OPTIMISING THE SELECTION OF
FULLY GROUTED CABLE BOLTS IN
VARYING GEOTECHNICAL ENVIRONMENTS

ACARP PROJECT C22010

END-OF-GRA NT REPORT

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SUMMARY

The primary objective of this research project was to develop a laboratory-scale test facility in Australia that can be used to determine the behaviour and assess the load transfer performance of fully grouted cable bolts under axial loading conditions. The facility should be capable of testing the range of cable bolts available for use in the Australian coal mining industry under varying test conditions.

Work undertaken in recent years found a number of shortcomings with the current test developed and available in the U.K. These shortcomings made it difficult to draw firm conclusions concerning the performance of 14 cable bolts that were tested in that study. The lack of a locally available reliable testing method capable of assessing the extensive range of cable bolts has hamstrung geotechnical engineers in their ability to optimise the design of ground support systems from a cost and performance perspective at a time when mining conditions are increasingly more arduous and in response to continual drive to reduce operating costs.

As part of this ACARP project, a review was undertaken of the test methods developed for cable bolts. It confirmed there are several deficiencies in the range of tests that can impact on the integrity of some test results. For example, the tendency of some helical cable to unwind during a test induces an additional load on the cable bolt, grout and rock that can compromise performance and, the use of a steel pipe to confine a cable bolt that does not reflect conditions in the field.

The Laboratory Short Encapsulation Pull Test (LSEPT) forms the basis of the current British Standard and is the latest of testing methods. It was developed to suit a type of cable bolt that was prevalent in the British coal mining industry at that time but which is not necessarily suited to some of the modified, high capacity cable bolts developed since that time. A project recently funded by the Australian coal mining industry highlighted deficiencies in the LSEPT test and recommended the development of a modified or new test design that would address its shortcomings.

As part of this project, a new cable bolt testing facility based on the LSEPT test has been designed and commissioned together with a procedure capable of testing the full range of cable bolts including the high performance modified cable bolts available in Australia.

A series of tests was undertaken to gauge the sensitivity of several testing parameters. Many tests including the double-embedment test and the LSEPT comprise two sections; the embedment section where one length of a cable bolt is grouted into the borehole of a rock or test sample intended to model behaviour of the cable bolt in situ and, the gripping section that comprises the remainder of the cable bolt that is grouted in this case into a steel pipe or anchor tube.

With regards to the embedment section, previous work found the size of test sample can directly affect the load transfer behaviour of a cable bolt. Tests in this project found that the
size effect is a function of the type of cable bolt. While a cable bolt in the field is confined within an otherwise infinite rock mass, in the laboratory there is a practical limit to test sample size. Hence in order to ensure cable bolt performance is not compromised by the size of test sample, it was important to determine an appropriate size of test sample. In the worst case scenario of testing a modified high capacity cable bolt when the highest stresses are induced in the test sample the limiting sample diameter was found to be in the order of 300 mm above which there was little variation in performance. It was further found that variation in performance can be minimised by placing the 300 mm test sample within a large diameter steel cylinder, the latter providing passive confinement to the sample. This sample size is nearly double that currently used in the LSEPT test and uses a pressurised bi-axial cell to confine the test sample. Further, tightening of the bolts that join the two halves of the steel cylinder to a torque of 40 N·m provides a low but nevertheless consistent level of confinement to the sample.

A further point of difference to the standard LSEPT test is the embedment length of the cable bolt has been increased from 320 mm to 360 mm. This longer length is particularly important when testing some types of modified cable bolts with a long bulb length.

Another factor considered was borehole roughness. As expected this affected anchorage performance depending on the type of cable bolt tested and strength of test sample and whether failure occurred at the cable/grout or grout/rock interface. A technique was developed that can produce a manufactured rifled borehole in test samples that will provide consistent anchorage conditions.

Due to the much larger size of test sample, the samples are cast from a cement-mortar material rather than prepared from a cored sandstone sample. Variability in material properties can be reduced by mass casting of the samples. This approach has reduced the cost of sample preparation, ensures uniformity of material properties and importantly provides an ability to simulate rocks of differing strength such as coal and sandstone.

With respect to the gripping section, the effect of termination of the cable bolt was examined. During a test, load is gradually applied to the cable bolt via a constant displacement pump and hydraulic cylinder at the interface between the test sample and anchor tube. To minimise slippage of the cable within the anchor tube, various cable termination methods were examined such as the bail and wedge. It was found that a modified anchor tube with an internal machined thread and length of 600 mm prevented any slippage.

The final stage of the project involved a preliminary assessment of two types of cable bolt. This was to confirm the newly constructed axial-loading laboratory-scale testing facility could distinguish differences in the anchorage performance between two cable bolts at either end of the performance spectrum (a modified bulb cable and a plain strand cable), in materials of two different strengths (10 MPa and 60 MPa) and, in two different borehole diameters (the “as recommended” standard diameter borehole and a +10 mm diameter borehole).

As expected, a marked difference was found in the behaviour of the two cable bolts. The modified bulb cable was much stiffer and attained a high pull-out load. Once with the peak
load was reached, the load bearing capacity of the cable bolt reduced quickly to an insignificant level within the measured displacement range of 100 mm. Whereas the plain strand cable attained a much lower pull-out load however post-failure the cable bolt was able to provide a quite substantial level of load equivalent to 75% of the maximum load over the same range of displacement.

The strength of the test sample had a marked effect on cable bolt performance. For example, the maximum load of the modified bulb cable in the strong test sample material was almost twice that achieved in the weak or soft material. Conversely performance of the cable bolt in soft material was nearly half that in strong material. Hence performance of the bulb cable is sensitive to the properties of the host rock mass.

Finally regarding borehole size, surprisingly a larger borehole in weak rock improved performance of both cable bolts. It is thought the additional grout acts as a large diameter plug and in effect increases the surface area in contact with the test sample thereby increasing the effective resistance to load.

