STATIC TESTING OF SHOTCRETE AND MEMBRANES FOR MINING APPLICATIONS

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1 ABSTRACT

The Western Australian School of Mines (WASM) has developed a facility for the static testing of large scale ground support elements. The static test facility consists of several stiff steel frames used to support the sample and a screw feed jack for loading the sample.

A punch test method has been developed to assess the performance of shotcrete and membranes. Each sample is sprayed onto a rock substrate containing a loading disc. The sample is rotated 180 degrees, placed onto the sample frame and constrained on all sides. The loading disc is displaced at a constant rate by the screw feed jack which in turn loads the sample. Instrumentation is used to measure the load being applied to the sample through the loading disc and the displacements that occur.

The testing method is described in detail. Results from a number of different materials is presented and discussed.

2 INTRODUCTION

The principle of sprayed concrete was developed in the early 1900's for civil engineering construction applications. It was adapted to tunnelling applications in the mid 1950's and to mining applications in the early 1960's.

There have been significant technological advances associated with shotcrete materials and their placement over the last 20 years. These advances include improved mix design (e.g. the use of silica fume to improve cohesiveness), chemical admixtures (e.g. the development of alkali free accelerators), the development of steel and plastic fibres for internal reinforcement, and advances in the equipment used for placement.

Shotcrete usage in mining applications has increased significantly in recent years. Shotcrete provides a strong, continuous areal support for an excavation and therefore has the potential

to improve production rates and lower ground support costs compared with the placement of mesh. It is possible with shotcrete to have rock bolt patterns with wider spacings than those that are governed by the requirement to restrain mesh. It has been estimated that up to 40% more bolts are installed to restrain mesh than experience has shown are required to adequately reinforce the rock mass.

Spray on polymer liners (membranes) were first used as a form of surface support as early as the 1950's. Membranes are said to have the ability to replace mesh and shotcrete layers. Many test setups have been developed for membranes, but no standards of testing have been developed.

The Western Australian School of Mines has recently undertaken a test program on sprayed layers (shotcrete and membranes) at its recently developed Static Test Facility (Morton et al., 2007). The aim of the program was to develop a method to enable the testing of the sprayed layer as it would be placed in an underground environment at the actual thicknesses specified by site engineers. The results will enable the evaluation and comparison of support layers with different thicknesses and mix designs at various curing times.

3 SPRAYED LAYER SUPPORT MECHANISMS

The interaction between a deforming rock mass and a sprayed layer is very complex. The failure of a layer usually comprises of several failure mechanisms that are generally not well understood. Stacey (2001) went some way to explaining some of the individual failure mechanisms. He suggested that shotcrete and membranes provide support to the rock mass through the promotion of block interlock, the reduction of rock mass degradation by sealing dilated joints and the creation of an arching effect which transfers loads to bolts installed through the layer into the rock mass. These mechanisms generally rely on good adhesion between the sprayed layer and the rock mass. It is necessary for the layer to also have high shear strengths to provide effective areal support between the bolts installed around an excavation.

Studies by Holmgren (1976, 1998) and Fernandez-Delgado et al. (1976) showed that adhesion loss and flexure are the primary modes of shotcrete failure. A further review

conducted by Barrett and McCreath (1995) identified that shotcrete capacity in blocky ground, under static conditions, is governed by four mechanisms: namely, adhesion loss, direct shear, flexural failure or punching shear. These mechanisms are shown in Figure 1. The writers disagree with the definitions provided for Direct Shear and Punching shear. Direct shear occurs over a single plane and is not shown in these diagrams. Punching shear (shown as direct shear) occurs when an area pushes through the layer causing direct shear failure over the circumference of the area. The punching shear mechanism shown in Figure 1 is a mechanism of flexural failure and indicates the complexity of shotcrete failure mechanisms. Compressive failure, direct tensile failure and buckling are also mechanisms of shotcrete failure but will not be discussed in this paper.

Testing by Tannant et al. (1999a 1999b), and Archibald Mercer and Lausch (1992) indicate that membranes fail progressively through adhesion loss, followed by tensile failure of the material.

