
Curing Period (Days)

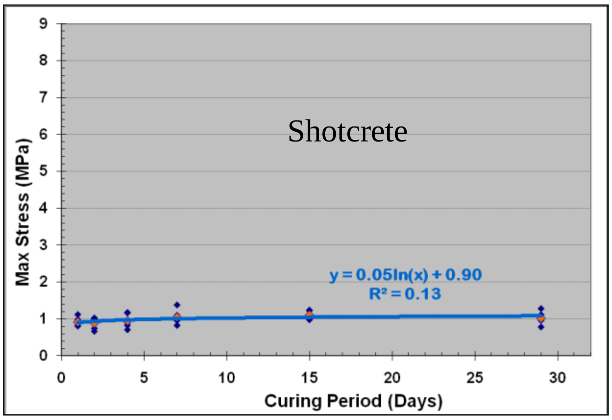

TSL P
y = 0.32ln(x) + 0.91
R² = 0.61
Max Stress (MPa)
Curing Period (Days)


TSL Q
y = 0.07ln(x) + 3.00
R² = 0.03
Max Stress (MPa)
Curing Period (Days)


TSL R
y = 0.41ln(x) + 2.48
R² = 0.27
Max Stress (MPa)
Curing Period (Days)


TSL S
y = 0.16ln(x) + 2.81
R² = 0.12
Max Stress (MPa)
Curing Period (Days)


TSL T
y = 0.79ln(x) + 4.15
R² = 0.80
Max Stress (MPa)
Curing Period (Days)


Shotcrete
y = 0.05ln(x) + 0.90
R² = 0.13
Max Stress (MPa)
Curing Period (Days)

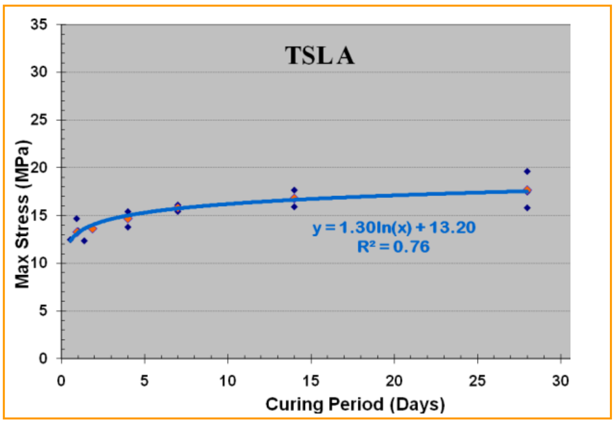
Appendix III– Shear-bond strength test statistics

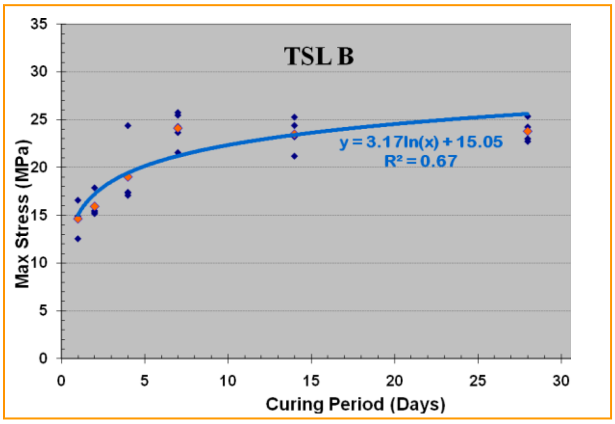
Mean (MPa)	Days	St Dev (MPa)	CV (%)	Mean (MPa)	Days	St Dev (MPa)	CV (%)	Mean (MPa)	Days	St Dev (MPa)	CV (%)
TSL A				**TSL B**				**TSL C**			
3.40	1	0.28	8.1	3.57	1	0.49	13.6	4.58	2	0.14	3.0
3.64	2	0.69	18.9	4.16	2	1.04	25.1	4.85	4	0.35	7.2
4.29	4	0.57	13.4	6.19	4	1.13	18.2	4.66	7	0.47	10.0
3.62	7	0.48	13.4	6.14	7	1.73	28.2	5.43	14	0.42	7.8
4.34	14	0.81	18.7	5.41	14	1.13	21.0	4.99	28	0.65	13.0
5.85	28	0.40	6.9	6.41	28	1.84	28.8				
TSL D				**TSL E**				**TSL F**			
0.29	1	0.02	8.0	2.35	1	0.25	10.5	0.14	1	0.02	11.6
0.47	2	0.10	21.6	2.28	2	0.36	15.7	0.99	4	0.10	10.5
0.70	4	0.11	15.5	2.99	4	0.39	13.1	0.98	7	0.29	29.4
0.84	7	0.11	13.4	3.55	7	0.48	13.5	1.01	15	0.23	22.4
1.03	14	0.07	6.9	3.89	14	0.71	18.2	0.99	28	0.15	15.0
1.08	28	0.30	28.0	4.70	28	0.70	15.0				
TSL G				**TSL H**				**TSL I**			
1.76	1	0.16	8.9	0.91	1	0.41	45.7	0.15	1	0.04	29.4
2.97	2	0.38	12.7	1.51	2	0.39	26.0	0.24	2	0.02	9.7
4.10	4	0.72	17.5	1.54	5	0.34	21.8	0.30	4	0.05	15.0
5.43	7	0.95	17.5	1.65	7	0.28	16.8	0.38	7	0.03	8.9
6.82	14	1.99	29.2	1.56	14	0.40	25.7	0.54	14	0.15	27.4
6.32	27	1.23	19.5	1.24	28	0.51	40.8	0.91	28	0.06	7.1
TSL J				**TSL K**				**TSL L**			
1.49	1	0.28	18.7	0.87	1	0.10	11.1	0.82	1	0.16	19.0
1.99	2	0.77	38.8	2.77	7	0.77	28.0	0.77	7	0.32	41.9
2.64	4	0.57	21.5	2.50	14	0.64	25.5	1.01	28	0.32	31.9
2.09	7	0.39	18.8	2.85	29	0.40	13.9				
1.83	14	0.68	37.4								
2.00	28	0.48	23.8								
TSL M				**TSL N**				**Shotcrete**			
0.13	1	0.04	30.3	0.62	1	0.21	34.5	0.92	1	0.13	14.3
0.60	2	0.10	16.2	0.58	2	0.36	61.3	0.89	2	0.17	19.4
1.71	5	0.34	20.1	0.67	4	0.21	31.8	0.95	4	0.21	22.1
1.52	7	0.51	33.8	0.80	7	0.26	33.0	1.05	7	0.21	19.8
1.66	14	0.10	5.8	1.17	14	0.30	25.7	1.11	15	0.12	11.1
1.68	28	0.24	14.2	0.73	28	0.37	51.0	1.02	29	0.19	18.2
TSL O				**TSL P**				**TSL Q**			
0.16	2	0.02	13.5	0.93	1	0.43	46.8	3.12	1	0.33	10.5
0.40	8	0.14	36.0	1.76	7	0.29	16.5	2.88	4	0.83	28.7
0.58	28	0.11	18.6	1.84	28	0.22	12.1	3.11	7	0.66	21.1
								3.37	28	0.63	18.7
TSL R				**TSL S**				**TSL T**			
2.44	1	0.93	38.1	2.70	1	0.64	23.6	4.15	1	0.25	6.1
2.93	3	0.84	28.8	3.49	7	0.24	7.0	5.11	3	0.50	9.7
3.24	7	-	-	3.26	14	0.92	28.2	5.54	7	0.34	6.2
4.01	14	-	-	3.08	28	0.22	7.1	6.17	14	0.37	6.0
3.26	28	-	-					6.85	28	0.84	12.3

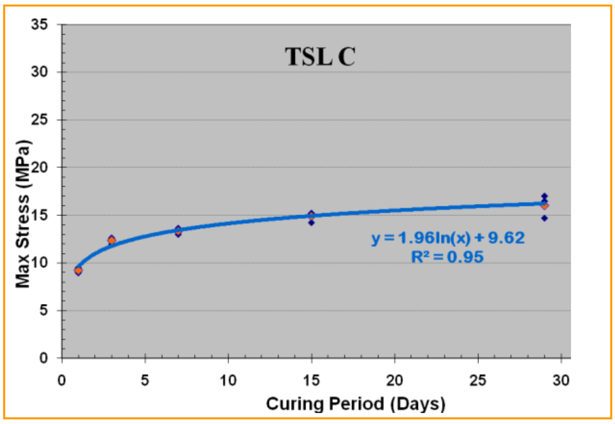
$\Sigma CV\% = 2091.6$

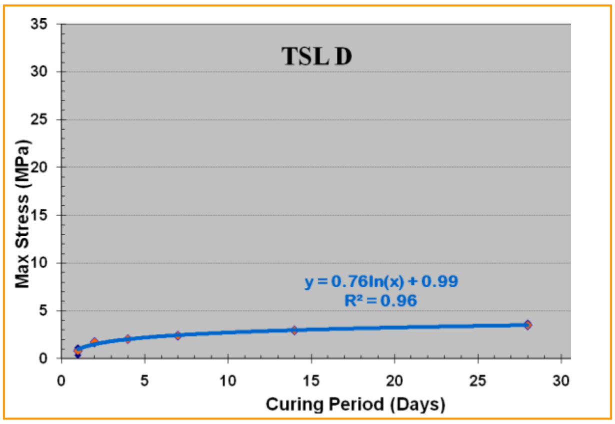
N = 104 (total number of curing times)

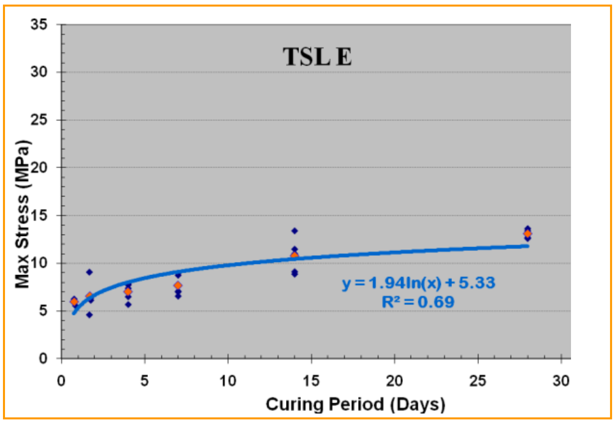
Appendix IV– Material shear strength test results