With respect to the revised proposal, all three project outcomes were achieved in this project, these being respectively.

1. To develop an axial-loading test procedure for cable bolts used in Australian underground coal mines.

2. To develop a laboratory-scale, axial-load test facility suitable to test cable bolt anchorage devices that can be used in Australian underground coal mines.

3. Complete a preliminary investigation of two cable bolts to enable some understanding of what range of testing would be appropriate in any subsequent research.
ACKNOWLEDGEMENTS

This project is part of a strategic research initiative at UNSW Mining Engineering to improve the design, performance and reliability of strata control systems for the benefit of the Australian underground coal mining industry and the people who work in the industry.

The funds provided by ACARP in this project have led to practical outcomes for industry in terms of:

- development of an up-to-date axial load test procedure suited to the types of cable bolts used in the Australian underground coal mining industry;
- establishment of a new axial-load test facility for cable bolts and assessment of its capability; and
- an initial evaluation of the performance of two types of cable bolts namely the MW9 and the Superstrand cable bolts that are used in the coal mining industry.

A number of people assisted in the design, construction and commissioning of the test facility and during the experimentation phase of the project. Their contributions to the project are acknowledged and appreciated. In particular, the assistance and guidance of the following Industry Monitors for this project is acknowledged.

- Peter Corbett, Centennial Coal
- Brian McCowan, Glencore
- Paul O’Grady, Glencore
- Dan Payne, BMA

Other persons who contributed to the project include

- Peter Craig, Jennmar Australia
- Kanchana Gamage, UNSW Mining Engineering
- Ron McKenzie, Megabolt Australia
- Ry Stone, Golders Associates
- Rob Thomas, Golders Associates
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Extract of published papers related to the project:

- The size effect of rock sample used in anchorage performance testing of cable bolts. Coal2014, February 2014 ................................................................. 88
- The load transfer mechanism of fully grouted cable bolts under laboratory tests. Coal2014, February 2014 ................................................................. 89
Consideration of the factors impacting on the design of the laboratory short encapsulation test for cable bolts. 8th Asian Rock Mechanics Symposium, October 2014 ................................................................. 91

Mechanical properties of cementitious grout serving in fully grouted cable bolting systems. AusRock2014, November 2014 ............................................................................................................. 92

The influence of concrete sample testing dimensions on assessing cable bolt load carrying capacity. Coal2015, February 2015 ............................................................................................................. 93
1 INTRODUCTION

A cable bolt is a flexible tendon consisting of a quantity of wound wires that are grouted in boreholes placed at predefined intervals that is intended to provide ground reinforcement in rock excavations (Hutchinson and Diederichs, 1996). They were initially introduced into the underground hard rock mining industry in the 1960s (Thorne and Muller, 1964) and were introduced a decade later to coal mining operations.

Originally, cable bolts were only intended as a temporary means of rock reinforcement. One reason for this being that many of the earlier cables were made from discarded steel ropes used in the mines which due to their smooth surface profile had very poor load transfer properties. They lacked the equivalent to ribs found on rockbolts. Over subsequent years a number of modifications were made to the basic plain strand cable, such as buttoned strand (Schmuck, 1979), double plain strand (Matthews, Tillmann and Worotnicki, 1983), epoxy-coated strand (Dorsten, Hunt and Kent, 1984), fiberglass cable bolt (Mah, 1990), birdcage strand (Hutchins et al, 1990), bulbed strand (Garford, 1990), and nutcage strand cable bolts (Hyett et al, 1993). These changes to the cable surface geometry were undertaken in an effort to improve the load transfer efficiency and anchorage capacity that as a consequence resulted in the more widespread use of cable bolts for permanent ground reinforcement. Furthermore, in order to clearly distinguish different characteristics of cable bolts used in the underground mining industry, Hutchinson and Diederichs (1996) proposed a cable bolt tool box as shown in Figure 1.

![Cable bolt tool box](image)

**Figure 1.** Cable bolt tool box (Hutchinson and Diederichs, 1996).
Despite these developments in design, failure of cable reinforcement systems still occurs. There are essentially five different failure types of cable bolting as illustrated in Figure 2, namely bond failure at the cable/grout interface, failure within the grout column, relative slippage at the grout/rock interface, failure within surrounding rock mass and rupture of the cable tendon itself (Jeremic and Delaire, 1983; Hutchinson and Diederichs, 1996). However, numerous laboratory and field tests show that breaking of the cables rarely occurs as it requires the shear resistance between the cable strand and the grouted surface of the strand being larger than the cable’s maximum tensile capacity, which is difficult to be realised in the field, especially under heavily jointed rock mass. Potvin, Hudyma and Miller (1989) pointed out that it is more likely for a cable bolt to fail at either of the cable/grout or grout/rock interfaces but more likely the cable/grout interface which is a function of the load transfer between the cable bolt and rock mass.

![Figure 2 Different failure modes of cable bolts (Hutchinson and Diederichs, 1996)](image)

Load transfer is a process resulting from differential movement within a rock mass, such as that caused by bed separation or movement along joint planes. It was originally defined as the mechanism by which force is generated and sustained in a supporting tendon as a consequence of strata deformation (Fabjanczyk and Tarrant, 1992). Later, Windsor (1997) modified this concept and indicated it is composed of three fundamental mechanisms: rock movement, which induces the transfer of load from unstable rock mass to the reinforcing tendon; transfer of load from unstable rock mass to interior stable rock mass by means of the reinforcing tendon; transfer of load from the reinforcing element tendon to the interior stable rock mass.

Based on the load transfer concept, the material used to bond the cable bolt to the rock mass surrounding the borehole, which is either a cementitious or resin grout, provides the mechanism for transferring force between the rock mass and the cable bolt by means of shearing forces within the grout. To be more specific, the shear stresses at the bolt/grout and grout/rock mass interfaces are responsible for the load transfer behaviour. However, due to the smaller contact area, the shear stresses at the cable/grout interface are generally larger than at the grout/rock interface. Therefore, assuming the rock mass and grout have similar
magnitudes of strength and the anchorage length is insufficient, failure is more likely to occur at the cable/grout interface. However, when the rock mass strength is relatively weak, failure is more likely to occur at the grout/rock interface.