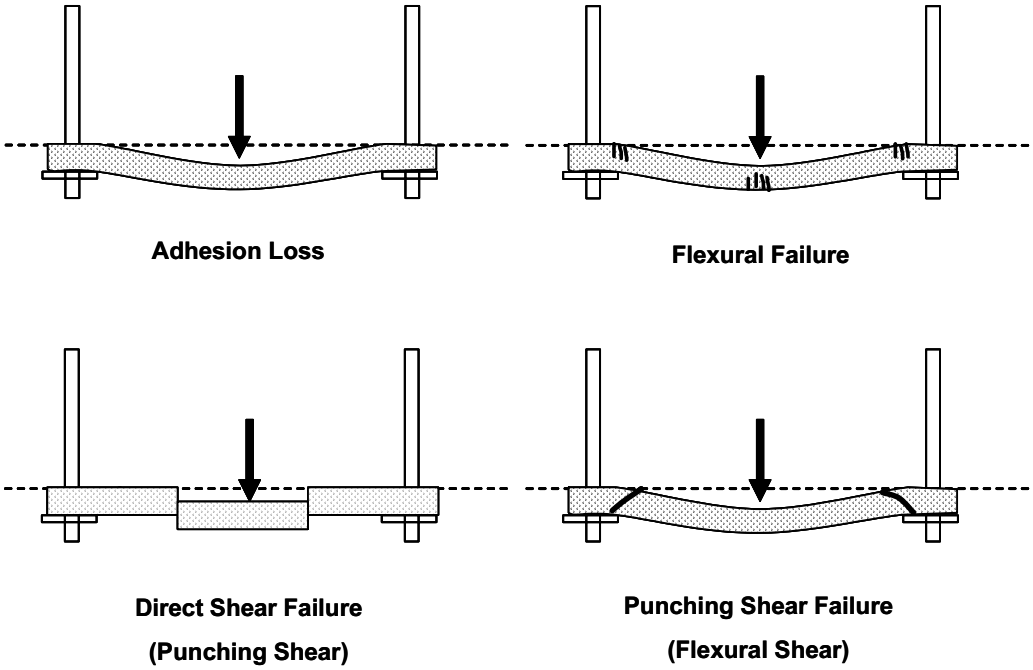

Figure 1: Shotcrete Failure mechanisms (Barrett and McCreath 1995)

4 SPRAYED LAYER USE IN THE MINING INDUSTRY

Surface support layers are used in mining in a variety of ground conditions. These conditions range from good rock masses, where surface support is required to control small scats that occur as a result of long term exposure, to highly stressed environments where the layer must attempt to improve the inherent rock mass strength by providing confinement at the boundary of the excavation. Where scat control is required, a thin layer of sprayed liner may be adequate. Some Australian mines specify 25mm of fibre reinforced shotcrete in these conditions to reduce rock mass degradation and maintenance. Shotcrete is also often used in good ground conditions to improve development rates. In order to achieve faster development rates, re-entry to headings is often required within a few hours of the shotcrete being sprayed. In some cases mines are specifying re-entry to headings 1 hour after spraying. This requires specific mix designs which have high early strength. These are often only possible with high accelerator dosages that are known to have a detrimental effect on the long term strength.

In high stress environments, thin layers are not adequate and multi-element support systems become necessary. Should the shotcrete confinement be insufficient to prevent failure, then high deformability and toughness are required to retain the rock mass after failure occurs. Full arches of shotcrete up to 150mm thick with mesh reinforcement may be specified to contain the broken rock mass and transfer load to the bolts through an arching effect.

Membranes are being promoted as a replacement for mesh and shotcrete (Potvin et al., 2004). Despite extensive research and marketing efforts, membranes have not been accepted as a suitable replacement for conventional surface support elements in the mining industry. The reasons for this are varied, though in general it has been shown that membranes are not capable of replacing conventional ground support other than in specialised circumstances where the rock mass demand is low.

5 STANDARD TESTING IN THE MINING INDUSTRY

Accepted standard protocols for shotcrete testing have been developed primarily in Europe (DIN, EN, EFNARC) and the United States (ASTM) and adopted throughout the rest of the world. Most of the standard protocols do not apply to mining situations. The most common

standard test methods used in the mining industry are UCS cylinders, the EFNARC tests (beams and panels) and the Round Determinate Panel (RDP) test.

The UCS test method is a quality control test that does not aid the understanding of shotcrete performance in mining applications. The cylinders are usually poured from the hopper and do not contain the accelerator that is added at the nozzle during spraying.

The EFNARC beam test and the RDP test methods only test materials at 75 – 100mm thickness. These tests are difficult to conduct on the actual sprayed product; accelerator dosages are often greatly reduced (in some cases to around 6% of the actual dosage) and realistic compaction is modified by the screening process. Furthermore, the mechanisms of loading and failure for these tests do not represent realistic loading conditions and responses for mining applications.

Many efforts have been made to develop standard test methods for membranes. In the 1970's Research was conducted by the United States Bureau of Mines (Schwendeman et al., 1972), the Mining Research Centre (a sub branch of the Department of Energy, Mines and Resources Canada) (Gyenge and Coates, 1973) and the Bureau of Reclamation (United States) (Graham, 1973). Much of this early test work involved small scale testing aimed at selecting the most appropriate polymer materials for potential surface support applications.