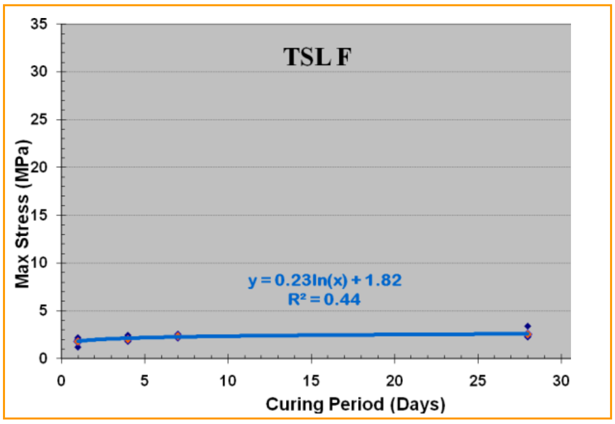


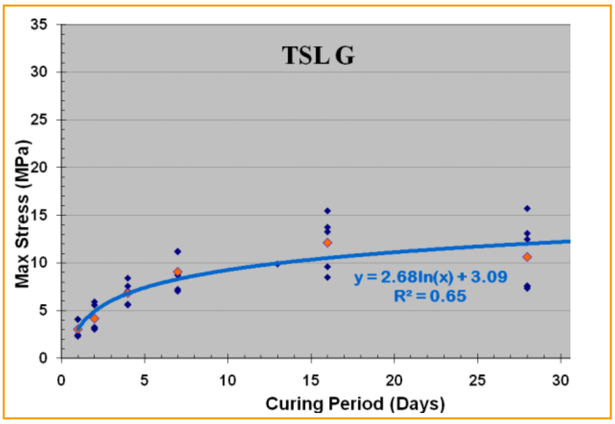


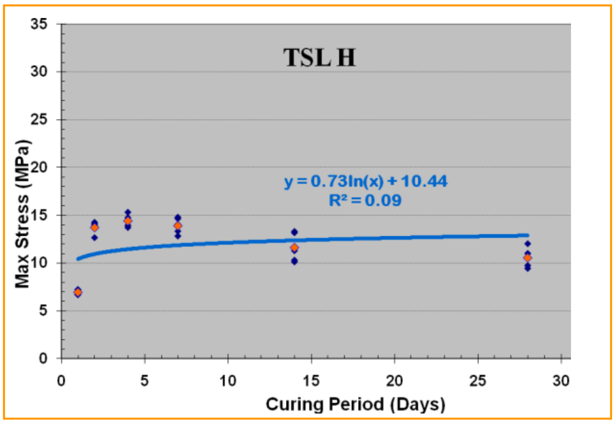


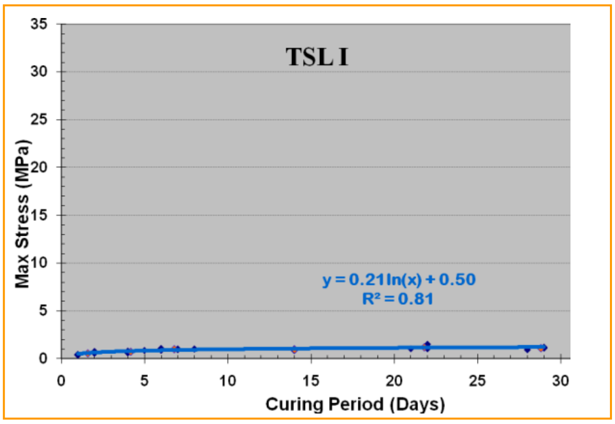


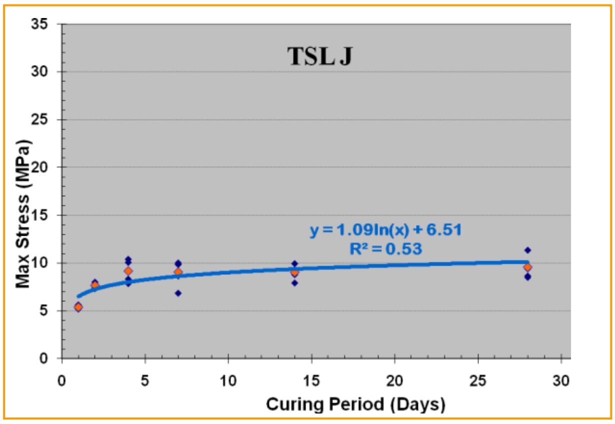


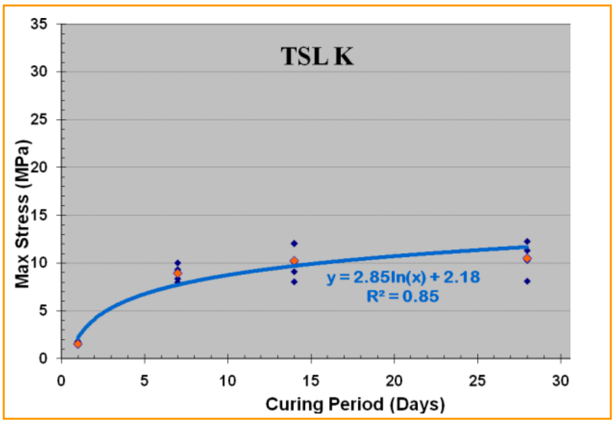


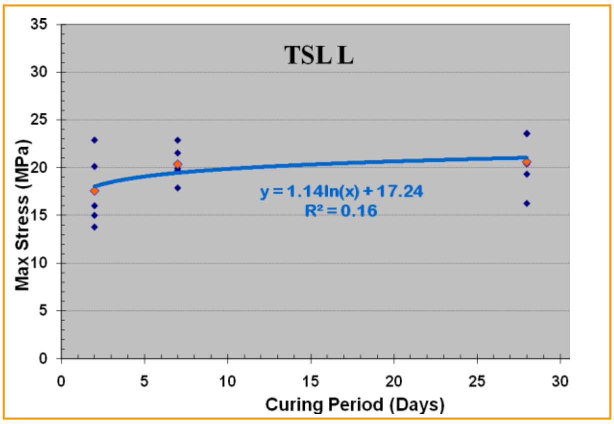

TSL G
y = 2.68ln(x) + 3.09
R² = 0.65
Max Stress (MPa)
Curing Period (Days)

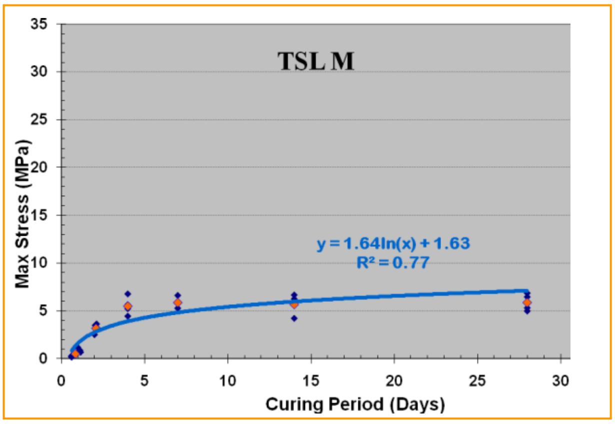

TSL H
y = 0.73ln(x) + 10.44
R² = 0.09
Max Stress (MPa)
Curing Period (Days)

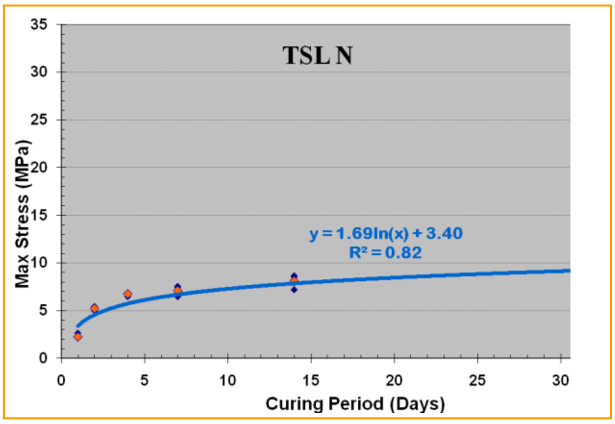

TSL I
y = 0.21ln(x) + 0.50
R² = 0.81
Max Stress (MPa)
Curing Period (Days)

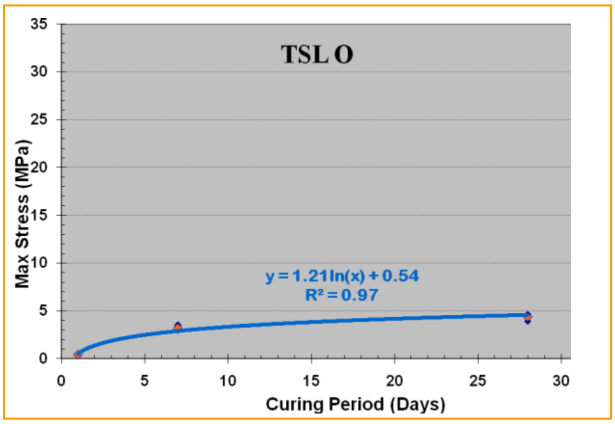

TSL J
y = 1.09ln(x) + 6.51
R² = 0.53
Max Stress (MPa)
Curing Period (Days)

