Shear-bond strength testing of thin spray-on liners

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Synopsis

A testing method for assessing the shear-bond strength of thin spray-on liner (TSL) on rock substrate was developed at Wits University Rock Mechanics Laboratories. The gap between a 20 mm thick steel ring and a rock core is filled with TSL along the depth of the ring. After the curing of the TSL for a predetermined period, the sample 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 TSL contact and punching it towards the void in the support base. Shear-bond strengths for different TSL products as well as shotcrete were measured. This paper describes the test set-up and points out the important aspects and procedures during sample preparation and test execution. The test results are also presented and discussed.

Introduction

Brief history

TSL materials for ground support were initially intended to be used as an alternative to mesh or shotcrete. The first trials on TSL technology were initiated in Canada in the late 1980s (Archibald *et al.*, 1992). Early research led to the development of a polyurethane based product. In the 1990s, numerous advantages in terms of speed of application and minimizing transportation of materials were realized. In the late 1990s, applications included a hybrid polyurethane/polyurea based mixture (Tannant, 2001).

Meanwhile in 1996 in South Africa, a latex-based product was developed and tested, and then later another product followed (Wojno and Kuijpers, 1997). Researchers in Australia have also been exploring the use of TSLs for rock support and have conducted field tests in Western Australia.

Many products have been tested so far and it was found that most did not possess adequate physical or chemical properties. Although the production of a number of products has been stopped and their names are not referred to any longer, newer products are continuously developed and introduced.

Recent developments on TSL support continue to receive increasing attention by the mining industry around the world due to considerable operational benefits, with the potential to greatly reduce mining costs. There were about 55 mines around the world in 2001 that were considering the use of TSL for rock support, and this number is increasing steadily. The greatest interest is in North America, Australia, and South Africa (Tannant, 2001).

Necessity of TSL testing

Assessment of TSL suitability and performance is mainly based on short-term visual observations at trial sites. Suitable testing methodologies, apart form tensile strength and bond strength testing, still need to be established for TSL support. There, recently, has been a considerable impetus towards developing a variety of testing methods in an attempt to address this problem. However, the description and reporting of tests, in general, have not been done accurately and often lack critical information. Therefore, absence of generally agreed testing methods causes lack of parameters, which are important in evaluating the quality and performance capabilities of TSL products in the market. For this reason, development of appropriate tests and derivation of acceptable parameters on TSLs are urgently needed so that design standards and requirements can be formulated. Subsequently, more effective and frequent use of TSLs will be possible as the confidence builds up among the currently hesitant end-users.

The frequently asked questions by the manufacturers or end-users, 'Is our product good?' or 'Which TSL is better?' have no

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simple answers in the absence of sound testing methods. A few parameters determined from tensile strength and bond strength testing would not be adequate for deciding a TSL's position among other products. Development of a variety of testing procedures and derivation of more parameters on TSL properties would undoubtedly assist in adding more words to answering the above questions.

TSL mechanical properties and test options

The following tests are considered to be most relevant in defining TSL mechanical properties, and research effort so far has mainly concentrated on some of these tests, i.e:

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

Bond and tear strength can be measured against tension and shear; therefore both characteristics need to be assessed. Boundary conditions and mechanisms of loading that need to be observed for the development of the abovementioned strength tests are summarized in Figure 1. The extent of loading is indicated in red. The expected position of failure is shown in yellow lines. Loading direction remains fixed in all tests; nevertheless, loading position may change during the test; particularly in tear strength testing due to progressive tear. Fixed boundaries are for clamping or support purposes, therefore TSL bonding takes place only on substrate but not on such boundaries.

Details of location of failure, loading characteristics and sample composition are given in Table I. While tensile, compressive, shear, tear and bend strengths involve TSL material only, the samples of bond and impact strength testing should incorporate a substrate. The location 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 the sample. This is a distinctive behaviour in tensional loading. On the other hand, the failure surface for tests involving shear, bend or impact loading will be inflicted along the positions where the loading is concentrated.

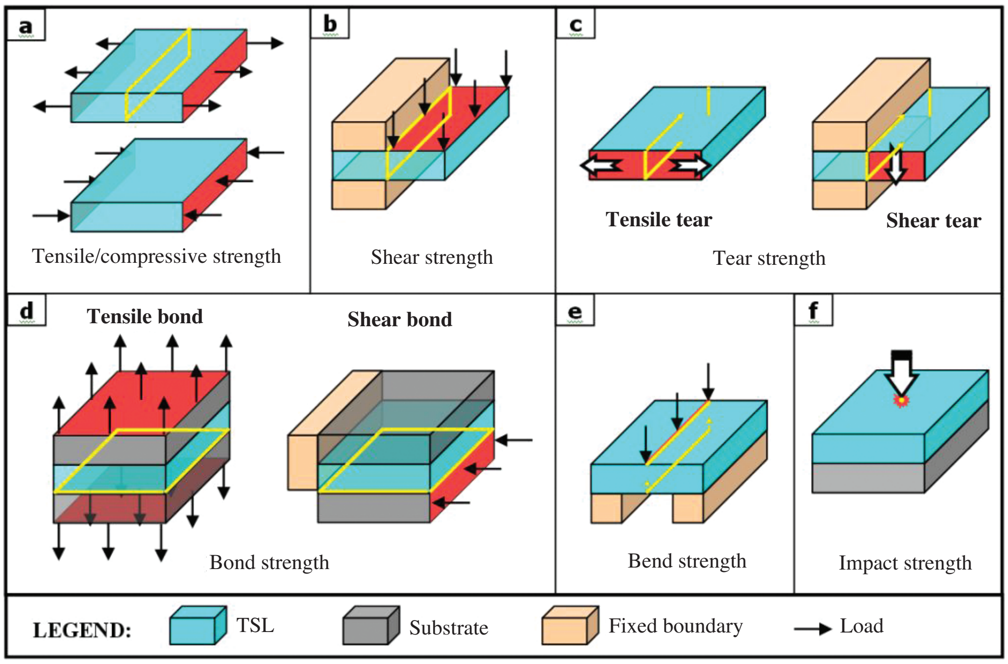

Figure 1—Boundary conditions and mechanisms of loading for mechanical TSL tests

Table I

Failure, loading and sample characteristics of TSL mechanical property testing

Mechanical property	Location of failure	Extent of failure	Loading	Sample 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

Previous TSL testing

Numerous tests have been done in assessing TSL mechanical properties either on a small scale or big scale. Table II lists the most relevant of these tests.

Standard testing methods to determine strength characteristics and physical behaviour of plastics, membranes and geotextiles are developed by various institutions such as 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). These test standards could be adapted to TSLs either directly or by appropriate modifications (Toper *et al.*, 2003).

Despite the significant variety of testing procedures as listed in Table II, only the tensile and bond strength tests met with the acceptance of the researchers so far. Large-scale tests were found to provide interesting results but were also found to be difficult to interpret in terms of TSL properties and behaviour.