The idea of a plastic polymer gained favour again in the early 1990's with research being conducted worldwide in North America (Archibald Mercer and Lausch, 1992, Archibald, Espley and Lausch, 1999, Tannant et al., 1999a, Tannant et al., 1999b, etc), Europe (Spearing and Champa, 2001, Spearing, Ohler and Attigobe 2001, Spearing and Pretorius, 2006), South Africa (Stacey 2001, Kuijpers, 2001) and Australia (Finn et al., 1999).

Many test setups have been developed for membranes, including several forms of punch test; but as yet no standards of testing have been developed.

6 WASM STATIC TEST FACILITY

In 2005, the Western Australian School of Mines designed, built and commissioned a large scale static testing facility (Morton et al., 2007) to complement the WASM Dynamic Test

Facility (Player et al., 2004). This new static testing facility, shown in Figure 2, comprises two steel frames; a load bearing, upper steel frame used to provide a loading reaction for the screw feed jack and a lower frame used to support the sample. The screw feed jack is driven at a constant displacement rate of 4mm per minute. Load is applied to the sample through a spherical seat to a 300mm square, 35mm thick hardened steel plate.

The resistance force is measured using a load cell mounted on the shaft behind the loading point. A video recorder is used under the test frame to record the sample behaviour.

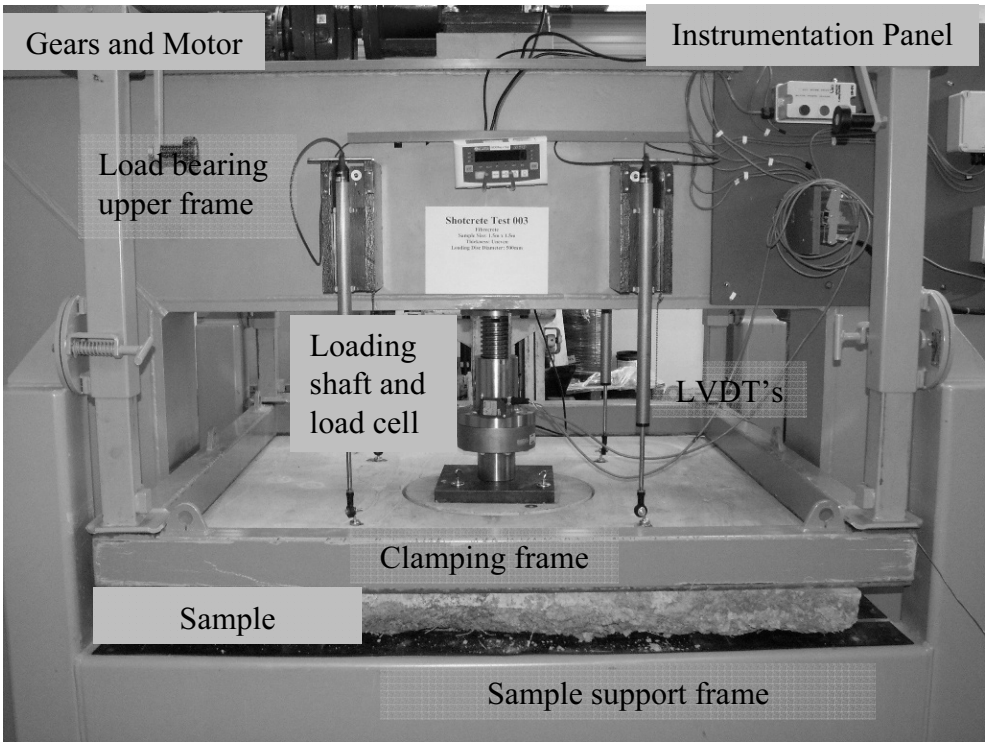

Figure 2: Static test facility

7 LARGE SCALE PUNCH TEST METHOD

7.1 Sample preparation

The Western Australian School of Mines has developed a large scale punch test method to investigate the combined reaction of adhesion and flexural strength. The method involves spraying a product over a thin substrate prepared with a centrally located disc that is cut and isolated from the surrounding substrate. After a specified curing period, the sample is placed on the test frame and load is applied by causing displacement of the disc.

Sandstone was selected as the most appropriate substrate due to its ready availability in slab form of various uniform thicknesses and its inherently rough surface texture. To prepare the substrate, a 500mm diameter disk is formed in centre of the slab by drilling through the slab with a special purpose diamond core bit. Figure 3 shows the substrate after the completion of drilling.