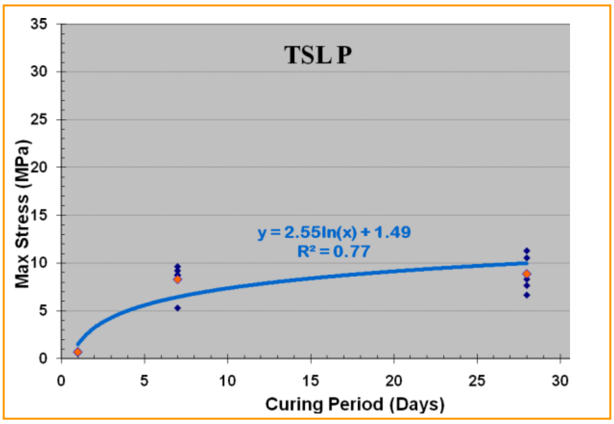

TSL K
y = 2.85ln(x) + 2.18
R² = 0.85
Max Stress (MPa)
Curing Period (Days)

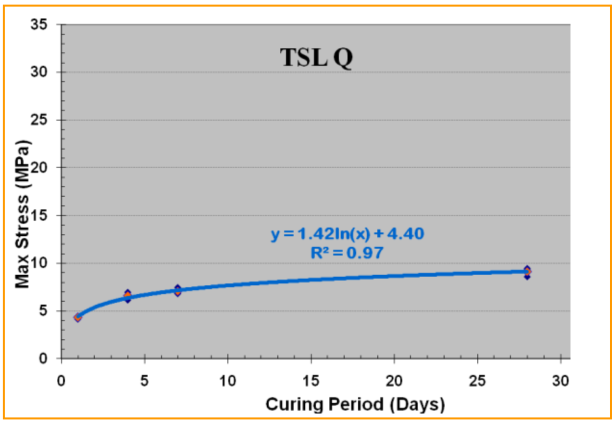

TSL L
y = 1.14ln(x) + 17.24
R² = 0.16
Max Stress (MPa)
Curing Period (Days)

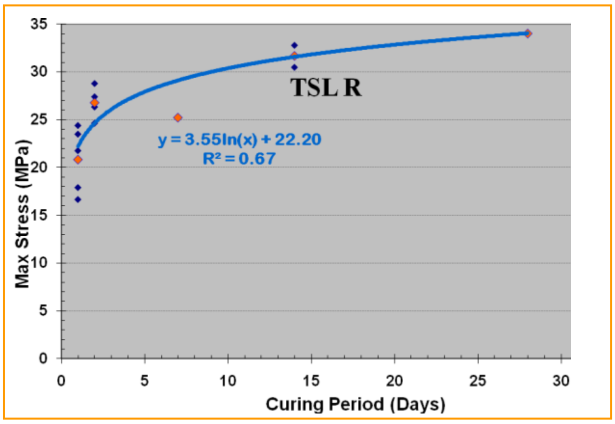

TSL M
y = 1.64ln(x) + 1.63
R² = 0.77
Max Stress (MPa)
Curing Period (Days)

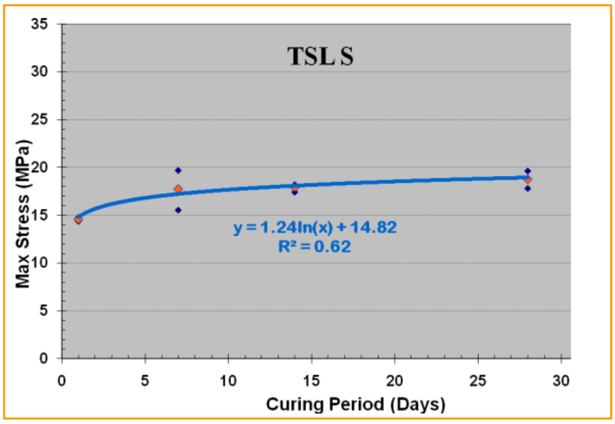

TSL N
y = 1.69ln(x) + 3.40
R² = 0.82
Max Stress (MPa)
Curing Period (Days)

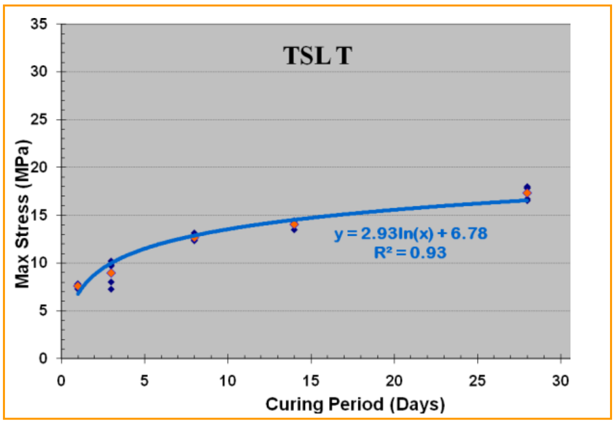

TSL O
y = 1.21ln(x) + 0.54
R² = 0.97
Max Stress (MPa)
Curing Period (Days)

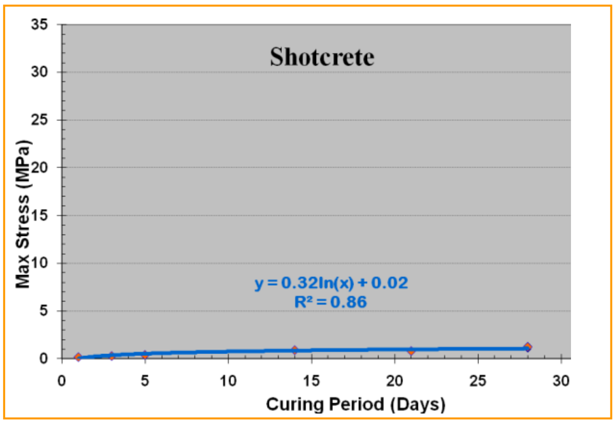

TSL P
y = 2.55ln(x) + 1.49
R² = 0.77
Max Stress (MPa)
Curing Period (Days)


TSL Q
y = 1.42ln(x) + 4.40
R² = 0.97
Max Stress (MPa)
Curing Period (Days)


TSL R
y = 3.55ln(x) + 22.20
R² = 0.67
Max Stress (MPa)
Curing Period (Days)


TSL S
y = 1.24ln(x) + 14.82
R² = 0.62
Max Stress (MPa)
Curing Period (Days)


TSL T
y = 2.93ln(x) + 6.78
R² = 0.93
Max Stress (MPa)
Curing Period (Days)


Shotcrete
y = 0.32ln(x) + 0.02
R² = 0.86
Max Stress (MPa)
Curing Period (Days)

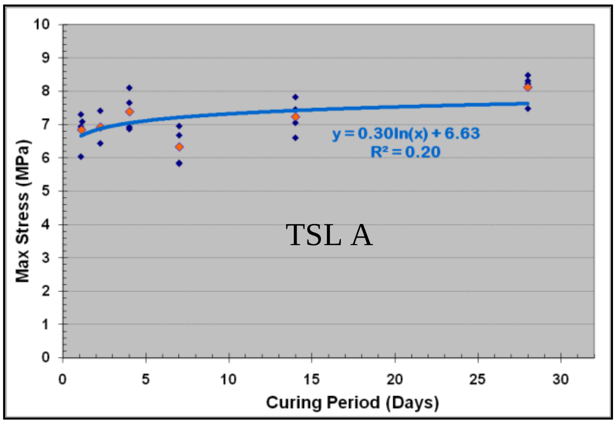
Appendix V– Material shear strength test statistics

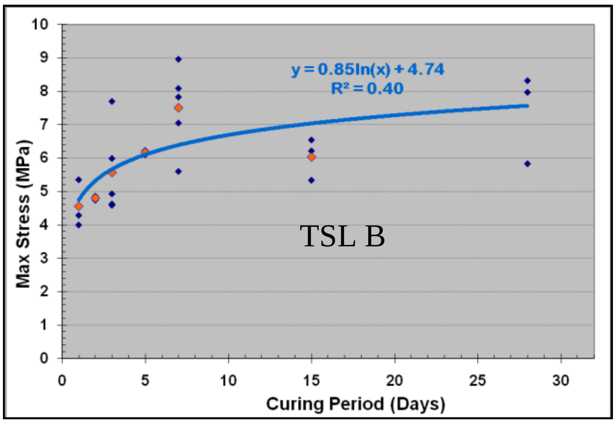
Mean (MPa)	**Days**	**St Dev (MPa)**	**CV (%)**	**Mean (MPa)**	**Days**	**St Dev (MPa)**	**CV (%)**	**Mean (MPa)**	**Days**	**St Dev (MPa)**	**CV (%)**
TSL A				**TSL B**				**TSL C**			
13.24	1	1.07	8.11	14.66	1	2.02	13.80	9.24	1	0.25	2.68
13.61	2			15.96	2	1.28	8.01	12.38	3	0.27	2.18
14.66	4	0.81	5.55	19.05	4	3.55	18.65	13.38	7	0.28	2.07
15.78	7	0.47	3.01	24.14	7	1.68	6.95	14.94	15	0.41	2.77
16.76	14	0.87	5.20	23.51	14	1.77	7.51	16.07	29	0.86	5.33
17.63	28	1.56	8.84	23.82	28	1.21	5.07				
TSL D				**TSL E**				**TSL F**			
0.84	1	0.29	35.10	5.97	1	0.29	4.92	1.82	1	0.39	21.29
1.75	2	0.13	7.23	6.54	2	1.86	28.44	2.06	4	0.26	12.68
2.05	4	0.05	2.49	7.02	4	0.91	13.01	2.38	7	0.16	6.89
2.41	7	0.10	4.03	7.67	7	1.10	14.36	2.57	28	0.48	18.72
2.96	14	0.10	3.41	10.78	14	1.86	17.27				
3.51	28	0.17	4.86	13.09	28	0.51	3.93				
TSL G				**TSL H**				**TSL I**			
3.06	1	0.94	30.54	6.93	1	0.23	3.38	0.57	2	0.12	21.45
4.19	2	1.43	34.09	13.74	2	0.73	5.34	0.74	4	0.10	13.24
6.86	4	1.22	17.81	14.44	4	0.64	4.44	1.01	7	0.07	6.45
9.09	7	2.05	22.52	13.93	7	0.85	6.08	0.98	14	0.07	7.00
12.13	16	2.95	24.30	11.63	14	1.53	13.14	1.22	22	0.20	16.48
10.64	28	3.61	33.91	10.55	28	1.03	9.80	1.13	29	0.10	9.12
TSL J				**TSL K**				**TSL L**			
5.42	1	0.20	3.64	1.55	1	0.19	11.92	17.55	2	3.81	21.71
7.67	2	0.27	3.55	8.95	7	0.80	8.96	20.36	7	1.90	9.35
9.15	4	1.09	11.86	10.26	14	1.79	17.42	20.61	28	3.09	14.97
9.04	7	1.34	14.86	10.52	28	1.55	14.75				
9.03	14	0.75	8.26								
9.55	28	1.15	12.01								
TSL M				**TSL N**				**Shotcrete**			
0.54	1	0.37	68.91	2.26	1	0.22	9.61	0.16	1	0.02	14.08
3.20	2	0.49	15.33	5.22	2	0.18	3.49	0.28	3	0.07	25.56
5.52	4	0.97	17.58	6.75	4	0.20	2.91	0.39	5	0.09	24.57
5.89	7	0.55	9.33	7.09	7	0.45	6.37	0.89	14	0.05	5.77
5.69	14	1.07	18.74	8.11	14	0.59	7.23	0.80	21	0.02	2.25
5.89	28	0.89	15.16	8.19	32	0.90	11.00	1.23	28	0.18	14.21
TSL O				**TSL P**				**TSL Q**			
0.41	1	0.05	13.39	0.70	1	0.10	13.68	4.32	1	0.15	3.45
3.22	7	0.27	8.45	8.33	7	1.73	20.78	6.59	4	0.34	5.21
4.39	28	0.28	6.36	8.89	28	1.96	22.00	7.05	7	0.29	4.17
								9.11	28	0.38	4.19
TSL R				**TSL S**				**TSL T**			
20.84	1	3.42	16.41	14.58	1	0.29	1.99	7.62	1	0.21	2.79
26.78	2	1.52	5.69	17.71	7	2.09	11.81	8.99	3	1.28	14.24
25.22	7			17.91	14	0.42	2.32	12.69	8	0.34	2.65
31.66	14	1.63	5.15	18.74	28	1.30	6.93	14.08	14	0.39	2.75
33.99	28							17.37	28	0.70	4.06