Tensile strength testing is done on dog-bone shaped TSL samples according to ASTM D638 (Tannant *et al.*, 1999; Archibald, 2001; Spearing and Gelson, 2002). Dog-bone tensile strength testing has been frequently performed and a sufficient amount of data on the results is available. This test, satisfying most of the researchers, has great potential to be accepted as a standard testing method.

Bond strength measurements, to date, involved pull type mechanisms and were performed in two ways. Firstly, TSL is pulled away from substrate by means of a dolly following ASTM D4541, DIN 1048-2 as guidelines (Tannant and Ozturk 2003; Lewis 2001). Secondly, two pieces of core are bonded together by TSL and then pulled apart (Spearing 2001).

Test requirements

The following requirements are used as guidelines during the initial design and developmental stages of shear-bond testing method i.e.;

- *Manageable size*—due to greater difficulties associated with large specimens in terms of preparation time, costs and manageability, the sample and apparatus size should be as small as possible.
- *Simplicity*—a complicated test method results in difficulties in sample preparation, test execution, interpretation of test data and therefore requires more time.
- *Time*—easy sample preparation and testing would eliminate unnecessary delays. Curing of TSL before testing inevitably takes time. However, testing should preferably be completed within 5 to 10 minutes from the start of loading. Tests requiring longer time periods will reduce the number of samples that can be tested in a day.
- *Cost*—this constraint is directly proportional to an increase in specimen size and time spent in sample preparation and test execution. If a TSL property could be measured by different test 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.
- *Reprocessing (recycling)*—test material, other than TSL, such as core, substrate and any other component should be processed for reuse in subsequent tests for cost-effectiveness. However, reprocessing may not need to be exercised if there is surplus amount of test material.
- *Adaptability*—testing method, with all the components, should easily be performed at another laboratory. Implementation of large-scale tests may not be possible at some laboratories due to availability of small capacity testing equipment.

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

The following sections will describe the small-scale laboratory testing method developed for measuring the shear-bond strength of TSL. Important aspects during sample preparation and test execution are pointed out. The test results are also presented and discussed.

Shear-bond strength testing method

The testing method developed is aimed at quantifying TSL bond resistance against shear (see Figure 1d), which has

Table II

Previous tests of TSL

Test description	Reference
Tensile strength and elongation testing	Tannant *et al*., 1999; Archibald, 2001; Spearing and Gelson, 2002
Bond (adhesive) strength testing	Tannant and Ozturk, 2003; Lewis, 2001
Core to core bond strength testing	Spearing, 2001
Torque testing method	Yilmaz *et al.*, 2003
Double-sided shear strength testing	Saydam *et al.*, 2003
Asymmetric core punch testing	Stacey and Kasangula, 2003
Punch (TSL displacement) testing	Spearing *et al*., 2001; Kuijpers, 2001
Large scale plate pull testing	Tannant, 1997; Espley *et al.*, 1999
Coated panel testing	Kuijpers, 2001; Naismith and Steward, 2002
Coated-core compressive testing	Espley *et al.*, 1999; Archibald and DeGagne, 2000; Kuijpers, 2001
Box of rocks (baggage load) testing	Swan and Henderson, 1999
Perforated plate pull testing	Tannant *et al*., 1999; Archibald, 2001
Material plate pull testing	Tannant *et al*., 1999; Archibald, 2001

been overlooked by researchers so far. In cases of TSL penetration in fractured rocks, quantification of shear-bond strength would be vital.

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

'Promotion of block interlock: the effect of this mechanism is the preservation of the rock mass in a substantially unloosened/jointed rock situation including very high stress situations in which some loosening and stress fracturing will have taken place. Liner material penetrates into joints and cracks where bonding to rock takes place. This in turn, inhibits movement of blocks preventing shear on the interface and restricting block rotation.'

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 essential and the value determined from such tests will be an important input in support design.

Brief test description

A 20 mm thick steel ring with a 52.5 mm diameter hole is used. A rock core of 27.5 mm diameter is centrally positioned in the hole (see Figure 2). The gap between the steel ring and the rock core is filled with TSL by pouring along the depth of the ring. After the curing of the TSL for a predetermined period, the sample 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 TSL contact and displacing it towards the void in the support base. Load deformation characteristics are observed until the TSL fails. In some cases loading continues until a residual load level is reached.

The loading of the TSL takes place due to shear movement and the failure takes place at the rock-TSL contact, causing bond failure in shear.

Test considerations

The TSL, as applied to a rock surface, is expected to penetrate into open rock fractures. Any dip, strike or apparent dip movements in this location, as seen in Figure 3, will cause shear loading of the TSL-rock contact and consequent failure. The displacement mechanism employed in the testing method is representative of this type of shear loading, which remains on the fracture plane. In some cases, dilation of fracture surfaces is also possible; however, this mechanism is not simulated in the testing method developed.

The application of shear loading on a laboratory specimen will induce rotation or bending of the specimen if the blocks subjected to shear are not secured well in their position, as experienced in the double-sided shear strength (DSS) testing of Saydam *et al.* (2003). Otherwise, tension rather than shear will be the cause of failure. The problem of bending in the shear-bond strength testing is overcome by imposing circumferential continuity of the TSL around a rock core. When the prepared sample is positioned on a support ring and load is applied on the rock core, no bending is involved therefore no clamping is necessary.

The fact that the TSL forms a component with the applied rock surface is one of the desired properties for any proposed standard testing. Interaction between the TSL material and the applied surface is taken into account. Diamond-cored cylindrical samples of norite were chosen as substrate. The surface resulting from diamond coring is accepted as standard substrate finish.

From among the various factors that significantly influence the performance of TSL materials (e.g. time, temperature, humidity, substrate type, substrate condition, rate of loading, specimen size, storage duration, etc.) the curing time (time elapsed from mixing to testing) was chosen as the main parameter to be tested against shear-bond strength. Tests were performed at 1, 2, 4, 7, 14 and 28 days of curing to provide a range of times that are thought to demonstrate the strength development reasonably well. Fast-setting TSLs may also be tested at 2, 6 or 12 hours to observe early strength development. All the other factors were kept at set values, as detailed later, at these curing times.