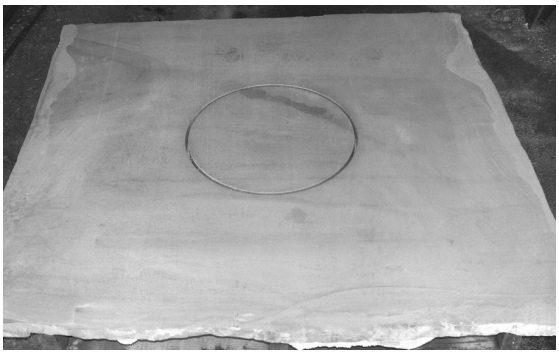

Figure 3: Sandstone substrate prepared for spraying.

A steel frame is attached to the sandstone substrate and the assembly is taken to site for placement of the sprayed layer. The bases are rotated to the steepest possible angle (given site restrictions and safety considerations) to prevent rebound build up and to provide more realistic spraying conditions.

The samples are first sprayed with water and then with the test material. The aim of the spraying is to place the material in a similar manner to that used underground. The standard accelerator dosage for the site is applied. The sample area of 1.5m x 1.5m cannot be sprayed without moving the nozzle; consequently a realistic sprayed result can be achieved. Due to the nature of the spraying process some unevenness in the thickness occurs. Where significant variations in thickness occur, the sample edges are levelled off to a distance of 150mm from the edge as shown in Figure 4. This action is taken to ensure the sample can be evenly supported on the boundaries. The central portion of the sample (1.25m x 1.25m) is not screened so as not to cause changes in the compaction of the sprayed shotcrete surface.

The membrane samples were not required to be screened due to the thinness of the layer.

Figure 4: Shotcrete sample after screening

After the samples have been sprayed, they are transferred to the laboratory and placed in a sea container specifically modified to enable a temperature and humidity controlled environment for curing. In cases where the samples were sprayed on site, the time period between spraying and storage varied between 2 and 12 hours. This is likely to have an effect on the sprayed product but cannot be avoided.

The temperature and humidity within the sea container are set to reflect conditions at the site where the sample was sprayed. This information was obtained from the site ventilation officer.

The samples are specifically not water cured as this may increase the hydration of the cement and result in a strength increase that would not normally be associated with mining applications.

The membrane tests were all sprayed on the same day and were cured for 7 days. Various curing times were applied to the shotcrete samples. These times are specified in the results.

7.2 Test Procedure

Immediately prior to testing the sample is removed from the curing chamber and the central axes are marked up. The sample is rotated 180 degrees about a horizontal axis so that the substrate is in the top position. The sample is then placed centrally on the test frame and boundary is lightly clamped. The steel loading plate is placed on the substrate disc and the jack is lowered to connect with the loading plate. Linear voltage displacement transducers (LVDT's) are attached to the substrate to enable the measurement of the deformation of the sandstone slab. The loading displacement rate is set to approximately 4mm per minute. The actual displacement rate is recorded by the data acquisition system. Testing is stopped once the sample has developed cracks approximately 20mm wide. After completion of the test, the crack pattern is drawn and the thickness of the layer is recorded at the position of the cracks.

8 TESTING RESULTS

A total of 10 shotcrete tests and 3 membrane tests were conducted using the test method described above. Four of the shotcrete tests were commissioning tests and, though they provided interesting observations, did not provide relevant results. All six shotcrete tests were conducted on mixes containing 6 kilograms of plastic fibres per cubic metre.

The force – displacement responses for 35mm, 60mm and 80mm shotcrete layers are shown in Figure 5. The force – displacement responses of the 3 membrane tests are shown in Figure 6. A comparison of shotcrete and membrane performance is shown in Figure 7.