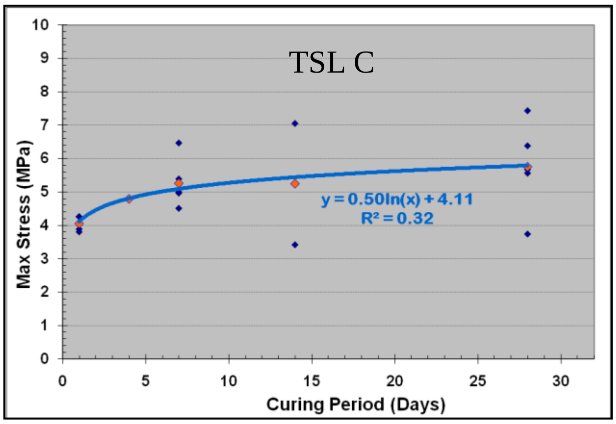
ΣCV% = 1187.3

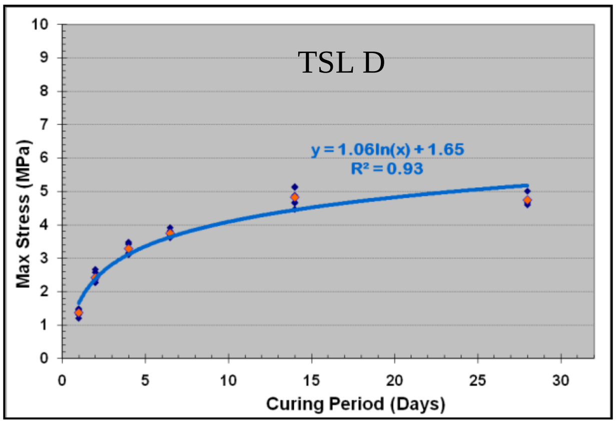
N = 103 (total number of curing times)

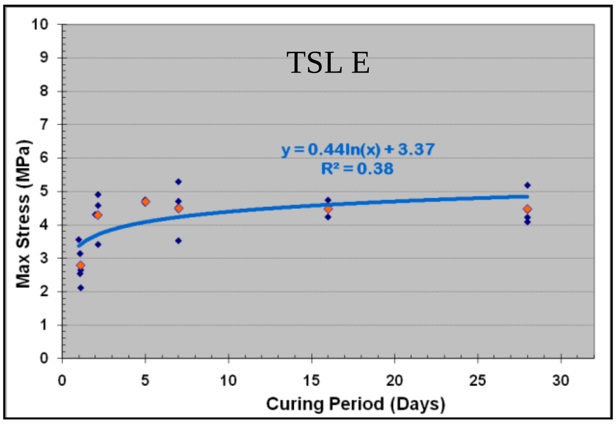
Appendix VI– Tensile strength test results

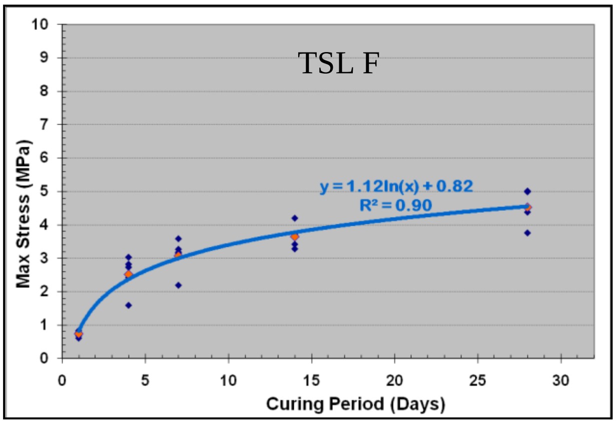


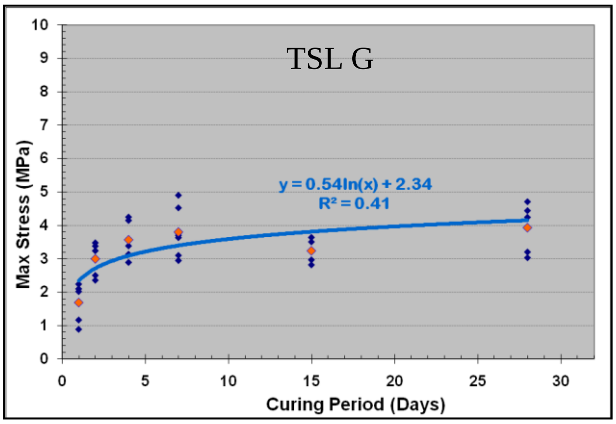


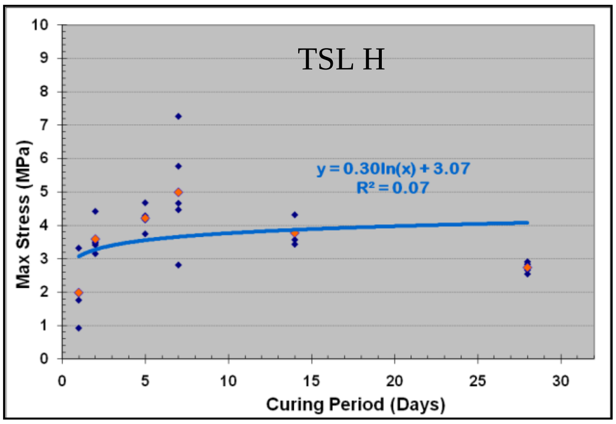


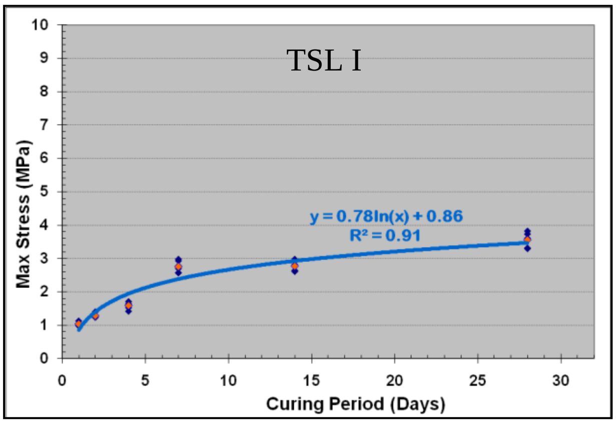


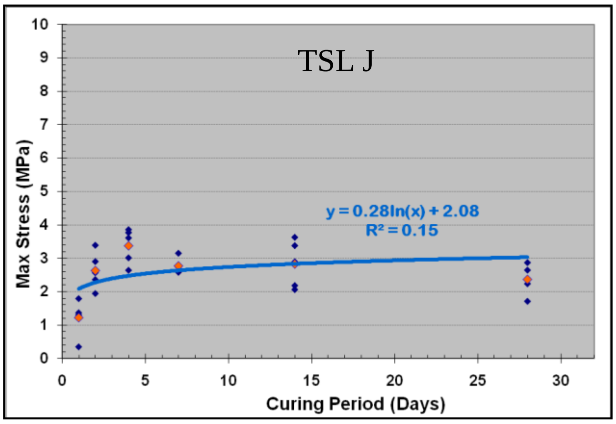


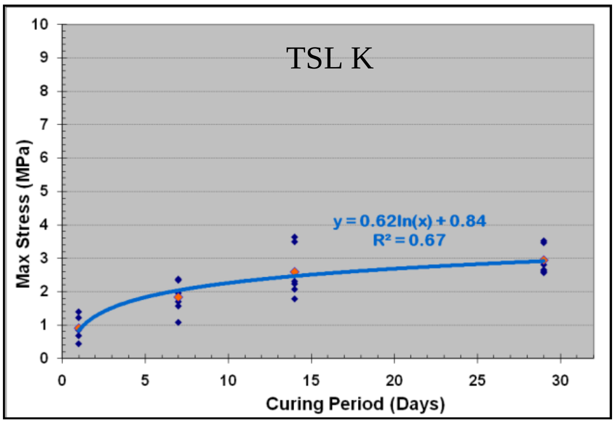


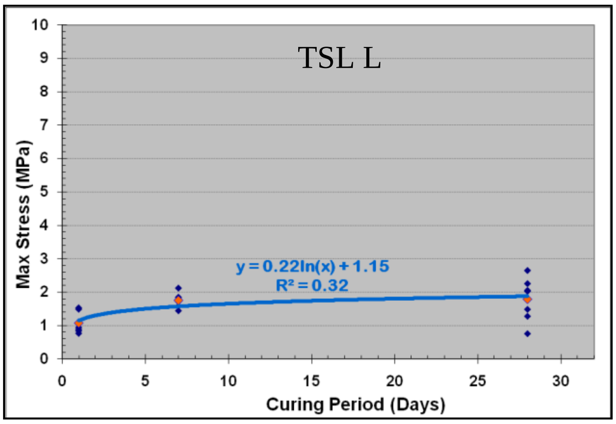

TSL G
y = 0.54ln(x) + 2.34
R² = 0.41
Max Stress (MPa)
Curing Period (Days)