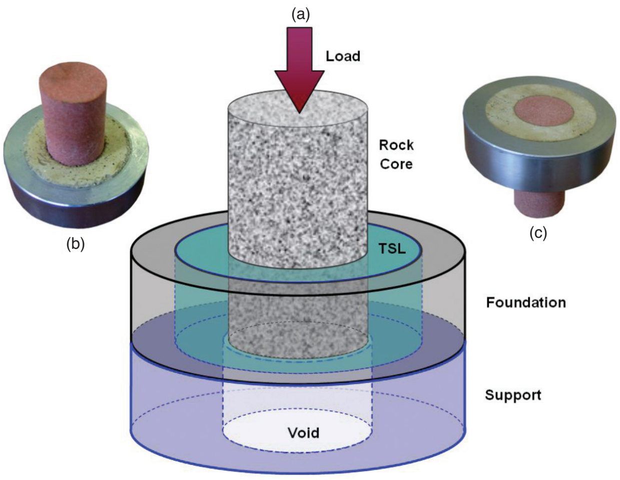

Figure 2—(a) Illustration of shear-bond testing, (b) specimen top view, (c) specimen bottom view

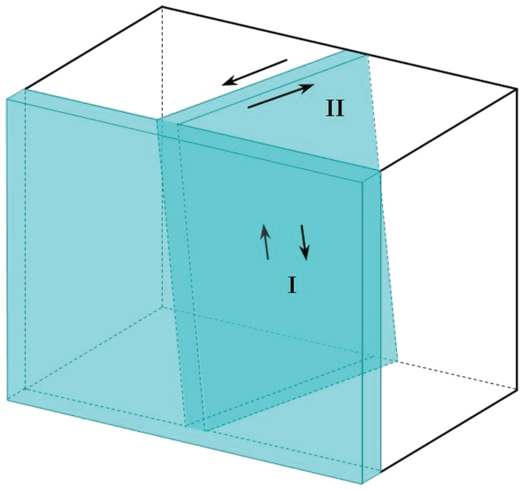

Figure 3—*In situ* loading mechanism of TSL relevant to shear-bond strength testing

The tests are performed at normal laboratory environmental conditions where temperature and relative humidity range from 20° to 27° and 50% to 60%. In addition, there is no throughflow of ventilation that could cause accelerated evaporation and air drying. Approximately 10% variation in environmental conditions will have an effect on the test results; however, this effect is considered to be minimal compared to the results under extreme environmental conditions at mines. One should not attempt to use the values derived in a laboratory for the evaluations underground where the deviation in environmental conditions is considerable. During rainy seasons, areas near to intake air in mines may experience 100% humidity, which may significantly interfere with the curing and bonding of some TSLs. Under these circumstances, testing of TSLs should extend beyond laboratory environmental conditions in order to approximate TSL's particular performance under extreme mining environments. Any variation in TSL's performance needs to be accounted for in support design. Underground performance of timber, for example, is lower than laboratory performance due to differences in loading rate and environmental conditions therefore; laboratory values are downgraded to underground performance by using loading rate adjustment curves to derive a correction factor. A similar approach may be adopted for downgrading TSL laboratory performance to underground performance, which obviously requires testing to be done at a full range of temperature and relative humidity values. However, determination of TSL properties by taking environmental effects into account will require an enormous amount of testing and therefore has not been attempted yet.

Loading rate is another parameter that affects the result of any TSL testing. Higher loading rates in rock testing result in higher strength, and similar behaviour is expected in TSL testing. The criteria taken for the establishment of standard loading rate is that the peak load should be reached within 10 minutes of load initiation. Loading may be done either in load control mode or displacement control mode. The differences of time to failure between low and high strength TSLs could cross over 10 minutes criteria when the load control mode is used. 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 should be exercised for shear-bond strength testing.

Description of apparatus, sample preparation and test procedures

Sample components

Steel ring

The steel ring is used for the purpose of housing TSL and the rock core. TSL bonds onto both the inner surface of the steel ring and the rock core. While the movement on the core surface takes place, the displacement on the steel contact surface is not allowed. Since debonding takes place on the core surface, the bonding of TSL to steel ring is for containment reasons only. Steel is preferred due to its high strength and low cost. The following dimensions are used for the steel ring as illustrated in Figure 4a.

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

Rock core

The side of the rock core is used for substrate purposes and no processing of this surface is done in addition to diamond coring. The top and bottom surfaces of the core are polished flat and parallel, in accordance with ISRM standards (Brown, 1981). Norite is used as the rock type among the other available ones, such as marble, sandstone, shale, coal, and kimberlite, primarily due to its availability and strength (approximately 200 MPa). The sensitivity of shear-bond strength on different rocks is subject to further research.

The core dimensions are illustrated in Figure 4b. The two main reasons for selecting core diameter of 27.6 mm are firstly the availability of a diamond drill barrel of 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 diameter core causes pouring difficulties, especially when TSL is more viscous or fast curing. Increasing this annulus may be considered by increasing the steel ring size for facilitating the pouring of TSL further. The length of core should be more than the steel ring thickness, preferably twice as much.

Steel support ring

The prepared sample, consisting of TSL filled in the annulus between the steel ring and the rock core, is placed on the

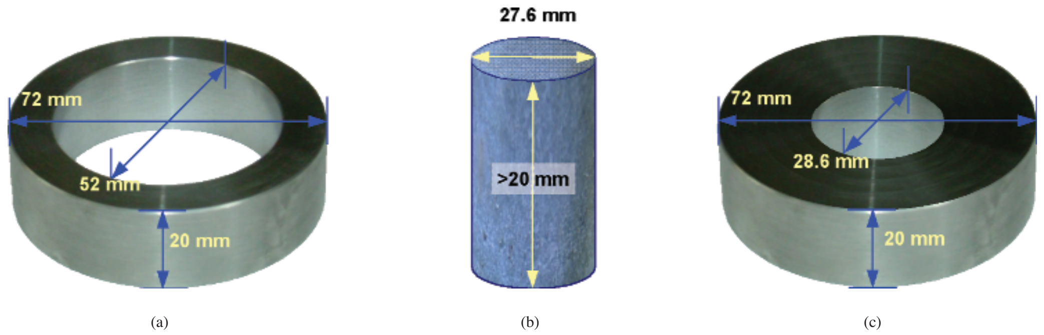

Figure 4—Dimensions of (a) steel ring (b) rock core and (c) steel support ring

steel support ring as shown in Figure 4c. Both the steel ring and the support ring are similar, with the exception that the inner 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.

TSL

TSLs from South African manufacturers were collected and tested. TSLs vary in composition and most of the products are cement-polymer based with the exception of only one product, which was polyurethane based. Table III summarizes the manufacturers and their products that were made available for the testing programme. Some manufacturers offered a number of products and some of their products were under continuous development. Product names will not be revealed under the results and analysis section in order to preserve confidentiality.

Sample preparation

The steps followed during sample preparation are illustrated in Figure 5. Firstly, the rock core is centrally positioned in the steel ring. After that, approximately 1 or 1.5 kg of TSL components are taken at a time and thoroughly mixed according to manufacturer's specification by a hand-held mixer. TSL is then poured into the space between the core and the ring. At least 30 samples should be prepared to cover for five samples at each curing time. Then, TSL material is allowed to cure for the required periods. Finally, a steel support ring is placed under the ring-core-TSL assembly before the start of loading.

The core and steel ring axis should remain parallel, preferably on the same line. Polishing of core ends as mentioned above assists to serve this purpose. In addition, the ring and core should lie on a flat surface and they should not be allowed to move when TSL is poured. Flattening of TSL's exposed top surface with the ring top surface will ensure uniform TSL thickness. Flattening may be done by tamping a sheet of plastic against this surface. Most TSLs de-bond from plastics in a short period as curing takes place.