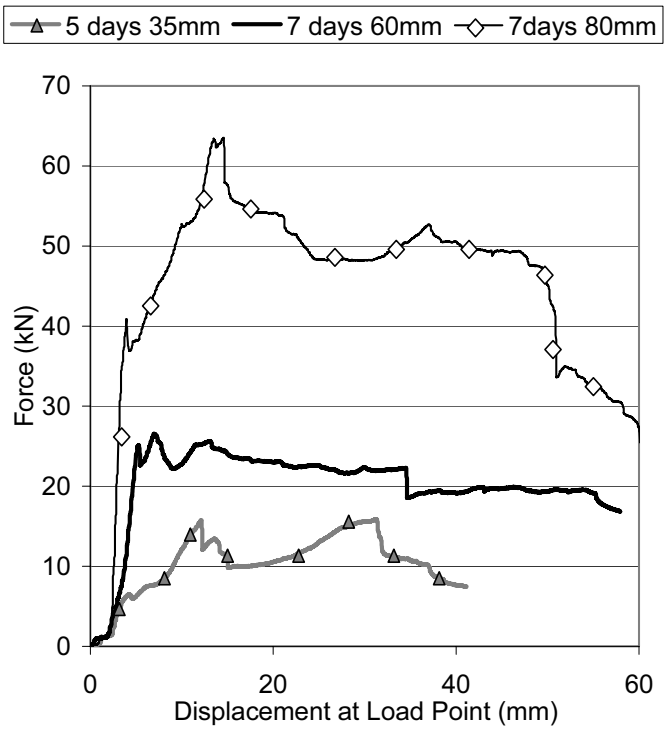

Figure 5: Shotcrete force-displacement responses

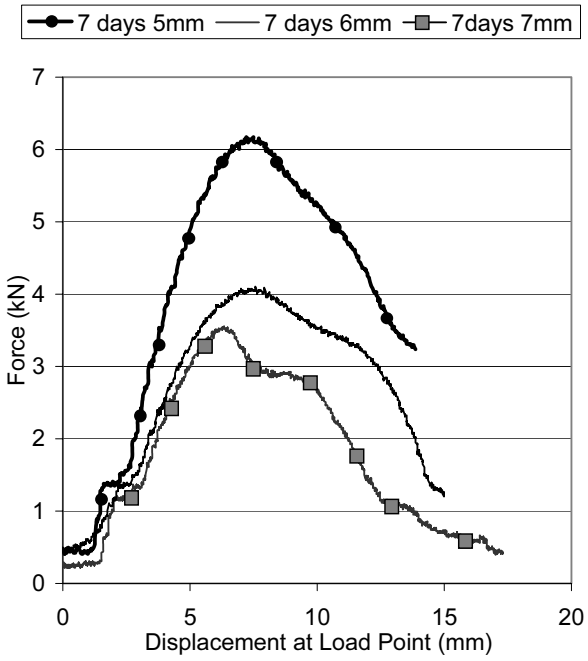

Figure 6: Membrane force-displacement responses

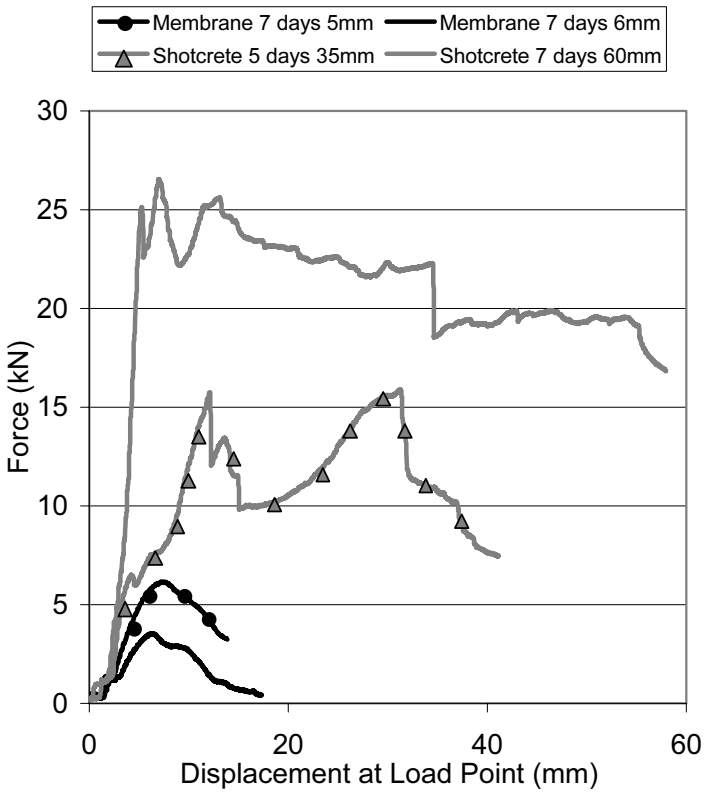

Figure 7: Comparison of shotcrete and membrane force-displacement responses

8.1 Observations

A number of critical observations were made during the testing. The shotcrete failure mechanism was a combination of adhesion loss and flexural failure. In most cases adhesion loss occurred some time after initial cracking. Observations from the shotcrete test program indicate that the first peak load corresponds to the breaking of the shotcrete matrix. Visible cracks are not discernable on the face of the sample at the time of first peak load.

The membrane performance was more plastic than the shotcrete layers with no clear peak load. The membrane exhibited a classic punching shear failure mechanism with minimal adhesion loss; this indicated that the low shear strength of the product governed the failure mechanism.

The LVDT results provided information regarding the deformation of the substrate and the extent of adhesion loss occurring between the sample and the substrate. The LVDT results from the membrane tests show between 1.5 and 2.5mm of deflection of the sandstone substrate (e.g. Figure 8) with no recovery of the sandstone during post peak testing.