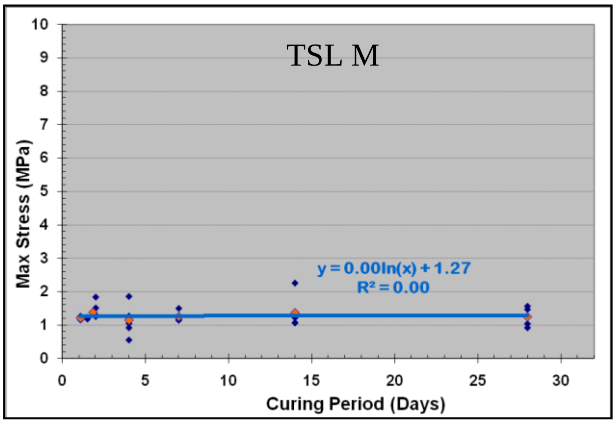

TSL H
y = 0.30ln(x) + 3.07
R² = 0.07
Max Stress (MPa)
Curing Period (Days)

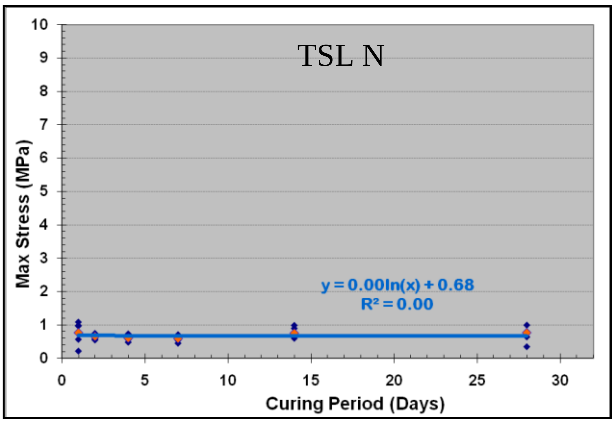

TSL I
y = 0.78ln(x) + 0.86
R² = 0.91
Max Stress (MPa)
Curing Period (Days)

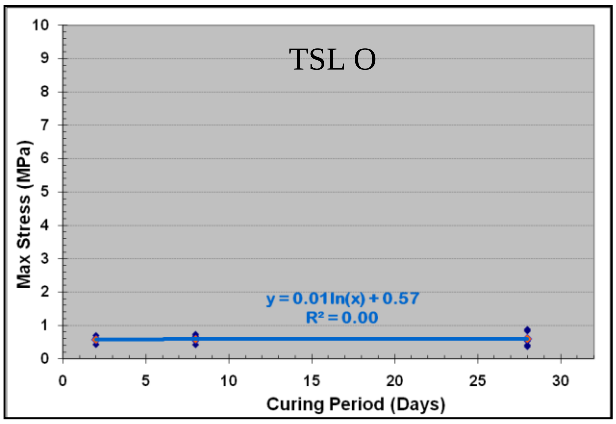

TSL J
y = 0.28ln(x) + 2.08
R² = 0.15
Max Stress (MPa)
Curing Period (Days)

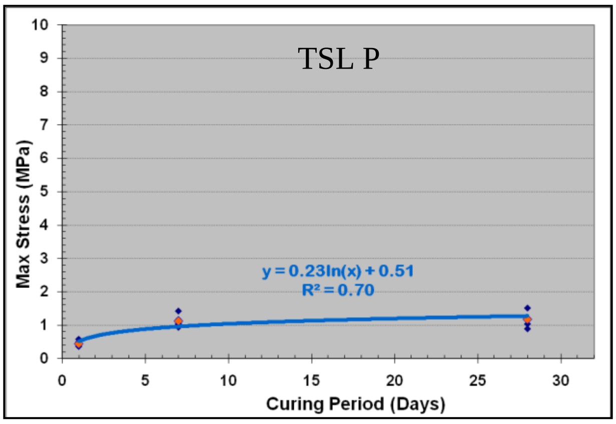

TSL K
y = 0.62ln(x) + 0.84
R² = 0.67
Max Stress (MPa)
Curing Period (Days)

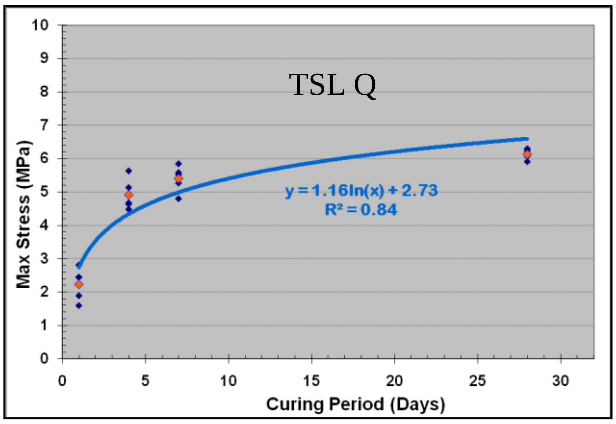

TSL L
y = 0.22ln(x) + 1.15
R² = 0.32
Max Stress (MPa)
Curing Period (Days)

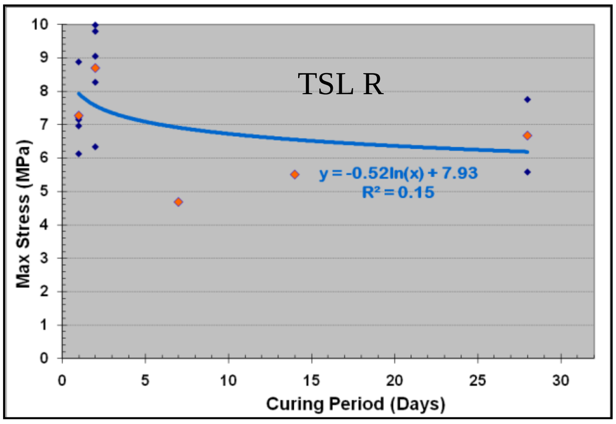

TSL M
y = 0.00ln(x) + 1.27
R² = 0.00
Max Stress (MPa)
Curing Period (Days)

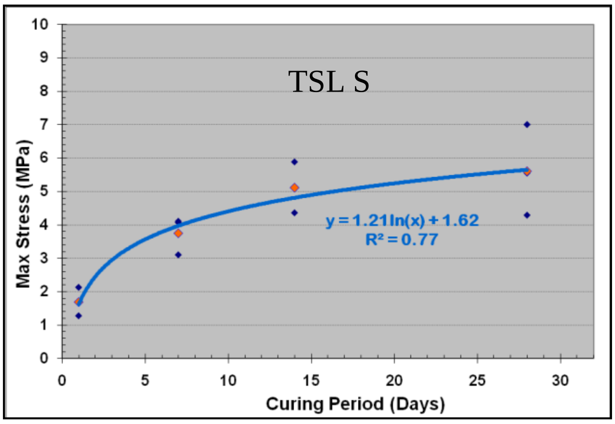

TSL N
y = 0.00ln(x) + 0.68
R² = 0.00
Max Stress (MPa)
Curing Period (Days)

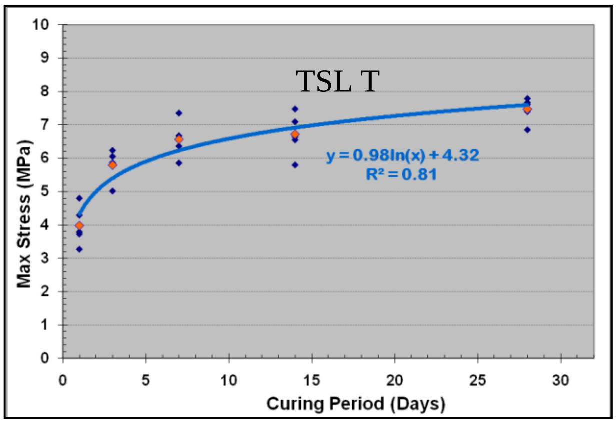

TSL O
y = 0.01ln(x) + 0.57
R² = 0.00
Max Stress (MPa)
Curing Period (Days)

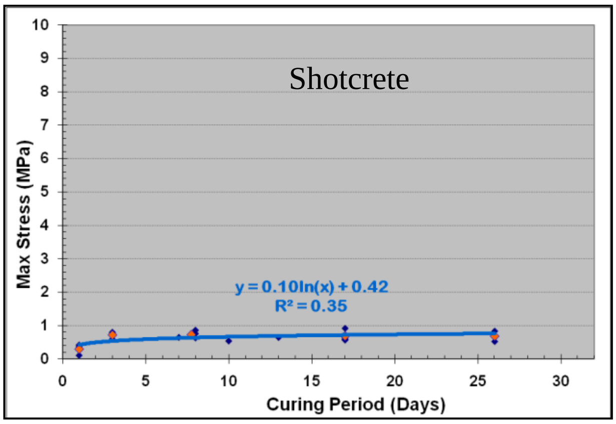

TSL P
y = 0.23ln(x) + 0.51
R² = 0.70
Max Stress (MPa)
Curing Period (Days)