In order to evaluate load transfer efficiency, both peak shear stress capacity and system stiffness need to be determined. Although values for these can be estimated, it is more usual to analyse the load versus displacement behaviour obtained from laboratory tests to study and compare the load transfer characteristics of cable bolts. In addition, the Load Transfer Index as proposed by Thomas (2012) can be used to evaluate the cable bolt load transfer capacity.

Hartman (2003) stated there are three sets of factors that have an impact on the rock tendon load transfer, including the reinforcing element system, rock mass and loading conditions. The following sections outline results of the effect of relevant parameters on cable load transfer together with the evolution in design of testing facilities showing the development in understanding the load transfer mechanism of cable bolts with respect to axial loading.

### 1.1 Project objectives

The project proposal outlined a staged approach to meet the overall aim of optimising the selection of fully grouted cable bolts in varying geotechnical environments. This has the advantage that it can better manage the risk of the project outcomes while meeting the needs of the Australian coal industry with the opportunity at the end of each stage to re-assess the value of the project outcomes and ensure the next staged outcomes are aligned with industry needs.

The following outcomes were defined for successful completion of the project.

1. A recommended axial-load test procedure for cable bolt anchorage applicable to Australian underground coal mines.
2. A recommended axial-load test facility suitable for the testing of cable bolt anchorage devices that can be used in Australian underground coal mines; and
3. Results of a preliminary investigation of the effect of different types of cable bolts anchors to enable some understanding of what range of testing would be appropriate in any subsequent research.

### 1.2 Approach

The methodology used in this project mainly included the following aspects:

- An extensive literature review within the area of load transfer performance on the various kinds of fully grouted cable bolts. The focus of the review was primarily on axial performance of cable bolts published in the past fifty years. A summary of the
literature review was published in the Proceedings of Coal Operators’ Conference, titled “The load transfer mechanisms of fully grouted cable bolts under laboratory tests” (Hagan, Chen and Saydam, 2014).

- Based on the literature review, a critical assessment was provided on previous testing methodologies. After that, a new robust axial testing rig overcoming the issues identified in earlier tests was proposed. An engineering consulting company, SOTO Engineering, was engaged to produce the engineering drawings consistent with the design brief to incorporate necessary safety features and be capable of meeting the load targets. They also sourced the engineering company and supervised construction of the testing facility.

- Tenders were called for the supply of a suitable hydraulic power pack that would achieve the required constant low displacement rate of the hydraulic cylinder of 0.2 mm/sec and be capable of operating over the very high pressures necessary with the hydraulic cylinder to achieve the high pull-out loads.

- Test samples were cast in cardboard moulds in the centre of which a tube was placed having a wound plastic pipe to achieve a consistent rifling effect in the borehole. A commercially available cementitious material was used to represent rock of two different strengths. A sufficient number of test samples were prepared from a single batch of material for each of the two strengths delivered to site in an “aggi” bowl truck for casting in the moulds. One day after being cast, the rifling tube and mould were removed and each test sample placed in a plastic bag and fully immersed to ensure consistent curing conditions. One of the two types of cable bolts, namely MW9 provided by Megabolt Australia Pty Ltd and Superstrand supplied by Jennmar Australia, was then placed in the rifled borehole of the test sample and grouted in place and later followed by grouting of the remaining top section of cable in the anchor tube using Stratabinder grout. The whole assembly was left to cure for a minimum of 28 days.

1.3 Information transfer to industry

As part of the knowledge transfer of the learnings from this project to industry, the following reports were produced during the project:

- Project Update: 15 April, 2014.
- Project Update: 6 June, 2014.
- Project Update: 25 September, 2014.

The following papers arising from this project have been published at various conferences as part of the information sharing and transfer strategy. In addition it is envisaged a number of papers will be published in several peer-reviewed journal publications.


2 RECOMMENDED TEST PROCEDURE

2.1 Introduction

Laboratory testing of the axial strength of cables bolts is performed by loading the fully grouted bolt system along the axis of the cable. The majority of the tests that have been developed to test the axial load capacity of cable bolts are derivations of the standard “split-pipe” test developed by Fuller and Cox (1975). The test involves applying a pulling force to induce failure in a cable bolt grouted into two separated pipes. Despite this commonality, there are differences in these testing methodologies that lead to significant differences in the final load capacity of the cable.

There are two fundamental types of testing techniques currently utilised in the industry, namely, unconstrained tests and non-rotating tests (Hutchinson and Diederichs, 1996). The simpler unconstrained tests, which allow the cable to rotate relative to the grout, tend to underestimate the load capacity of the bolts, while the more complex non-rotating tests, which restrict rotation of the cable, tend to overestimate the strength when compared with unconstrained pull test results. A comparison of the typical pull-out load versus the displacement graph of samples tested in unconstrained and non-rotating tests can be seen in Figure 3.

![Figure 3 Comparison between rotating and non-rotating tests (Bawden, Hyett and Lausch, 1992)]

Over the years, a multitude of different testing procedures and arrangements have been developed within these two types of testing techniques with the specific aim of determining, and potentially modelling, the effects of a variety of cable bolt system parameters on the overall axial strength of the bolts. The effects of the majority of these parameters, such as
water:cement (or w:c) ratios of grouts, borehole diameter, embedment length and cable geometries, have been comprehensively studied and are well known. However, there seems to be a lack of strength testing data comparing the range of cable bolts available in Australia. Pull-out tests have been conducted by Thomas (2012) but due to the consistency of the results and the omission of certain variables in the testing methodology such as varying confinement conditions, the results are inconclusive.