One can argue that the spraying of TSL material would make a difference to the test results as compared to the pouring process. However, spraying of TSL on small-scale laboratory specimens, as well as hand application of TSL on the surfaces of mining excavations would be two extremes of an overkill situation. The author's opinion is that whether TSL is sprayed, hand applied, poured or molded, the differences in the bonding of TSL to substrate would be negligible. However, this opinion needs to be quantified by further research.

The pouring process after the completion of TSL mixing needs to be faster for some products due to quick-hardening or fast-curing characteristics. Otherwise, smaller amounts of TSL should be mixed at a time.

Table III

TSL products tested

Manufacturer	TSL product
Carbontech	V-Seal
Cementation LP	Superseal
Concor	D21H, Standard (version 1 and 2)
MBT (Degussa)	Masterseal 845A
Minova SA	Capcem grey and white, Tekflex, Raplok
NS Consultancy	Ultraskin
SA Mining Eng. Supplies	Tunnelguard standard, TGNC, TGNT

Test execution

The prepared sample is carefully positioned in the loading machine where the movement of machine platens should be in line with the direction of bond surface. Then, a distributed load is applied on the top surface of the rock core. Loading is done by displacement control where the sample is initially loaded up to 0.01 mm by 0.001 mm/s and then by 0.002 mm/s up to failure. Initial trials showed that these loading rates would cause the failure of TSL bonding within 5 to 10 minutes of the start of loading. Load and displacement of the core along the TSL contact surface are measured.

Boundary conditions

Boundary conditions on the sample assembly are shown in Figure 6. Loading takes place on the top surface of the core with the reaction of the fixed support base as indicated in red lines. The green lines are the stress-free surfaces and only the ones on the core are allowed to displace. 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. These boundary conditions would be a useful guide when numerical modelling is exercised in future research.

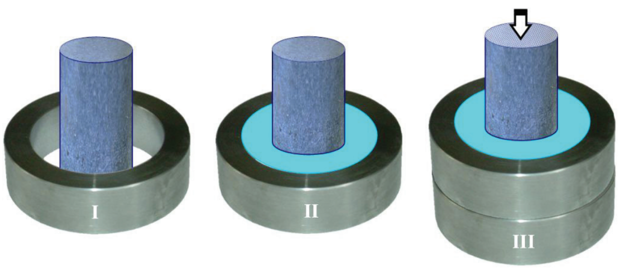

Figure 5—Steps followed in sample preparation

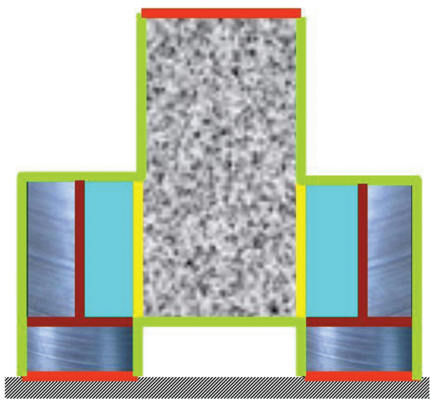

Figure 6—Boundary conditions

Test parameters

Tests are performed at 6 curing times (1, 2, 4, 7, 14, 28 days) and at least 5 tests are aimed to be done at each curing time. TSL thickness is the same as the steel ring thickness (20 mm). The dimensions of sample components, as mentioned earlier, were not altered during the testing programme. Loading was done under displacement control mode as indicated earlier. Norite is used as the substrate rock type and the same substrate finish is used in all tests.

The effect of environmental conditions, such as the changes in temperature or humidity levels, on the test results is not investigated. The determination of creep behaviour of TSLs is also not within the scope of this research.

Calculations

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

$$\tau_b = \frac{F}{\pi Dt}(Pa) \qquad [1]$$

where:

F: applied force (N)

D: rock core diameter (m)

t: TSL depth or ring thickness (m)

Equation [1] can be further simplified as

$$\tau_b = \frac{F}{A} \qquad [2]$$

where:

A: core-TSL contact area (m2)

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

Results and analysis

Graphs of shear-bond strength against curing period for all products are provided individually in Appendix I. The averages of test results at each curing time are indicated on all graphs. Shotcrete is also tested and included in the results for comparison. Figure 7 is the summary of all results depicting the shear-bond strength development over the period of curing time.

Shear-bond strength behaviour between different products as well as different versions of the same product is clearly distinguishable. TSLs A and B are improved versions of TSLs C and G respectively. All the TSL products in the market show strength improvement over time as far as the 28-day limit is concerned. Shear-bond strengths can be clustered into three groups taking, the scale of strength into account, as illustrated in Figure 8. Groups I, II and III TSLs exhibit low, medium and high levels of shear-bond strengths respectively. The time-dependent strength increase in Group I TSLs is not as remarkable as for Group II and III TSLs. One reason may be the high water content of Group I TSLs that were prepared by mixing powder or cement with water. Shotcrete, which is prepared in a similar manner, falls interestingly in the same Group I. The powder material of Group II and III TSLs are normally mixed directly with polymer. Shotcrete lies at the lower boundary of the shear-bond strength scale. TSL K is an exception and the manufacturer of this product has changed the chemistry of the composition after receiving the test results, and the new composition has not been tested yet.

The deformation behaviour of TSLs is an important property and should also be measured and taken into account in assessing the performance of TSLs. Force-deformation results are available; however, they are not included in the analysis within the scope of this paper.

The shear-bond strength equations and correlation coefficients (R^2) for all products are listed in Table IV. The most suitable trend to represent strength improvement over testing period is found to be logarithmic. The strength equation and R^2 are determined by setting the trend lines to best fit all test results for a particular TSL. Correlation coefficients, other than low strength category products H and J, are reasonably high; therefore, the testing method confidently displays the strength improvement over the duration of 28 days. These coefficients for products C, E, F, G and K are, in particular, remarkably high.