TSL Q
y = 1.16ln(x) + 2.73
R² = 0.84
Max Stress (MPa)
Curing Period (Days)


TSL R
y = -0.52ln(x) + 7.93
R² = 0.15
Max Stress (MPa)
Curing Period (Days)


TSL S
y = 1.21ln(x) + 1.62
R² = 0.77
Max Stress (MPa)
Curing Period (Days)


TSL T
y = 0.98ln(x) + 4.32
R² = 0.81
Max Stress (MPa)
Curing Period (Days)


Shotcrete
y = 0.10ln(x) + 0.42
R² = 0.35
Max Stress (MPa)
Curing Period (Days)

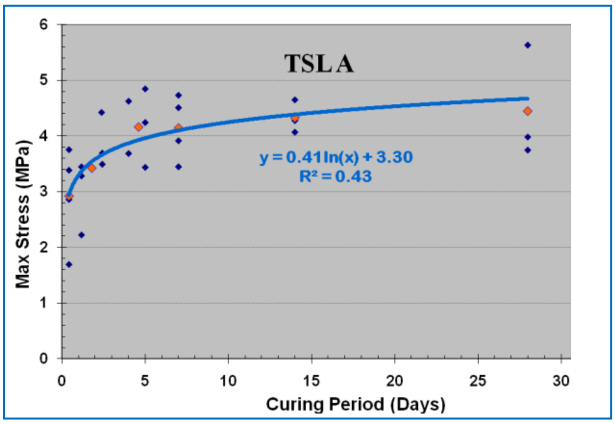
Appendix VII – Tensile strength test statistics

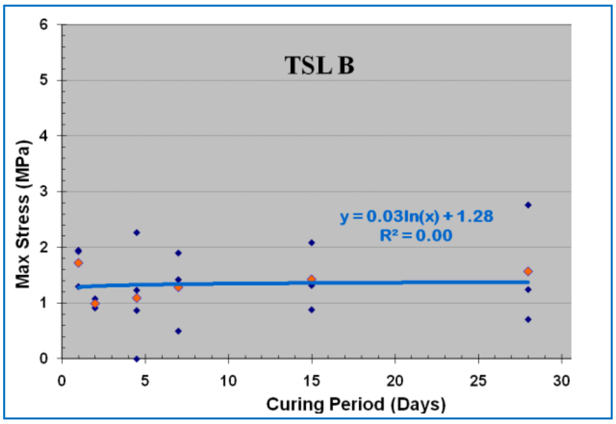
Mean (MPa)	Days	St Dev (MPa)	CV (%)	Mean (MPa)	Days	St Dev (MPa)	CV (%)	Mean (MPa)	Days	St Dev (MPa)	CV (%)
TSL A				**TSL B**				**TSL C**			
6.85	1	0.6	8.1	4.64	1	0.47	10.14	4.05	1	0.2	5.2
6.93	2	0.7	9.9	5.57	3	1.32	23.70	4.79	4		
7.39	4	0.6	8.1	6.18	5	0.07	1.09	5.26	7	0.7	12.6
6.34	7	0.6	9.1	7.51	7	1.26	16.83	5.25	14	1.8	34.6
7.24	14	0.5	7.2	6.03	15	0.62	10.33	5.76	28	1.4	23.5
8.13	28	0.4	5.4	7.38	28	1.35	18.25				
TSL D				**TSL E**				**TSL F**			
1.37	1	0.12	8.5	2.79	1	0.56	20.0	0.74	1	0.09	12.3
2.42	2	0.16	6.7	4.29	2	0.64	14.9	2.51	4	0.56	22.4
3.29	4	0.16	5.0	4.69	5	0.07	1.5	3.07	7	0.52	17.0
3.75	7	0.10	2.8	4.50	7	0.64	14.2	3.65	14	0.41	11.1
4.83	14	0.27	5.7	4.48	16	0.25	5.6	4.53	28	0.59	13.1
4.75	28	0.14	3.0	4.48	28	0.49	10.9				
TSL G				**TSL H**				**TSL I**			
1.69	1	0.6	36.2	1.99	1	0.86	43.2	1.03	1	0.05	4.8
3.00	2	0.5	17.4	3.59	2	0.48	13.4	1.28	2	0.07	5.3
3.57	4	0.6	17.0	4.22	5	0.38	9.1	1.58	4	0.10	6.4
3.80	7	0.7	18.6	5.00	7	1.65	33.0	2.75	7	0.17	6.3
3.24	15	0.4	12.4	3.78	14	0.47	12.6	2.76	14	0.17	6.0
3.93	28	0.8	19.3	2.74	28	0.17	6.0	3.55	28	0.21	6.0
TSL J				**TSL K**				**TSL L**			
1.22	1	0.53	43.5	0.91	1	0.39	43.0	1.08	1	0.3	31.7
2.63	2	0.55	20.8	1.83	7	0.50	27.0	1.75	7	0.2	13.3
3.38	4	0.53	15.6	2.59	14	0.78	30.2	1.79	28	0.6	36.1
2.77	7	0.23	8.1	2.94	29	0.44	15.0				
2.83	14	0.70	24.7								
2.37	28	0.51	21.5								
TSL M				**TSL N**				**Shotcrete**			
1.21	1	0.08	6.4	0.76	1	0.4	48.0	0.29	1	0.1	46.6
1.39	2	0.25	17.8	0.65	2	0.1	12.8	0.71	3	0.1	12.6
1.15	4	0.39	34.1	0.60	4	0.1	15.3	0.72	8	0.1	14.9
1.25	7	0.13	10.4	0.59	7	0.1	18.8	0.68	17	0.1	21.1
1.37	14	0.50	36.4	0.75	14	0.2	20.6	0.68	26	0.2	32.5
1.25	28	0.31	25.2	0.77	28	0.3	37.4				
TSL O				**TSL P**				**TSL Q**			
0.58	2	0.10	17.6	0.45	1	0.09	21.0	2.23	1	0.49	21.8
0.59	8	0.12	21.1	1.13	7	0.19	16.9	4.91	4	0.47	9.6
0.60	28	0.22	36.4	1.18	28	0.23	19.9	5.40	7	0.39	7.3
								6.12	28	0.15	2.5
TSL R				**TSL S**				**TSL T**			
7.27	1	1.00	13.8	1.70	1	0.60	35.5	3.98	1	0.58	14.7
8.69	2	1.48	17.0	3.75	7	0.57	15.2	5.79	3	0.47	8.0
4.68	7			5.12	14	1.08	21.1	6.56	7	0.62	9.5
5.50	14			5.61	28	1.36	24.2	6.71	14	0.63	9.4
6.67	28	1.54	23.1					7.46	28	0.37	5.0

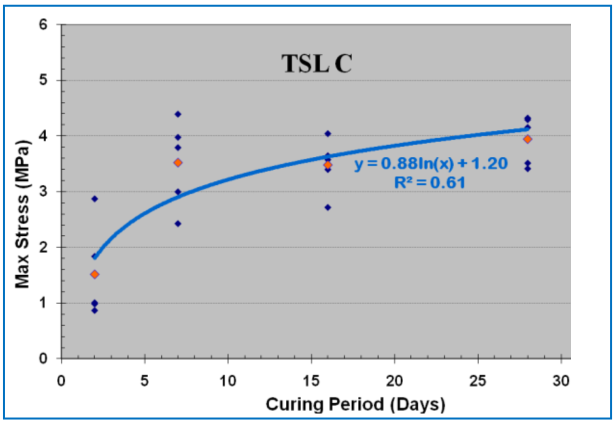
ΣCV% = 1763.5

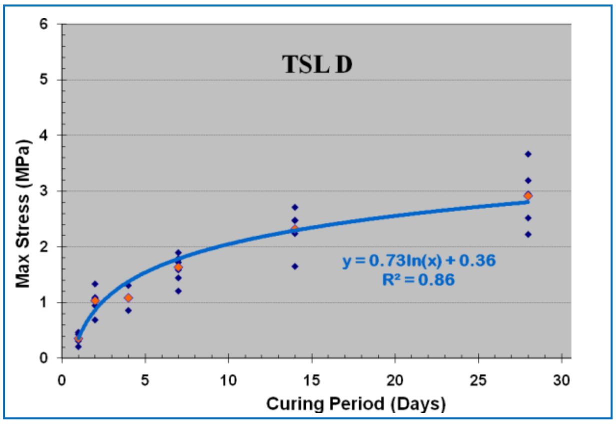
N = 103 (total number of curing times)

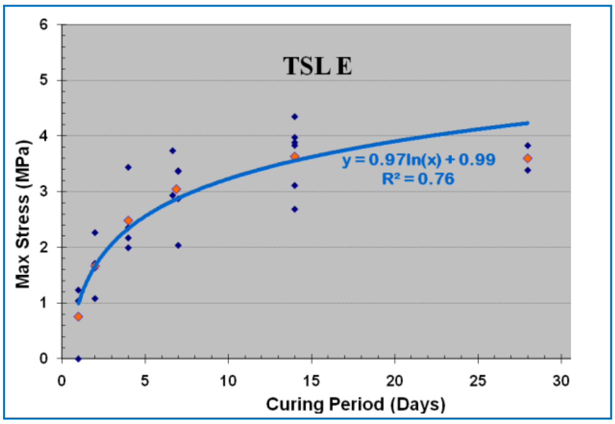
Appendix VIII– Tensile-bond strength test results