The following sections discuss the methodology and results of past and current laboratory programs for testing the pull-out strength of cables bolts.

### 2.2 Unconstrained single embedment pull tests

The single embedment pull test is the simplest method used in rock anchor testing. With this approach, one section of the cable bolt is embedded in a confining medium, such as a block of rock or a metal tube. While the other section is left free for a gripping device to apply a pulling load.

Testing conducted by Hyett and Bawden (1996) aimed to test the effects of bulb frequency of Garford cable bolts on the ultimate pull out capacity and they compared their results with results from previous plain stranded cable tests. Over 75 tests were conducted under this testing program that increased the validity and reliability of the results, and by extension the testing methodology used. The cables were embedded using a 0.4 w:c ratio grout at embedment lengths of 600 mm, 900 mm and 1800 mm and cured for 26 days. The grout was constrained under constant radial stiffness boundary conditions with the use of Schedule 80 steel pipes and Schedule 40 aluminium pipes.

This type of testing configuration was also used by Chen and Mitri (2005) during a testing program that aimed to determine the effects of embedment length, w:c ratio and borehole diameter on the pull out capacity of the standard seven-stranded cable. The testing methodology also used two different grouting materials, a cement based grout and polyester resin. The differential embedment length between the resin and cement samples, of 185 mm and 152 mm respectively, reduced the comparability of the pull out loads. This was exacerbated by the small number of resin based grout tests that were conducted, which rendered any specific magnitude of the pull out strength invalid, a problem that was identified by the researchers.

Aoki et al (2002) conducted long embedment pull tests to investigate the inconsistencies between the non-linearity found in in situ pull tests and linearity in short embedment length pull tests. The test consisted of grouting two types of cable bolts, namely standard plain strand and 0.5 m spaced bulbend strand, into 4 m x 1.2 m x 0.6 m testing blocks using a 0.4 w:c ratio grout. Two testing blocks were used to represent competent and poor quality rock mass conditions typically experienced in situ. A schematic of the testing apparatus is shown in Figure 4. In this case, the pull out load was applied at a rate of 10 kN/min.
Results from these tests revealed that the strength of the bulbed strand in Block A, that is meant to represent competent rock, was approximately 35% more than the strength of plain strand cable. While with Block B which represents weak rock conditions, showed almost no difference in the load capacities between the bolts. This was attributed to the low confining stiffness in Block B that provides little resistance to the dilation of the grout as the bulbed strand fails, resulting in similar pull out strengths to the plain strand.

Tests conducted by Mosse-Robinson and Sharrock (2010) used this testing methodology to evaluate the effect of large borehole diameters on different cable bulb densities and poor quality grout conditions. An Avery machine was used to load Garford cable bolts that were grouted into steel pipes to a depth of 1000 mm. Over the 37 different testing configurations were conducted with failure occurring either by decoupling at the grout-cable interface or rupturing of strands in the cable. They concluded there was no correlation between borehole diameter and load capacity. A similar result was earlier reported by Rajaie (1990) using plain strand cable bolts who conducted pull out tests with borehole diameters ranging between 20 mm and 60 mm.

It can be seen that the single embedment pull test has been used in the cable bolt anchorage testing in earlier studies. Although this kind of approach is recommended by the ISRM standard to test rock bolt anchorage (ISRM, 1985), it is not so sufficient for cable bolts. The main reason is that the free end of the cable bolt is likely to rotate during the pull-out process due to its helical surface geometry and low torsional rigidity. According to Stillborg (1984), the cable bolt within the embedment section is more likely to unwind from the confining medium when there is a short encapsulated length of less than seven times of the cable diameter, this will lower maximum pull-out load, a result consistent that shown in Figure 3.

2.3 Rotationally constrained tests

2.3.1 Split-pipe pull/push tests

The pioneering work regarding constrained axial tests on cable bolts was conducted by Fuller and Cox (1975). According to their design, two mild steel tubes were used to represent rock mass to confine the grouted cable bolt and a washer occurred in the middle (Figure 5),
representing the rock joint. Since the grouted length of cable bolts within the support section is longer than that in embedment section, failure would always occur in the lower part. By changing conditions in this testing section, influences of kinds of parameters such as embedment length, w:c ratios were studied.

Goris (1990) developed a similar pull test to examine the effects of single or multiple stranded cable bolt systems as well as the presence of breather tubes in the grout, the latter being an issue when grouting cable bolts up-hole. The pull out testing program was extended in 1991 to include determining the effects of standard cable modifications, such as birdcage geometry, steel buttons and epoxy-coated cables (Goris, 1991). The equipment set-up of the pull test was a modified version of the test arrangement developed by Fuller and Cox (1975), which incorporated a barrel and wedge anchor as a means of securing the cable from failure in the upper pipe.

The pull out testing was performed under constant radial stiffness boundary conditions in order to prevent rotational failure of the cable from the grout, which is highly likely with the helical surface profile of the cable bolt. However using this approach to restrict cable rotation is problematic as the steel pipe used to maintain constant radial stiffness has different stress-strain conditions than can typically be expected in rock, an issue that was identified in the report but not rectified. The embedment lengths for the testing side and anchored side of the split-pipe test were 300 mm and 500 mm respectively. A 28-day curing time was allowed for the grout using a w:c grout ratio of 0.45 taken as standard with no chemicals added to the grout mixture.

A hydraulic testing machine with a capacity of 180 tonnes was commissioned to separate the two halves of the sample at a rate of 15 mm per minute to a total cable displacement of 150 mm; with linear variable differential transformers (LVDT) and potentiometers used to measure the loads and displacement of the cable bolts. The results from the two testing programs performed by revealed the presence of two cables in the borehole increased the
capacity of the system two-fold, as well as, no significant influence of the breather tubes when filled with grout.