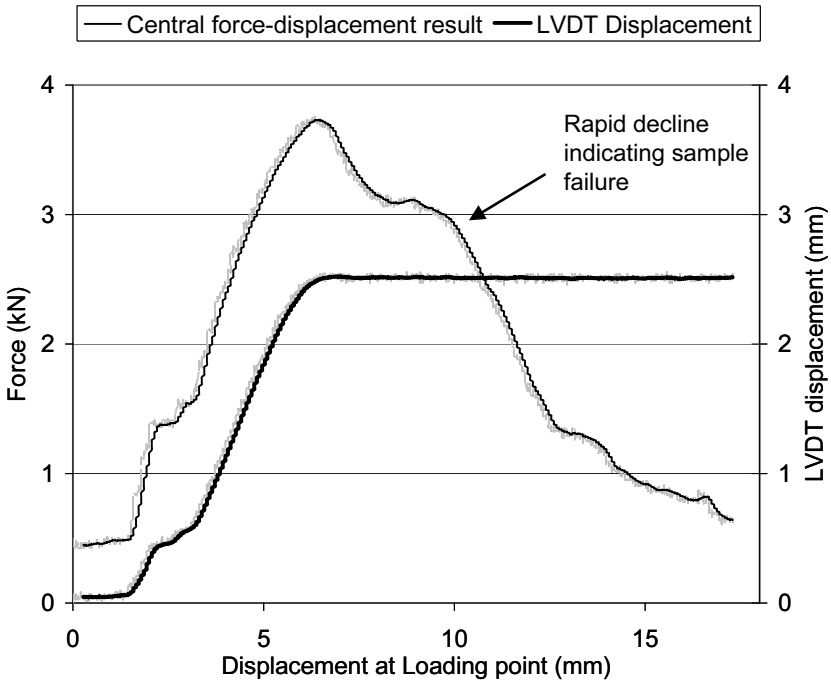

Figure 8: Membrane LVDT results

The LVDT results from the shotcrete tests clearly indicate the primary failure mechanisms. In cases where adhesion loss was the primary failure mechanism, the deflection of the substrate begins to recover as adhesion loss is propagated. An example of this effect is shown in Figure 9. The net deflection of the substrate, after adhesion loss is complete, is zero.

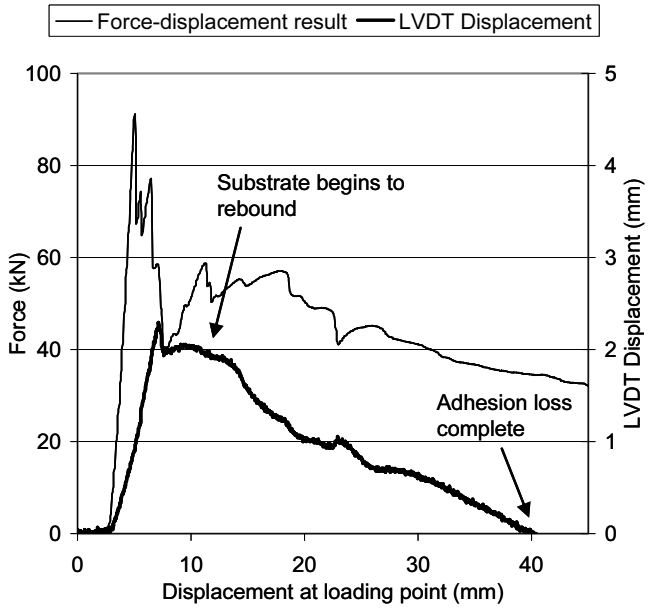

Figure 9: LVDT result where adhesion loss in the primary mechanism

The shotcrete tests where adhesion loss was not observed showed significant deflection, up to 35mm, in the sandstone substrate (e.g. Figure 10). Generally the sandstone substrate began to crack after 4 – 6mm of deflection of the substrate. The breaking up of the substrate greatly influenced the post peak results of the tests. Post peak analysis including energy calculations have not been undertaken due to this influence.