Detailed statistics on test results in terms of mean strengths and standard deviations are summarized at each testing day in Appendix II. Standard deviations on Category III TSLs (A, B, C, D and E) are comparably higher than other categories, especially Category I TSLs. Percentage coefficient of variation (CV%) is used in Appendix II in order to arrive at a better parameter to measure the dispersion of strength values between the three strength categories. There is no

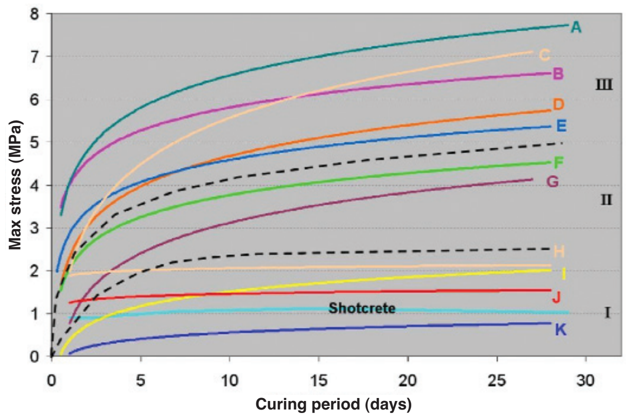

Figure 7—Shear-bond strength results

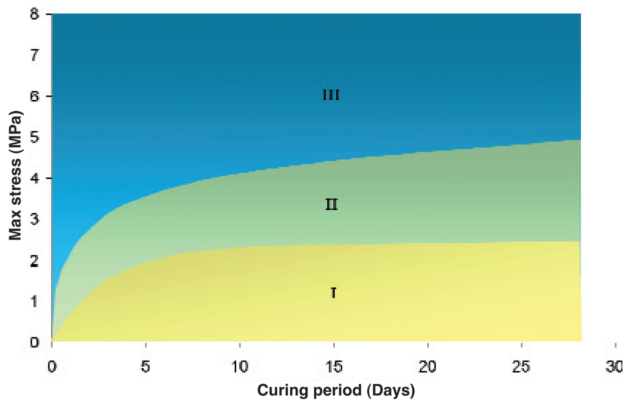

Figure 8—Shear-bond strength categories

Table IV

Shear-bond strength equation, correlation characteristics

TSL	Shear-bond strength equation	R^2	Rank category	Strength
A	1.09Ln(x) + 4.05	0.46	1	III High
B	0.77Ln(x) + 4.00	0.31	2	
C	1.45Ln(x) + 2.08	0.65	3	
D	1.05Ln(x) + 2.30	0.40	4	
E	0.71Ln(x) + 2.89	0.70	5	
F	0.74Ln(x) + 2.06	0.74	6	II Medium
G	1.02Ln(x) + 0.76	0.94	7	
H	0.08Ln(x) + 1.86	0.02	8	I Low
I	0.48Ln(x) + 0.47	0.59	9	
J	0.04Ln(x) + 1.30	0.01	10	
Shotcrete	0.05Ln(x) + 0.90	0.13	11	
K	0.21Ln(x) + 0.07	0.82	12	

definite trend in the spread of CV% over the testing period for all products. Some materials (B, C, F and H) show increasing CV%, while the remaining ones show decreasing CV% over 28 days. CV% of shotcrete remains noticeably around similar values.

Repeatability of testing method, somehow, could be assessed from the test results. However, repeatability comparison or judgement on repeatability would be possible only if similar data from other testing methods are available. Average CV%, taking into account the shear-bond strength test results done on all the TSL materials, could be used to quantify the repeatability. A simple 'repeatability index' could be calculated as:

$$RI = \frac{\sum CV\%}{N} \qquad [3]$$

Where:

$\Sigma CV\%$: is the sum of coefficient of variation percentages at each curing time for all tests, and

N: is the total number of curing times

Appendix II shows that ΣCV% is 1472.5 and N is 72 for all the tests and the repeatability index is calculated as 20.5. Currently, four other testing methods are being performed on TSLs by the author. In future research, the intention is to assess each testing method's repeatability by using the Equation [3].

Figure 9 shows the distribution of average CV% for each TSL material tested and the overall position of the repeatability index for the shear-bond strength testing method. If TSL D, which significantly differs from other TSLs in terms of its average CV%, is neglected the remaining TSLs vary between 8% and 27% on this average.

Failure mode

Failure of the core is not a concern since the rock core strength is not reached. The only failure takes place on the TSL-core contact surface, as seen in Figure 10a. Once the core is taken out it leaves a well-defined surface where shear debonding takes place (Figure 10b). The reason for having the failure particularly on TSL-core contact surface is that the support ring used allows movement only along this contact. Having consistent failure location for all TSL materials makes the interpretation of test results easier. Test set-up remains stable throughout the testing process as the failure elsewhere does not take place. Post failure behaviour is also easily observed.

Conclusions and recommendations

The proposed testing method is capable of measuring the shear-bond strength of TSLs taking into account the penetrating nature of TSL into the cracks on the applied rock surface. Therefore, the testing method approximates and

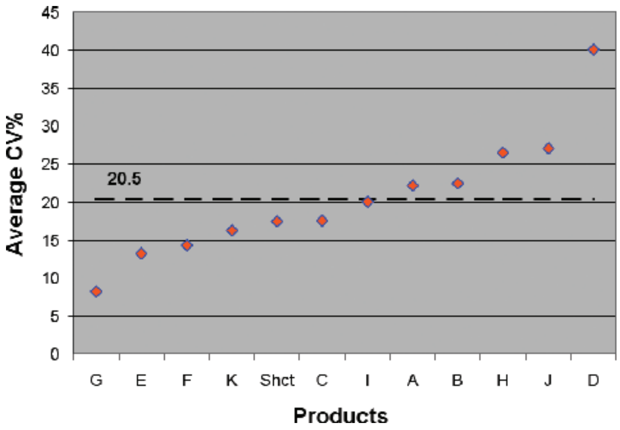

Figure 9—Distribution of average CV%

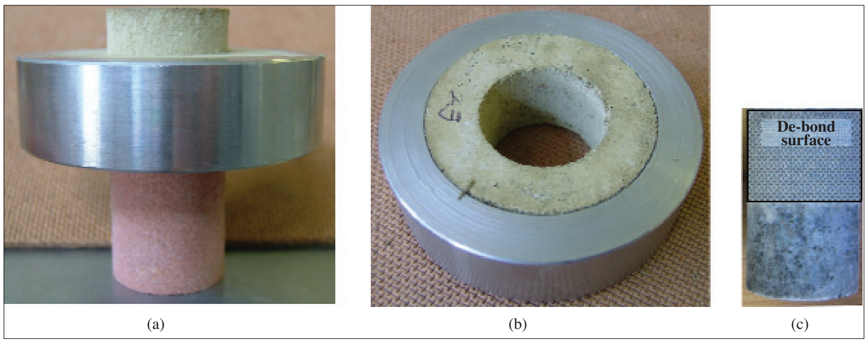

Figure 10—Failure mode (a) sample (b) TSL (c) core

relates to one mechanism of the *in situ* TSL behaviour. Testing also results in comparable shear-bond strength values between TSLs.

Components used during sample preparation are small and manageable. Therefore, sample preparation is quite simple, quick and low cost. The same test can easily be performed anywhere else with minimal difficulty due to its portable nature or simple components, which can be machined at any workshop. One of the aims of developing this testing method was reusing the cores and steel rings after cleaning TSL material. The task of removing any TSL, whether strong bonding or not, from substrate and steel ring is a simple and easy process.

Test execution, where loading takes place in a compressive manner along the core axis, is also simple. The maximum load required for shear-bond failure for high strength materials on 28-day tests is 20 kN. The deformation of TSLs is also measured; however, their analysis is not included in this paper.