Later, as depicted in Figure 6, a laboratory-testing program was developed by Reichert (1991) to investigate the effects of cement characteristics, embedment length and the radial confinement of the cement annulus on the pull out strength of cable bolts. The test apparatus was designed as a modification of the standard split-pipe pull test developed by Fuller and Cox (1975) where the alteration involved pushing the grout surrounding the embedded cable, so as to incorporate variable confining stiffness pipes that would not have been feasible under the gripping mechanisms of the pull test. The validity of this modification was confirmed by comparing the two testing techniques and concluded that there was no significant difference in the peak loads between each test method.

![Figure 6 Modified push test apparatus (Reichert, 1991)](image)

The reasoning behind developing an alternate testing methodology was centred on the dissimilarities between previous laboratory pull out test results and equivalent *in situ* tests. Research conducted by Bawden, Hyett and Lausch (1992) revealed that there were significantly lower load capacity results obtained from short embedment *in situ* tests that were conducted at Golden Giant Mine in Canada, compared to the results from tests conducted in the laboratory using the Schedule 80 steel split-pipe test setup. Reconciling this discrepancy was achieved through the introduction of Schedule 40 aluminium and PVC pipes, which have lower radial stiffness properties than steel, as a means of representing variable *in situ* confinement conditions.
This testing methodology was used in further testing undertaken by Hyett and Bawden (1994) to establish and compare the performance of the 25 mm Garford cable with the standard plain strand cable bolt. The cables were embedded into steel and aluminium pipes using a 0.4 w:c ratio grout and loaded in a universal testing machine at a constant loading rate of 0.3 mm/s.

2.3.2 Modified split-pipe pull/push tests using a Hoek cell

A modification of the standard pull test was developed by Macsporran (1993) to test the effects of constant confining pressure on the axial strength of the cable bolt. Previous research conducted by Hyett, Bawden and Reichert (1992), revealed that higher bond capacities are exhibited in tests performed under high constant radial stiffness constraints through the use of grouted directly into small diameter steel pipes. The introduction of a modified Hoek cell into the testing apparatus aimed to overcome this problem by maintaining a constant confining pressure. A schematic of the test apparatus can be seen in Figure 7. The results from the test revealed a reduction in the bond strength and confining pressure when using the standard cable bolt. This is evident in the axial load versus displacement graphs for confining pressures ranging from 2 MPa to 15 MPa as shown in Figure 8.

A similar testing procedure was adopted by Moosavi, Bawden and Hyett (1996) which aimed to determine the performance of modified bolt geometries, specifically the Garford bulb and nutcase, on the ultimate pull out load of a cable bolt system. The comprehensive testing program measured the capacity of the cable bolts using two different confinement methods, namely constant radial stress and constant radial stiffness. The test used the modified triaxial Hoek pressure cell as described earlier (Macsporran, 1993; Hyett et al, 1995), to maintain constant pressure on the sample as well as aluminium and steel piping to maintain constant stiffness. They reported that as constant radial pressure confinement conditions decreased so did the peak load. While with the constant radial stiffness results, no significant difference was observed in the load capacity of either modified geometry cables.
2.3.3 Double embedment pull test

Hutchins et al (1990) devised the double embedment length test shown in Figure 9 to investigate the load transfer features of birdcage cable bolts. The newly devised testing method was different from the previous pull test methods in that it enabled the study of the effect of embedment lengths either side of the discontinuity on load transfer.

The performance of the birdcage cable bolt was compared to standard cable bolts and their results showed that the ultimate resistance of birdcage cables was much larger than that of standard cable bolts, indicating that the birdcage structure had a positive effect on load transfer. It was postulated that this was due to the increase in the cable cross sectional area that, in turn, increased the tendon-grout contact area. The effect of debonding was also studied whereby parts of the surface of the cable bolt were painted. In the case of standard cable bolts, the ultimate pull-out load decreased significantly. This reduction in load was not observed.
with birdcage cables; however, there was a reduction in the system stiffness. The effect of the node location relative to the discontinuity on the load transfer found there was little impact. It was suggested that birdcage cables could be best used to reinforce jointed rock mass, especially in pre-reinforcement cases where load transfer was acquired without using surface anchors.

A similar testing methodology was used in a testing program performed at the CSIRO Rock Mechanics Research Centre in Perth, which compared the cable performance of an Ultrastrand cable bolt with the plain and birdcage cable bolts (Renwick, 1992). The only difference between the apparatus used in their testing procedure to that used by Goris (1990) is the location of the loading points on the samples which are applied at both ends of the fully encapsulated cable bolt. This resulted in an effective embedment length of 1 m to 2 m. A schematic of the pull test setup is illustrated in Figure 10. Due to the inconsistencies between the embedment lengths of the birdcage and plain cables, which were twice as long as the Ultrastrand cable, the results are not directly comparable.

![Schematic of the dual loaded double embedment pull test (Renwick, 1992)](image)

Further work conducted by Martin and Pakalnis (2000) on the distribution of the load along a cable bolt also implemented the double embedment pull test. Only three pull tests were conducted on instrumented king wire cables, a modification to the standard cable bolt through the replacement of the king wire with a king wire containing strain gauges, which significantly reduced the reliability of the results and, by extension, the modification made to the cable bolt.
2.3.4 **Laboratory short encapsulation pull test**

Clifford *et al* (2001) developed the Laboratory Short Encapsulation Pull Test (LSEPT) as an adaption of the double embedment test. The testing setup is similar to the double embedment test except for the inclusion of an actual rock sample. It is identified confinement issues regarding the use of steel tubes in the double embedment test methodology with replacement of rock mass confinement conditions. This was claimed to significantly alter the performance of cable bolts compared to *in situ* rock mass conditions. Here one end of the cable bolt is embedded into a sandstone core, as opposed to steel piping, and applying a constant pressure from a biaxial cell to simulate a semi-infinite rock mass. This methodology was also adapted by Kent and Bigby (2001) for the Health and Safety Executive.