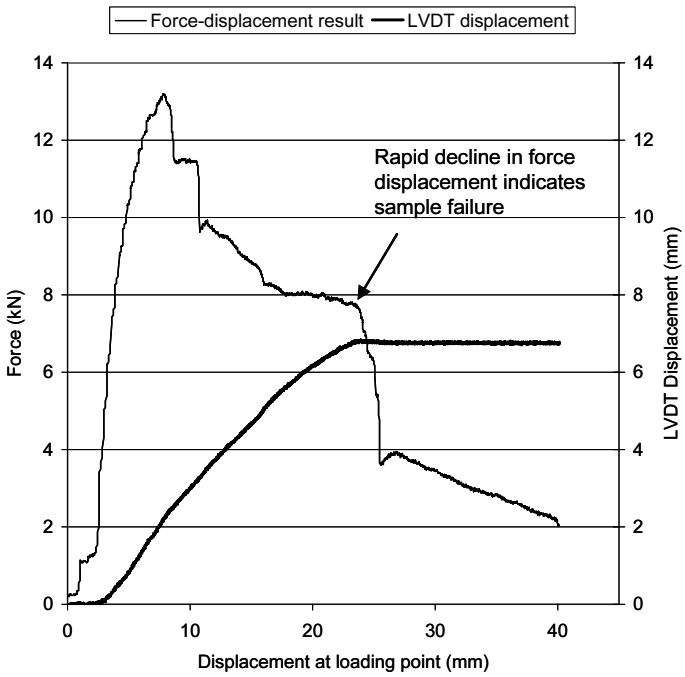

Figure 10: LVDT result where adhesion loss is minimal

Crack patterns were mapped at the completion of the shotcrete tests. Theoretical yield line crack patterns were not produced as a result of this test method. An example of the crack patterns from one test can be seen in Figure 11. Comparison of the test crack patterns with actual underground crack patterns (e.g.
Figure 12) show that the patterns are more realistic than the traditional yield line patterns.

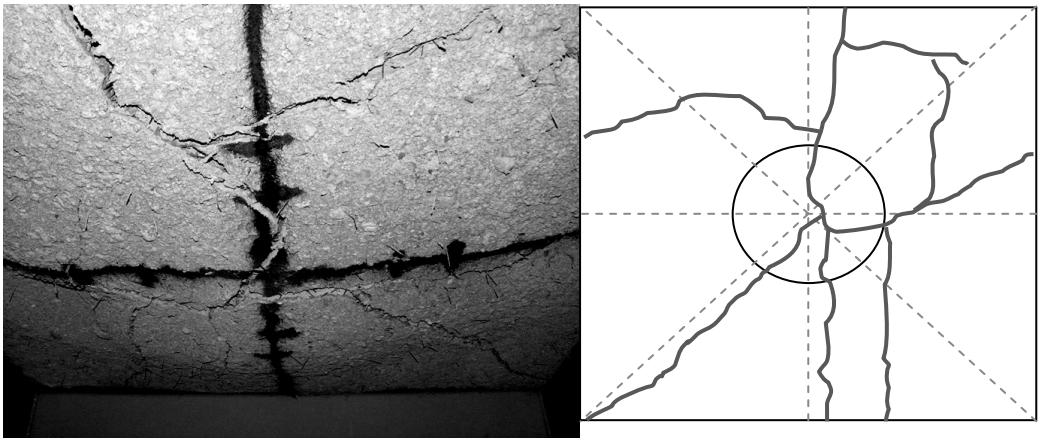

Figure 11: Crack patterns generated from a shotcrete test

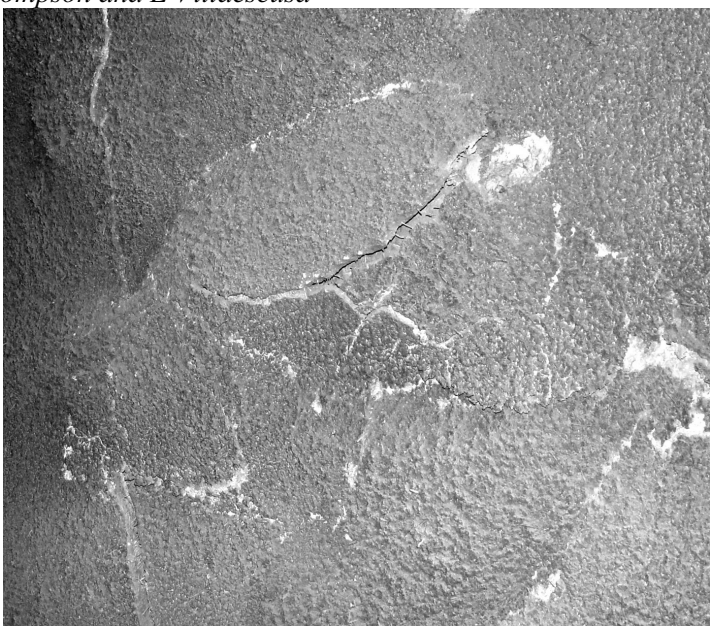

Figure 12: Crack patterns observed underground

9 CONCLUDING REMARKS

The WASM large scale punch test method is in the early stages of development but shows some promising results. Force-displacement responses can be used to gain an understanding of performance, and allow comparisons between, shotcrete and membranes. The results clearly show that the membrane product tested is not capable of replacing shotcrete in medium to high loading scenarios.

The membrane failure mechanism differed from published examples of membrane performance.

The shotcrete performance was very complex with several failure mechanisms occurring within the sample.