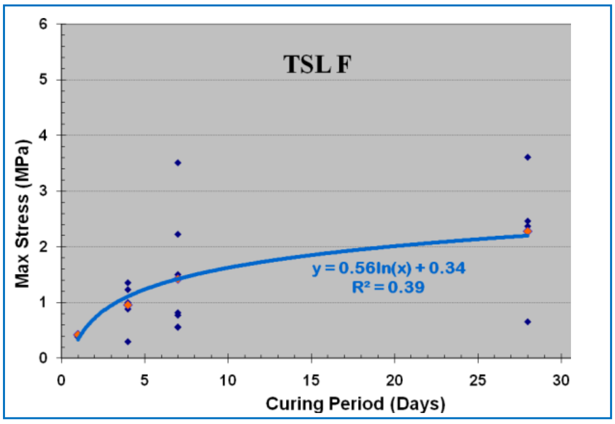


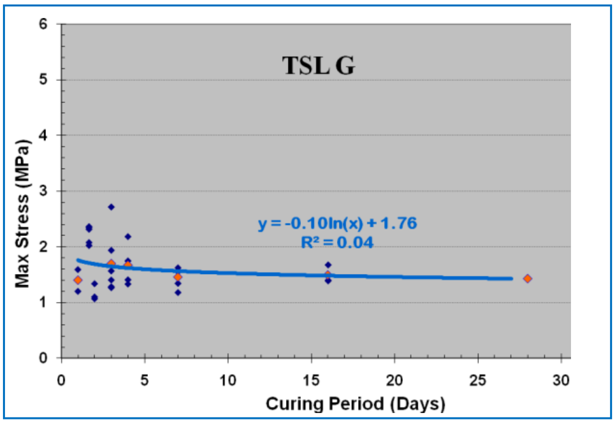


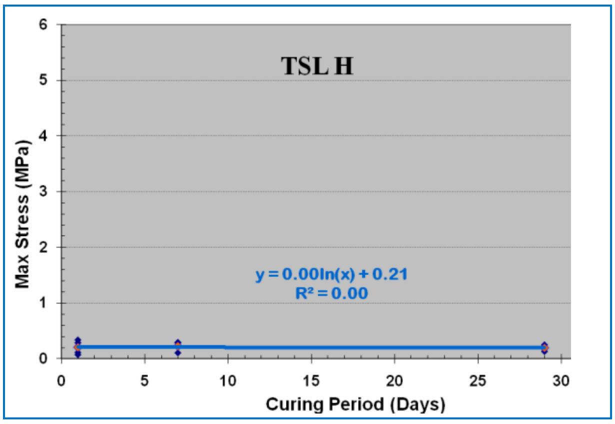


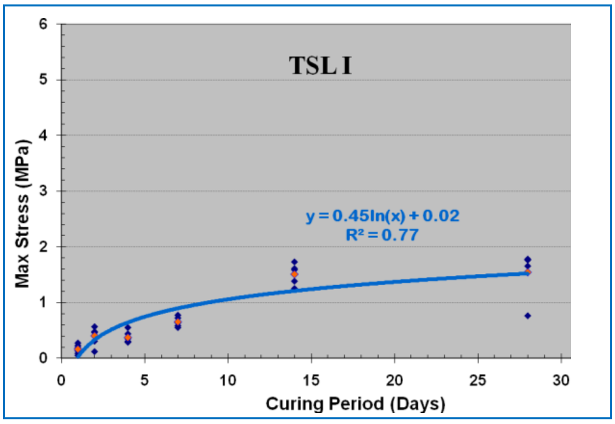


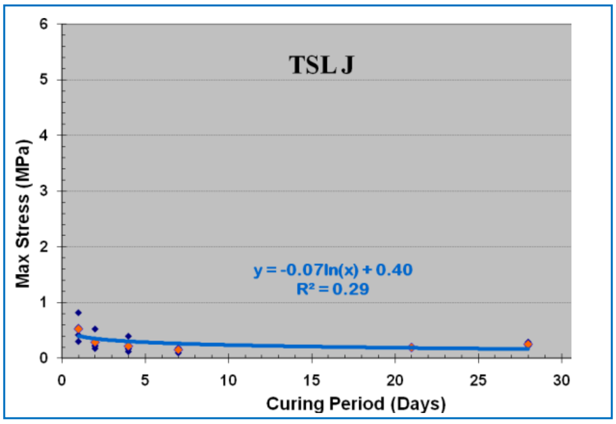


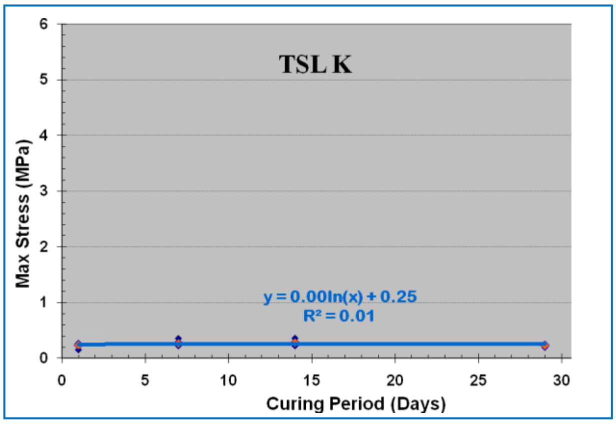


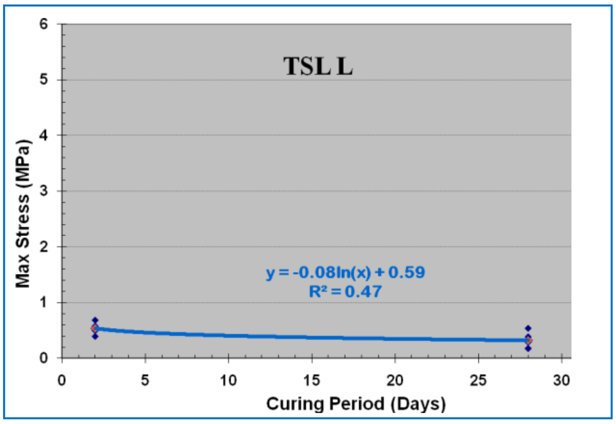

TSL G
y = -0.10ln(x) + 1.76
R² = 0.04
Max Stress (MPa)
Curing Period (Days)

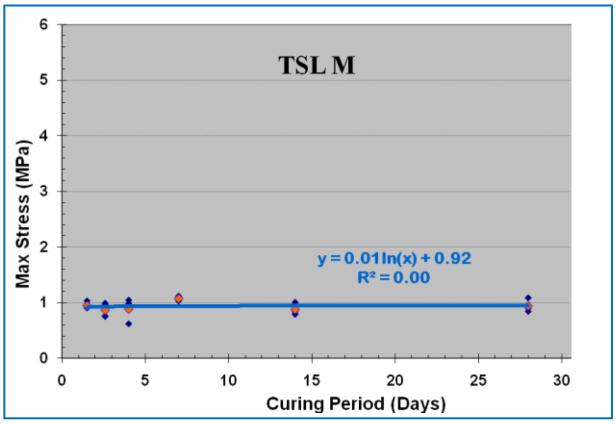

TSL H
y = 0.00ln(x) + 0.21
R² = 0.00
Max Stress (MPa)
Curing Period (Days)

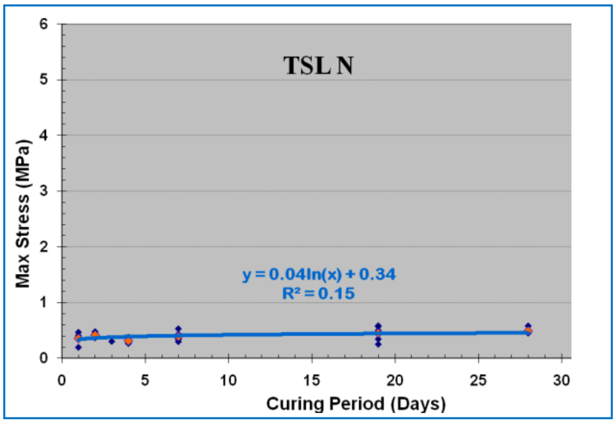

TSL I
y = 0.45ln(x) + 0.02
R² = 0.77
Max Stress (MPa)
Curing Period (Days)

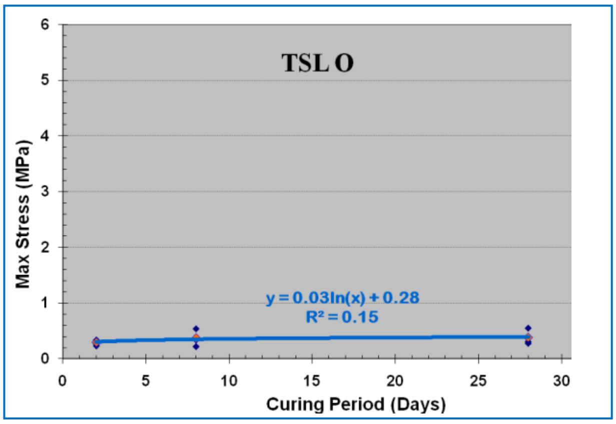

TSL J
y = -0.07ln(x) + 0.40
R² = 0.29
Max Stress (MPa)
Curing Period (Days)

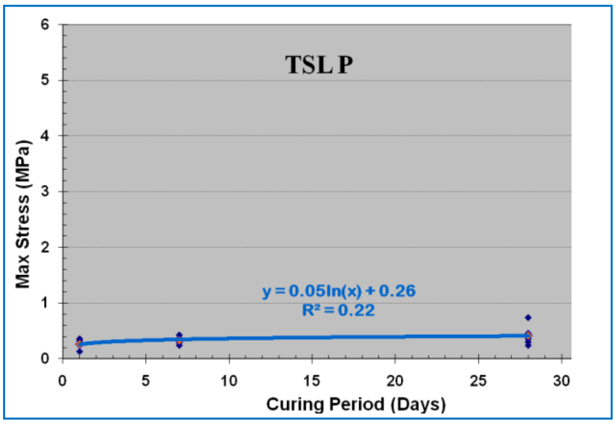

TSL K
y = 0.00ln(x) + 0.25
R² = 0.01
Max Stress (MPa)
Curing Period (Days)