The curing periods (1, 2, 4, 7, 14 and 28 days), substrate (norite), core diameter (27.6 mm), ring thickness (20 mm), ring diameter (inner: 52 mm, outer: 72 mm), support ring hole diameter (28.6 mm), loading rate (0.002 mm/s) were all fixed; however, the effect of varying each parameter as well as temperature and humidity on the results needs to be investigated further.

Strength increase over increasing curing time can easily be distinguished. High correlation coefficients of shear-bond strengths over the curing time show that the testing method developed is stable and repeatable.

One difficulty experienced during sample preparation is caused by quick setting TSLs where filling of the void between the core and ring becomes harder in a shorter period. Preparation of all the samples (30) would not be possible; therefore smaller amounts of TSL should be mixed to compensate for fast curing.

Shear-bond strength alone is not sufficient to make decisions on the quality or suitability of a TSL product; other material properties should also be blended in the decision-making process. Tensile, tensile-bond, material shear and uniaxial compressive strength tests are also performed and all of these results are going to be evaluated collectively in future publications.

Acknowledgements

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References

Archibald, J.F. Assessment of wall coating materials for localized wall support in underground mines. *Report of Phase 4 Investigations for the Mining Industry Research Organization of Canada* (MIROC), 1992. 34 pp.

Archibald, J.F. and DeGagne, D.O. Recent Canadian Advances in the Application of Spray-on Polymeric Linings, *Mining Health and Safety Conference*, April 2000, Sudbury, Ontario. 2000.

Archibald, J.F. 2001. Assessing acceptance criteria for and capabilities of liners for mitigating ground falls. *Mining Health and Safety Conference*, Sudbury, Ontario. 2001.

Espley, S., Tannant, D.D., Baiden, G., and Kaiser, P.K. Design criteria for thin spray-on membrane support for underground hardrock mining. Canadian Ins. Of Mining and Metallurgy Annual Meeting, Calgary. 1999.

Kuijpers, J. Evaluation of membrane support behaviour. *Surface Support Liners: Membranes, shotcrete and Mesh*. Australian Centre for Geomechanics, Perth. 2001.

Lewis, B. Mondi Rock-HoldTM the development of this structural membrane support. *Surface Support Liners: Membranes, shotcrete and Mesh*. Australian Centre for Geomechanics, Perth. 2001.

Naismith, W.A. and Steward, N.R. Comparative Performance Testing of Ultra-Thin Structural Liners. *2nd Int. Seminar on Surface Support Liners: Thin Sprayed Liners, Shotcrete, Mesh*. SAIMM, Sandton, South Africa, Sect. 18. 2002.

Saydam, S., Yilmaz, H., and Stacey, T.R. A New Testing Approach For Thin Spray-On Liners: Double-Sided Shear Strength (DSS). Test. *3rd International Seminar on Surface Support Liners: Thin Spray-On Liners, Shotcrete and Mesh*, Quebec City, Canada. Section 18. 2003.

Spearing, A.J.S. MBT's approach to thin support membranes in mines Underground Construction Group MBT International. Unpublished PowerPoint presentation. 2001.

Spearing, A.J.S., Ohler, J., and Attogbe, E. 2001. The effective testing of thin support membranes for use in underground mines. *Surface Support Liners: Membranes, Shotcrete and Mesh*, Australian Centre for Geomechanics, Australia. 2001.

Spearing, A.J.S. and Gelson, J. Developments and the future of thin reactive liners since the previous conference in Australia. *2nd Int. Seminar on Surface Support Liners: Thin Sprayed Liners, Shotcrete, Mesh*. SAIMM, Sandton, South Africa, Sect. 13, 2002. pp.1–10.

Stacey, T.R. Review of membrane support mechanisms, loading mechanisms, desired membrane performance, and appropriate test methods. *J S. Afr. Inst. Min. Metall.*, vol. 101, no. 7, 2001. pp. 343–351.

Stacey, T.R. and Kasangula, M. Results from Testing of TSL's Using a Simple, Low Cost Laboratory Test. *3rd International Seminar on Surface Support Liners: Thin Spray-On Liners, Shotcrete and Mesh*, Quebec City, Canada. Section 17. 2003.

Stacey, T.R. and Yu, X. Investigations into mechanisms of rock support provided by sprayed liners. Ground Support in Mining and Underground Construction, E. Villaescusa and Y. Potvin, (eds.) *Proc. 5th Int. Symp. on Ground Support*, Perth, Australia, A A Balkema, 2004. pp. 209–215.

Swan, G. and Henderson, A. Water-based Spray-on liner implementation at Falconbridge Limited. *Proceedings CIM/AGM*, Calgary. 1999.

Tannant, D.D. Large-scale pull tests on Mineguard Spray-on Liner. Report to INCO Ltd. Geomechanics Centre, Sudbury, Ontario, Canada. 1997.

Tannant, D.D., Swan, G., Espley, S., and Graham, C. Laboratory test procedures for validating the use of thin sprayed-on liners for mesh replacement. Canadian Ins. Of Mining and Metallurgy Annual Meeting, Calgary, published on CD-Rom, 1999. 8 p.

Tannant, D.D. Thin Spray-on liners for underground rock support. *17th Int. Mining Congress and Exhibition of Turkey*. IMCET 2001, E. Unal, B. and E. Tercan. (eds.) Ankara, Turkey, 2001. pp. 57–65.

Tannant, D.D. and Ozturk, H.U. Evaluation of Test Methods for Measuring Adhesion Between a Liner and Rock. *3rd International Seminar on Surface Support Liners: Thin Spray-On Liners, Shotcrete and Mesh*, Quebec City, Canada. Section 13. 2003.

Toper, A,Z., Kuijpers, J.S., Stacey, T.R., Yilmaz, H., and Saydam, S. Proposed Procedures for the Testing of TSL Properties. *3rd International Seminar on Surface Support Liners: Thin Spray-On Liners, Shotcrete and Mesh*, Quebec City, Canada. Section 14. 2003.

Brown, E.T. (ed.) *Rock Characterization Testing and Monitoring: ISRM Suggested Methods*. Pergamon, Oxford. 1981.

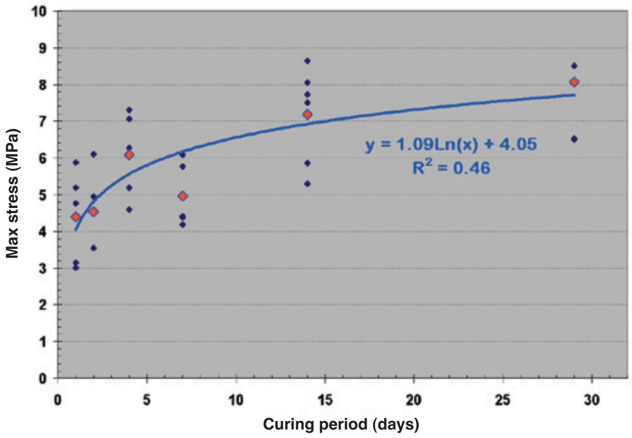
Wojno, L. and Kuijpers, J.S. Spray-on, user friendly and flexide support for mine excavations. *Proc. Int. Symp. on Rock Support*, Lillehammer, 1997. pp. 671–683.