The LSEPT test methodology became the basis for the British Standard (BS7861-2, 2009) replacing the earlier used double embedment tensile test method. Bigby and Reynolds (2005) identified the double embedment performance testing methodology to be unsatisfactory in accurately representing *in situ* conditions and were described as “very artificial”. Differences in the results from testing resin grouted bolts concluded that the deviations between the LSEPT and the double embedment pull test can be attributed to the omission of the interaction between the borehole wall and grout in the double embedment tests.

![Figure 11 Schematic of the modified LSEPT pull test (Ito *et al*, 2001)](image)

A similar testing methodology was adopted by Ito *et al* (2001) shown in Figure 11 although it was never classified as a LSEPT. Two types of cable bolts, namely bulb and plain stranded cables, were axially loaded to failure using a hollow-ram jack with an anti-rotational device at a rate of 0.05 kN/min. The testing apparatus deviates from the LSEPT through the introduction of an artificial rock simulant to represent *in situ* rock mass confinement conditions. A 100 cm x 50 cm x 50 cm cement paste block was cast to allow embedment of
cables to a depth of 350 mm. The drilling procedure used to drill the borehole was applied to accurately replicate the drilling conditions experienced in the field to test the effects of borehole damage caused by drilling and borehole rifling.

The idea of testing the pull out strengths of short embedded cable bolts in artificial rock mass simulants was also used by Martin, Girard and Curtin (1996). Concrete blocks having a Uniaxial Compressive Strength (UCS) of 35 MPa were manufactured to confine Garford cable bolts using polyester resin as the grout material to a depth of 914 mm. They stressed that their results are only sufficient as a guideline due to the idealised, homogeneous nature of the concrete blocks, which is not representative of normal ground conditions.

One of the most recent adaptions of the LSEPT methodology was used to test the performance of the wide range of cable bolt that are currently available for use in the Australian coal mining industry. In this testing program, Thomas (2012) conducted a comprehensive testing program on 14 out of 15 of the different cable bolt configuration and geometries. The tests involved grouting the cable bolts to a depth of 320 mm in a diamond cored sandstone sample having a nominal UCS of 25 MPa and diameter of 142 mm at a loading rate of 10 kN/s. A modified version of the LSEPT testing apparatus was used that rectified some of the fundamental shortcomings regarding the application of the constant radial pressure borehole condition. Other issues identified included the unscrewing failure mechanisms of the cable bolts as the biaxial cell could not restrain rotation of the sample; application of a nominal 10 MPa confining stress which might not accurately model behaviour related to the magnitude of in situ borehole closure; and, the dynamic nature of the applied stress. As a result, the modified test apparatus replaced the pressure cell with a thick steel pipe that constrained rotation and introduced a constant stiffness boundary condition. A schematic of the modified LSEPT testing apparatus is illustrated in Figure 12.
2.4 Summary

In order to understand the axial performance of fully grouted cable bolts in the underground mining industry, a number of testing methods have been developed. However, it is generally accepted that unconstrained tests are relatively much better than rotating tests to study the load transfer behaviour of cable bolts due mainly to the advantage that it can prevent the helical cable bolt from unwinding during the pull-out process, which is a true reflection of cable bolt performance in the field.

In recent years, from among the different types of testing methodologies that have been developed, the LSEPT that is incorporated in the current British Standard has been regarded as the best method to evaluate the performance of cable bolts. It overcomes the behaviour resulting from confinement in metal tubes as used in either the split-pipe test or double embedment pull test. Even so, recent work has highlighted the shortcomings in this testing method. Firstly, the sandstone core used in the LSEPT has a diameter of only 142 mm, which is not sufficient to provide stable confinement for the high loads capable of cable bolts especially the large diameter, high performance modified bulbed cable bolts. As well, the biaxial cell is unable to prevent a cable bolt from unwinding during a test. Furthermore, the constant 10 MPa confinement provided by the biaxial cell does not reflect the underground field stress conditions as confinement around the grouted cable bolt may be dynamically variable within the service life of the cable bolt. Finally, although previous research has
already showed that the bearing plate does have an effect on the pull-out performance of cable bolts, this effect is not account for in the design.

Overall, while the current LSEPT has been the best development to date to assess the axial performance of cable bolts, it has a number of shortcomings. In consideration of these issues, a new testing procedure for the range of cable bolts used in the Australian underground coal mining industry should be developed based on the LSEPT that overcome the shortcomings.
3 DESIGN OF THE NEW AXIAL TEST FACILITY

3.1 Introduction

Design of the new axial loaded cable bolt test facility is based on the LSEPT as specified in British Standard (BS7861-2, 2009) but which overcomes the identified shortcomings for testing the wider range of available cable bolts on the market including high capacity modified bulb cable bolts. The new design is comprised of two sections, namely the embedment section and the cable anchor section. This is in line with the reinforcement model proposed by Freeman (1978) for grouted rock tendons as depicted in Figure 13 with at least one anchor section and a pick-up or embedment section.

![Figure 13 The fundamental concept of load transfer for grouted rock tendons (Freeman, 1978)](image)

3.2 Aspects of test facility design

3.2.1 Components of the test rig

The axis of the equipment is vertically aligned as shown in Figure 14. The test unit is comprised of the followings elements: embedment section; bearing plate; anchor section in a steel tube; and, terminating device. A double-acting hollow cylinder and specially designed electrically actuated hydraulic power pack are used to apply a load near the mid-point of the embedded cable bolt adjacent to the bearing plate. A load cell measures the actual load and three displacement transducers measure displacement. Detailed information regarding the important parts within this equipment is given in the following sections.
3.2.2 Dimensions of the anchorage test sample

Within this section the cable bolt is embedded in the test sample, the latter is intended to simulate conditions of a rock mass. While the BS7861-2, 2009 standard calls for the use of a 142 mm cylindrical sample of sandstone, a much larger cylinder of 300 mm diameter has been incorporated in the new design.