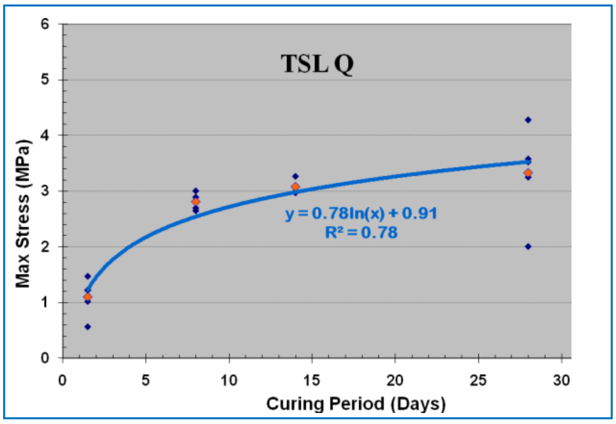

TSL L
y = -0.08ln(x) + 0.59
R² = 0.47
Max Stress (MPa)
Curing Period (Days)

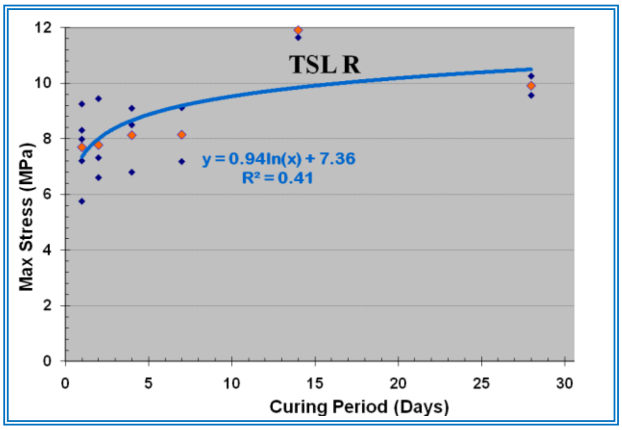

TSL M
y = 0.01ln(x) + 0.92
R² = 0.00
Max Stress (MPa)
Curing Period (Days)

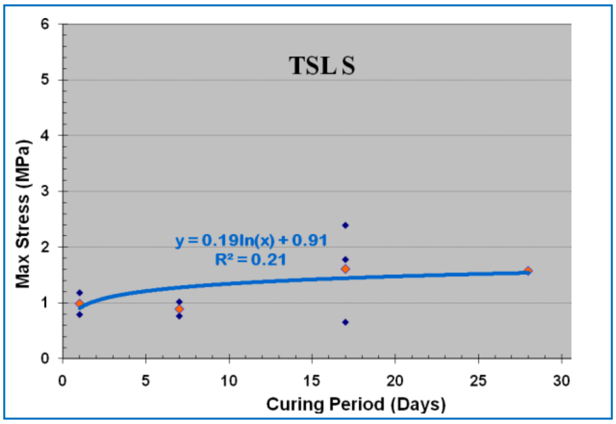

TSL N
y = 0.04ln(x) + 0.34
R² = 0.15
Max Stress (MPa)
Curing Period (Days)

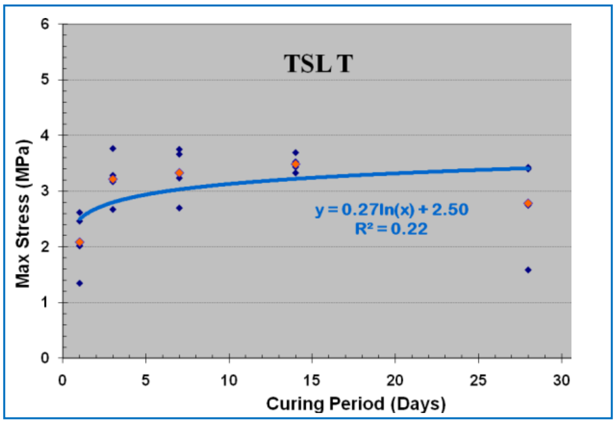

TSL O
Max Stress (MPa)
Curing Period (Days)
y = 0.03ln(x) + 0.28
R² = 0.15

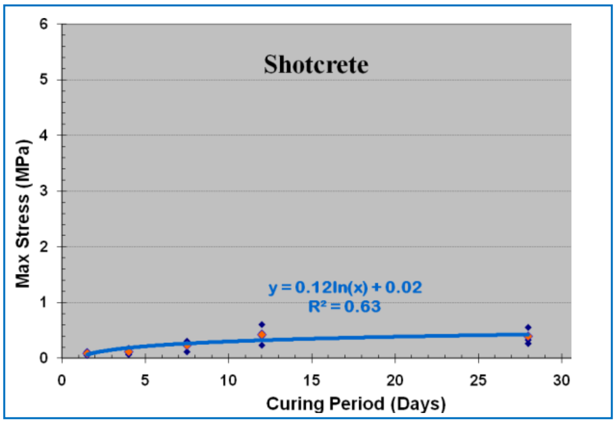

TSL P
Max Stress (MPa)
Curing Period (Days)
y = 0.05ln(x) + 0.26
R² = 0.22


TSL Q
Max Stress (MPa)
Curing Period (Days)
y = 0.78ln(x) + 0.91
R² = 0.78


TSL R
Max Stress (MPa)
Curing Period (Days)
y = 0.94ln(x) + 7.36
R² = 0.41


TSL S
Max Stress (MPa)
Curing Period (Days)
y = 0.19ln(x) + 0.91
R² = 0.21


TSL T
Max Stress (MPa)
Curing Period (Days)
y = 0.27ln(x) + 2.50
R² = 0.22


Shotcrete
Max Stress (MPa)
Curing Period (Days)
y = 0.12ln(x) + 0.02
R² = 0.63

Appendix IX– Tensile-bond strength test statistics

Mean (MPa)	Days	St Dev (MPa)	CV (%)	Mean (MPa)	Days	St Dev (MPa)	CV (%)	Mean (MPa)	Days	St Dev (MPa)	CV (%)
TSL A				**TSL B**				**TSL C**			
2.92	0	0.90	30.69	1.72	1	0.37	21.42	1.51	2	0.85	56.35
3.43	2	0.66	19.36	0.99	2	0.08	8.32	3.52	7	0.79	22.53
4.17	5	0.71	16.96	1.09	5	0.94	85.91	3.48	16	0.49	13.95
4.15	7	0.58	14.01	1.28	7	0.58	45.21	3.94	28	0.44	11.18
4.33	14	0.29	6.79	1.43	15	0.61	42.61				
4.45	28	1.03	23.05	1.57	28	1.06	67.70				
TSL D				**TSL E**				**TSL F**			
0.36	1	0.12	33.16	0.76	1	0.54	71.21	0.42	1	0.03	6.06
1.03	2	0.21	20.40	1.67	2	0.48	28.88	0.96	4	0.41	42.86
1.09	4	0.32	29.22	2.49	4	0.65	26.08	1.43	7	1.10	77.20
1.63	7	0.24	14.60	3.05	7	0.59	19.34	2.28	28	1.22	53.40
2.32	14	0.36	15.65	3.64	14	0.61	16.91				
2.91	28	0.56	19.39	3.60	28	0.31	8.67				
TSL G				**TSL H**				**TSL I**			
1.40	1	0.19	13.86	0.21	1	0.11	54.96	0.16	1	0.08	52.74
1.70	3	0.55	32.65	0.23	7	0.11	47.27	0.40	2	0.16	40.15
1.67	4	0.33	20.02	0.20	29	0.05	25.83	0.37	4	0.10	28.24
1.46	7	0.18	12.63					0.65	7	0.09	14.27
1.49	16	0.11	7.68					1.51	14	0.19	12.66
								1.55	28	0.44	28.51
TSL J				**TSL K**				**TSL L**			
0.52	1	0.19	37.04	0.24	1	0.05	20.35	0.54	2	0.11	20.14
0.28	2	0.16	57.12	0.27	7	0.05	20.01	0.32	28	0.14	42.82
0.21	4	0.11	50.13	0.28	14	0.06	22.93				
0.15	7	0.05	33.30	0.23	29	0.02	9.74				
0.19	21	0.01	3.49								
0.25	28	0.03	10.09								
TSL M				**TSL N**				**Shotcrete**			
0.95	2	0.06	5.98	0.36	1	0.12	32.97	0.09	2	0.03	31.15
0.87	3	0.13	14.78	0.42	2	0.04	10.58	0.12	4	0.05	44.08
0.89	4	0.16	18.29	0.31	4	0.05	15.10	0.24	8	0.07	30.90
1.08	7	0.03	3.21	0.39	7	0.09	23.66	0.42	12	0.13	31.17
0.88	14	0.09	10.52	0.45	19	0.15	32.92	0.39	28	0.11	27.38
0.94	28	0.13	13.37	0.49	28	0.06	13.12				
TSL O				**TSL P**				**TSL Q**			
0.29	2	0.04	14.37	0.26	1	0.09	33.19	1.10	2	0.34	30.80
0.37	8	0.13	35.45	0.33	7	0.07	21.55	2.81	8	0.14	5.14
0.38	28	0.12	32.05	0.42	28	0.20	46.62	3.08	14	0.16	5.32
								3.33	28	0.83	24.94
TSL R				**TSL S**				**TSL T**			
7.70	1	1.31	17.07	0.99	1	0.20	19.79	2.09	1	0.50	23.70
7.77	2	1.21	15.53	0.89	7	0.18	20.17	3.22	3	0.45	13.95
8.13	4	1.19	14.68	1.61	17	0.88	54.82	3.33	7	0.42	12.53
8.15	7	1.37	16.82	1.57	28			3.49	14	0.13	3.84
11.91	14	0.38	3.15					2.79	28	0.86	30.95
9.91	28	0.49	4.94								

$\Sigma CV\% = 2548.3$

N = 99 (total number of curing times)

Appendix X – CD ROM: TSL test data and photographs

CD ROM contents:

- Tensile-bond test
- Tensile test
- Shear-bond test
- Material shear test