Yilmaz, H., Saydam, S., and Henderson, D. Torque Testing of Thin Spray-on Liner Coated Cores. *3rd International Seminar on Surface Support Liners: Thin Spray-On Liners, Shotcrete and Mesh*, Quebec City, Canada. Section 15. 2003. ◆

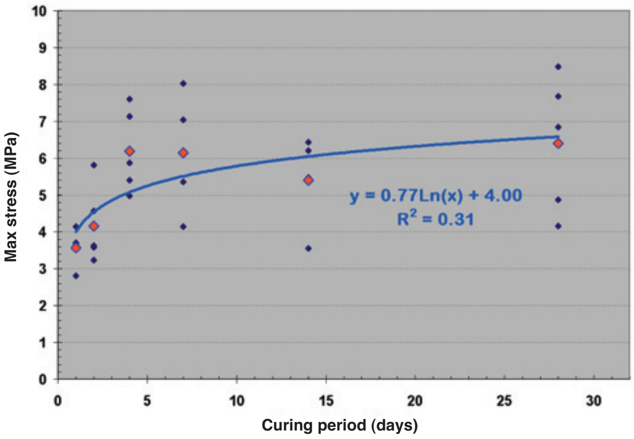
APPENDIX I

Test results

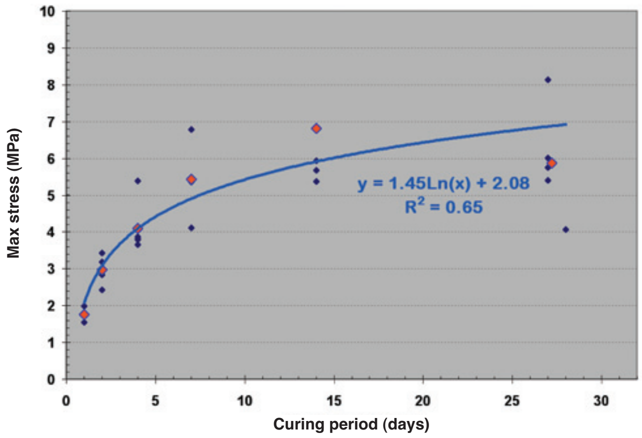
TSL A



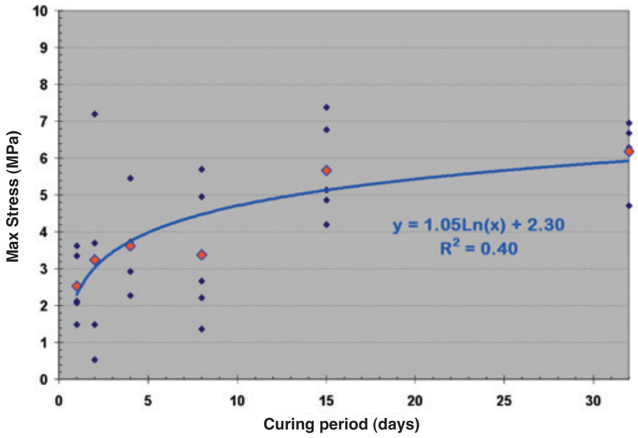
TSL B



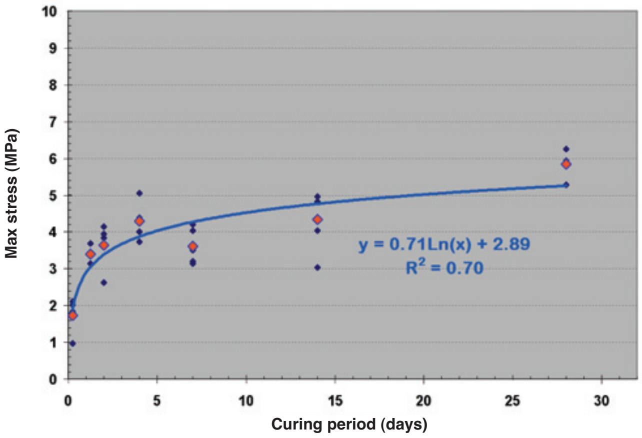
TSL C



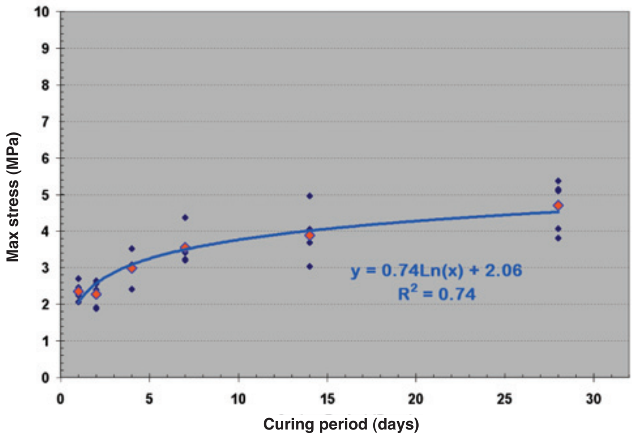
TSL D



TSL E



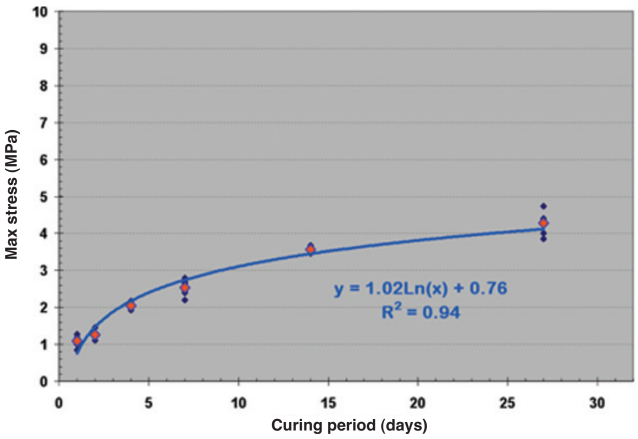
TSL F



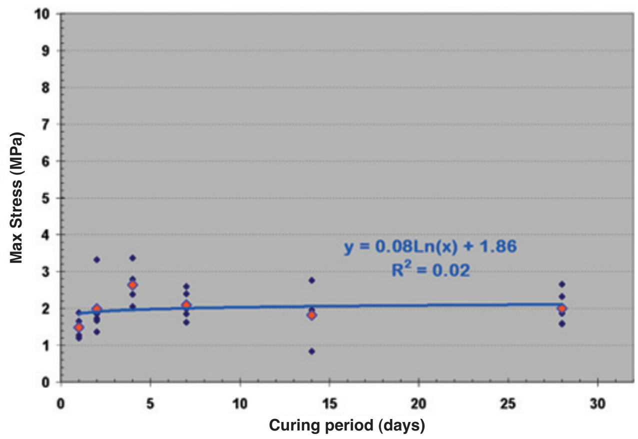
APPENDIX I (continued

Test results

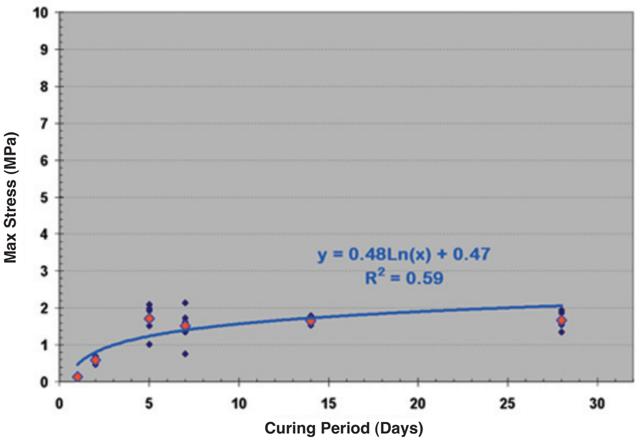
TSL G



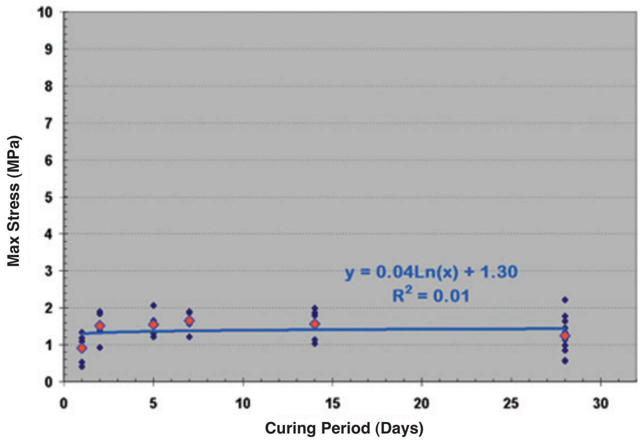
TSL H



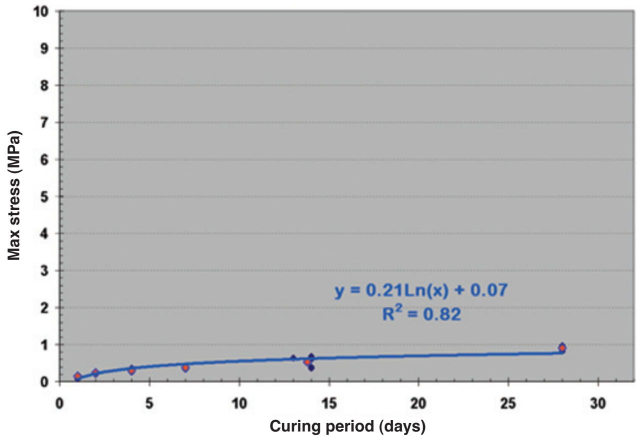
TSL I



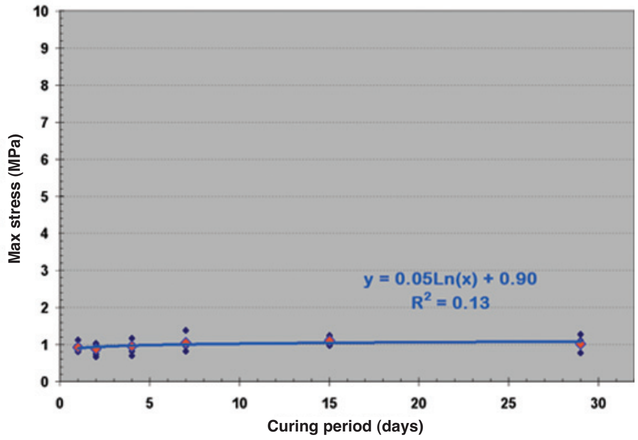
TSL J



TSL K



Shotcrete



Appendix II

Shear-bond strength test statistics

Mean (MPa)	St Dev (MPa)	CV (%)	Days	Mean (MPa)	St Dev (MPa)	CV (%)	Days	Mean (MPa)	St Dev (MPa)	CV (%)	Days
TSL A				**TSL E**				**TSL I**			
4.40	1.27	28.8	1	3.40	0.28	8.1	1	0.13	0.04	30.3	1
4.54	1.07	23.6	2	3.64	0.69	19.0	2	0.60	0.10	16.2	2
6.08	1.17	19.2	4	4.29	0.57	13.4	4	1.71	0.34	20.1	5
4.97	0.89	17.9	7	3.62	0.48	13.4	7	1.52	0.51	33.8	7