During testing of a cable bolt, the friction-dilation mechanism between the cable bolt and surrounding material is activated, leading to stresses being induced in the test sample. Given sufficient load being applied to the cable bolt, the resultant induced stresses in the test sample activated by load transfer may result in dilation and eventual radial cracking dependent on the size of the sample impacting on the load transfer performance (Chen, Saydam and Hagan, 2014). Previous work by Rajaie (1990) found a correlation between test sample diameter and maximum pull-out force of a cable bolt as shown in Figure 15 whereby the pull-out capacity increased with test sample diameter. He also observed a threshold diameter of approximately 250 mm above which there was no significant change in pull-out force and sample size no longer influenced the performance of the cable bolt.

Hence for the performance of a cable bolt to be independent of sample size effect, the sample must have a minimum diameter of at least 250 mm. Rajaie used in his test work a 15.2 mm plain strand cable bolt, whereas many cable bolts in use today especially high capacity cables, this minimum size may not be applicable due to increased dilation which has been verified by...
Holden and Hagan (2014). It is therefore appropriate to determine whether there is any further influence of test sample diameter on the pull-out force of modified cable bolts.

![Graph showing variation in pull-out force or bearing capacity of a plain cable bolt with size of test sample](after Rajaie, 1990)

Figure 15 Variation in pull-out force or bearing capacity of a plain cable bolt with size of test sample (after Rajaie, 1990)

Cylindrical test samples with five different diameters ranging from 150 mm to 508 mm were made using a cement-based material, examples of which are shown in Figure 16. The samples were cast with boreholes having a diameter of 42 mm and length of 280 mm for installation of a cable bolt. A Sumo cable bolt manufactured by Jennmar Australia was selected as it has one of the largest load transfer capacity used in Australian underground coal mining and therefore representing the worst-case scenario. In this way, the results obtained would be no less applicable to other lower load transfer cable bolts. The bulb with a diameter of 36.5 mm was located mid-way in the borehole. The cable bolt was grouted in the borehole using a polyester resin.

![Images of unconfined test samples and typical failure after loading of cable bolt](a) unconfined test samples (b) typical failure after loading of cable bolt)

Figure 16 Range of samples of increasing diameter used in unconfined tests

Single embedment pull-out tests were conducted with the samples, the arrangement shown in Figure 17. The arrangement comprised a hydraulic cylinder used to provide the axial pull-out force to the cable bolt during each test in which force and displacement were recorded with a
typical load/displacement characteristic graph shown in Figure 18. Note the test samples were tested in an unconfined condition.

![Figure 17 Fully assembled single embedment length pull-out test equipment.](image1.png)

**Figure 18** Performance of Sumo cable bolt in a 305 mm diameter test sample

Each test configuration was replicated three times with the results are summarised in Table 1 and the variation between pull-out load of Sumo cable bolt and specimen diameter is given in Figure 19. In most instances, the samples split with typically after three cracks formed.
Table 1 Variation in pull-out force with sample size

<table>
<thead>
<tr>
<th>Sample diameter (mm)</th>
<th>Mean pull-out force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>27.4</td>
</tr>
<tr>
<td>254</td>
<td>46.4</td>
</tr>
<tr>
<td>305</td>
<td>80.5</td>
</tr>
<tr>
<td>356</td>
<td>95.0</td>
</tr>
<tr>
<td>508</td>
<td>105.0</td>
</tr>
</tbody>
</table>

It can be seen from Figure 19 that the maximum pulling force of the Sumo cable bolt increases with the test sample diameter in a similar fashion to that observed by Rajaie (1990). A major difference in this case is that pull-out load continued to increase beyond 250 mm. Indeed, it is only after 370 mm had been reached that it is shown to have plateaued. The sample size tests were then repeated this time with each sample placed within a cylindrical tube corresponding to the sample diameter. This provides passive confinement to the sample that better reflects field conditions. The confinement resulted in a slightly elevated maximum pull-out load but more interestingly, it lowered the inflection point from 370 mm to approximately 300 mm corresponding to the new standardised diameter of test samples.

As to the construction of the test sample cylinder holder tube, Thomas (2012) stated that the bi-axial cell used in the British Standard has difficulty in dealing with the induced torque as the cable tends to unwind when under load. In place of a bi-axial cell, the new design incorporates a steel cylinder that provides passive confinement to the cementitious sample as shown in Figure 20. The cylinder is assembled by bolting together two half cylinder making it easier to disassemble after a test to remove and inspect the failure mode in the test sample.
3.2.3 Anchor tube

An anchor tube is used to secure the free-end of the cable bolt; the anchor tube grips the cable bolt preventing it from unwinding during the pull-out process. The anchor tube shown in Figure 21 has an internal diameter of 50 mm, which is sufficient to contain all types of cable bolts. In addition, a high strength cementitious grout with low viscosity is used to fill the gap between the internal surface of the anchor tube and the cable bolt. It should be noted that the internal surface of this anchor tube is threaded with a pitch of 2 mm and a depth of 1 mm to ensure good bonding contact between the anchor tube and the cable bolt, as depicted in Figure 22.
3.2.4 Bearing plate

The bearing plate is an important element in the test unit. Its purpose is to evenly distribute the axial pull-out load from the hydraulic cylinder across the full surface of the test sample. Importantly, the borehole size in the middle of the bearing plate has a crucial role in determining the failure mode of this cable bolting system. However, there is only limited research regarding the borehole diameter effect as indicted by Hagan (2004). Generally, it is common to see that in some tests the internal diameter of the bearing plate is of similar size as the rock tendon outsider diameter. As a result, the grout annulus within the borehole is constrained by the bearing plate and failure must occur at the bolt/grout interface. This arrangement does not simulate reality where there is no confinement around the cable bolt at the surface of a discontinuity where the ground separates. In fact, there is no restriction around the borehole when a rock joint develops between the embedment and anchor length in reality (Thomas, 2012), hence the bearing plate used in the laboratory should have a larger internal hole diameter compared to the borehole size.