The LVDT measurements provide some indication of the effects of progressive adhesion loss that occurs during testing and the influence on the post peak force-displacement response.

The crack patterns generated using this method are more representative of observed underground reactions, than traditional yield line patterns.

The flexure and resulting cracking of the sandstone substrate complicates the post peak behaviour of the shotcrete and needs to be considered in the data analysis to improve the test method.

10 ACKNOWLEDGEMENTS

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11 REFERENCES

Potvin, Y, Stacey, D and Hadjigeorgiou, J (ed). 2004. Surface support in mining.

Archibald, J, Mercer, R and Lausch, P 1992. The evaluation of thin polyurethane surface coatings as an effective means of ground control. Rock support in mining and underground construction. Kaiser, P and McCreath, D (ed). Jun, pp. 105-115.

Archibald, J, Espley, S and Lausch, P 1997. Field and laboratory support response of spray on MINEGUARD polyurethane liners. International symposium on rock support. Applied solutions for underground rock structures. Broch, E, Myrvang, A and Stjern, G (ed). Jun, pp. 475-490.

ASTM C 1609 2006. ASTM C 1609/C 1609M - 06. Standard test method for flexural performance of fibre reinforced concrete (using beam with third point loading).

Barrett, S and McCreath, D 1995. Shotcrete support design in blocky ground: Towards a deterministic approach. Tunnelling and Underground Space Technology, Vol.10, No.1, pp. 79-89.

EFNARC 1996. European specification for sprayed concrete.

Fernandez-Delgado, G, Mahar, J and Parker, H 1976. Structural behaviour of thin shotcrete liners obtained from large scale tests. Shotcrete for ground support. Proceedings of the engineering foundation conference. Oct 4-8. ACI, pp. 399-442.

Finn, D, Teasdale, P and Windsor, C 1999. In-situ trials and field testing of two polymer restraint membranes. Rock support and reinforcement practice in mining. Villaescusa, E, Windsor, C and Thompson, A (ed). pp. 139-153.

Graham, J 1973. Polymer shotcrete. Use of shotcrete for underground structural support. Proceedings of the engineering foundation conference. July, pp. 418-435.

Gyenge, M and Coates, D 1973. The support mechanism of sprayed thin linings. Proceedings of the 8th Canadian rock mechanics symposium. Toronto 1972. Horn W (ed). pp. 101-117.

Holmgren, J 1976. Thin shotcrete layers subject to punch loads. Shotcrete for ground support. Proceedings of the engineering foundation conference. Oct, pp. 443-459.

Holmgren, J 1998. Shotcrete linings in hard rock. Australian shotcrete conference. Session 6. Bernard, S (ed).

Kuijpers, J 2001. Evaluation of membrane support behaviour. Section 21. International seminar on mine surface support liners: Membrane, shotcrete and mesh. August,

Morton, E, Thompson, A, Villaescusa, E and Roth, A 2007. Testing and analysis of steel wire mesh for mining applications of rock surface support. 11th congress of the International Society for Rock Mechanics. Ribeiro e Sousa, Olalla and Grossman (ed). Vol.2, July, pp. 1061 - 1064.

Player, J, Thompson A, and Villaescusa E, 2004. Dynamic testing of rock reinforcement using the momentum transfer concept. Ground Support in Mining and Underground Construction, 327-340, Balkema: Leiden.

Schwendeman, J, Sun, S and Salyer, I 1972. Plastic liners extended with sand and other fillers for use in coal mines. United States Bureau of Mines open file report.

Spearing, A and Champa, J 2001. Superskin - The present and the future. Section 16. International seminar on mine surface support liners: Membrane, shotcrete and mesh. August,

Spearing, A, Ohler, J and Attigobe, E 2001. The effective testing of thin support membranes (superskins) for use in underground mines. Section 26. International seminar on mine surface support liners: Membrane, shotcrete and mesh. August,

Spearing, S and Pretorius, H 2006. The development of a high strength thin support liner and two case studies. Golden Rocks 2006. 41st U.S. symposium on rock mechanics. June 17-21,

Stacey, T 2001. Review of membrane support mechanisms, loading mechanisms, desired membrane performance, and appropriate test methods. J. S. Afr. Inst. Min. Metall., Oct, pp. 343-351.

Tannant, D, Barclay, B, Espley, S and Diederichs, M 1999a. Field trials of thin sprayed-on membranes for drift support. 9th International congress on rock mechanics. Vouille, G and Berest, P (ed). Vol.2, pp. 1471-1474.

Tannant, D, Swan, G, Espley, S and Graham, C 1999b. Laboratory test procedures for validating the use of thin sprayed on liners for mesh replacement. Proceedings of the 101st CIM/ AGM. Calgary.