7.18	1.31	18.3	14	4.34	0.81	18.7	14	1.66	0.10	5.8	14
8.07	2.02	25.0	29	5.85	0.40	6.9	28	1.68	0.24	14.2	28
TSL B				**TSL F**				**TSL J**			
3.57	0.49	13.6	1	2.35	0.25	10.5	1	0.91	0.41	45.7	1
4.16	1.04	25.1	2	2.28	0.36	15.7	2	1.51	0.39	26.0	2
6.19	1.13	18.2	4	2.99	0.39	13.1	4	1.54	0.34	21.8	5
6.14	1.73	28.2	7	3.55	0.48	13.5	7	1.65	0.28	16.8	7
5.41	1.13	21.0	14	3.89	0.71	18.2	14	1.56	0.38	24.5	14
6.41	1.84	28.8	28	4.70	0.70	15.0	28	1.24	0.34	27.8	28
TSL C				**TSL G**				**TSL K**			
1.76	0.16	8.9	1	1.09	0.16	15.1	1	0.15	0.04	29.4	1
2.97	0.38	12.7	2	1.25	0.13	10.4	2	0.24	0.02	9.7	2
4.10	0.72	17.5	4	2.05	0.09	4.4	4	0.30	0.05	15.1	4
5.43	0.95	17.5	7	2.53	0.22	8.7	7	0.38	0.03	8.9	7
6.82	1.99	29.2	14	3.56	0.09	2.4	14	0.54	0.15	27.4	14
6.32	1.23	19.5	27	4.28	0.35	8.1	27	0.91	0.06	7.1	28
TSL D				**TSL H**				**Shotcrete**			
2.53	0.91	36.0	1	1.49	0.28	18.7	1	0.92	0.13	14.3	1
3.24	2.56	79.0	2	1.99	0.77	38.8	2	0.89	0.17	19.4	2
3.62	1.20	33.1	4	2.64	0.57	21.5	4	0.95	0.21	22.1	4
3.38	1.85	54.9	8	2.09	0.39	18.8	7	1.05	0.21	19.8	7
5.67	1.34	23.7	15	1.83	0.68	37.4	14	1.11	0.12	11.1	15
6.17	0.87	14.1	32	2.00	0.48	23.8	28	1.02	0.19	18.2	29

$\Sigma CV\% = 1472.5$
N = 72 (total number of curing times) = 12 TSLs x 6 curing times