On the other hand, Khan (1994) had earlier suggested that if the internal hole of the bearing plate was too large (over 100 mm bigger than the cable bolt diameter) then it would have an adverse impact on the results as shown in Figure 23.

![Figure 23 Effect of hole diameter in the bearing plate on pull-out load (after Khan, 1994)](image)

Considering these problems, a bearing plate with an internal diameter of 70.4 mm is used as shown Figure 24. Since the largest borehole within all tests is limited to 50 mm, there is a minimum difference of 20 mm between the borehole diameter and the internal hole diameter of the bearing plate, allowing the grout column and concrete surrounding the borehole to be liberated. By this means, different failure modes of the cable bolting system that commonly occur in the field can be studied (Jeremic and Delaire, 1983).
3.2.5 Anti-rotation devices

Cable bolts when under load can untwist, freeing itself from the confining medium and thus result in a lower pull-out force. This can be prevented successfully within the embedment length by locking the thick-wall steel tube that confines the cementitious sample to the anchor tube via a keyway and a locking key as shown in Figure 25. As the bearing plate is prevented from rotation with respect to the sample holder tube by two keyways, the whole system within the anchor length section can move along the axial pull-out direction but is constrained from rotation.
3.3 Test sample preparation

3.3.1 Casting and curing of test samples with rifled borehole

Cardboard cylinders were used as moulds to make the test samples. Each cylinder had a length and internal diameter of 450 mm and 300 mm respectively as shown in Figure 26.

![Figure 26 Profile of a cardboard casting cylinder](image)

The cylinder was glued using silicon to a wooden base plate to provide a waterproof seal. The board also provided a flat surface during testing for the bearing plate. In the centre of each cylinder was placed a hollow plastic pipe around which was wound a plastic tube with an outer diameter of 5 mm and a pitch of 20 mm as shown in Figure 27a. The purpose of this was to create a rifled borehole within the sample as shown in Figure 27b.

![Figure 27 Rifling tube assembly](image)

A foam mix was used to fill the internal space of the tube as shown in Figure 28 and fasten it to the base plate. The fully assembled casting mould with rifling tube is shown in Figure 29.
A single batch of cement-based mortar was delivered in a 5 m$^3$ mixer oraggi bowl truck to cast all the test samples of a given strength as shown in Figure 30.
The samples were placed on a basement frame and moved to an area to set, as shown in Figure 31.

![Figure 31 Newly cast test samples](image)

A standard commercial mix was used for each of the two sample strengths as listed in Table 2.

<table>
<thead>
<tr>
<th>Name</th>
<th>Product Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated strength (MPa)</td>
<td>10 (weak) 30 (strong)</td>
</tr>
<tr>
<td>Cement (kg/m³)</td>
<td>365 650</td>
</tr>
<tr>
<td>Fly ash (kg/m³)</td>
<td>- 150</td>
</tr>
<tr>
<td>Fine Sand (kg/m³)</td>
<td>1000 1025</td>
</tr>
<tr>
<td>Admixture (ML/m³)</td>
<td>- 1600</td>
</tr>
<tr>
<td>Admixture (ML/m³)</td>
<td>1000 -</td>
</tr>
<tr>
<td>Admixture (ML/m³)</td>
<td>- 3520</td>
</tr>
<tr>
<td>Water (litre/m³)</td>
<td>400 300</td>
</tr>
</tbody>
</table>

1. Hanson Construction Materials

A total of 50 test samples were cast as shown in Figure 32a. After curing for 48 hours the rifling tube was extracted from each test sample. Because of difficulties in extraction, the tubes should be removed after no more than 24 hours. The outer cardboard casing was also removed and each sample placed in a large plastic bag filled with untreated tap water and secured for the remaining 28 days of curing as shown in Figure 32b. Full immersion in water ensures a more consistent level of cement hydration during the curing process and hence consistent material properties between each test sample.
As the rifling tube was fixed to the base plate in the centre of each casing during casting of the test samples, the rifling borehole consequently extended for the full height of each sample. After the an curing period of 48 hours and the rifling tube was extracted, each sample was up-ended and the borehole back-filled with cement to reduce it to the pre-determined embedment length for cable bolt testing of 320 mm as shown in Figure 33a. During backfilling, the borehole length was measured to confirm sufficient cement had been added to achieve the required borehole length as shown in Figure 33b.

A general purpose cement was used to backfill the boreholes with a w:c ratio of 0.55. This ratio was a compromise between desired strength and low viscosity. To ensure the rifling spirals in the upper section of the borehole were not filled during the pouring process, the cement was poured down a plastic tube that was lowered into the borehole.
3.3.2 Cable bolt and anchor tube installation

The samples shown in Figure 34 were cured for a minimum of 28 days.

![Figure 34 Fully cured test samples](image)

Two types of cable bolts were used in the project: Superstrand manufactured by Jennmar Australia and, MW9 manufactured by Megabolt Australia as shown in Figure 35 and Figure 36. Each cable bolt had an overall length of 1180 mm.

![Figure 35 Profile of the Superstrand (top) and MW9 (bottom) cable bolts](image)

![Figure 36 Dimension of MW9 cable bolt with a special ending plate attached](image)

During the installation process, the cable bolt may tilt and/or move to one side in the borehole. To prevent this from occurring, a special clamp made from angle iron welded to a heavy base was manufactured as shown in Figure 37. Together two clamps were used to centre and ensure vertical alignment of the cable bolt during curing as shown in Figure 38.
Figure 37 The special clamp designed to ensure alignment of the cable bolt in the borehole during the curing process

Figure 38 Twin set of clamps assembled for holding and aligning the cable bolt

Prior to installation the top surface was troweled to ensure an even top surface as shown in Figure 39.

Figure 39 a) Level check at Position 1 with levelling instrument
A Stratabinder grout having a w:c ratio of 0.42 with a strength of 60 MPa was poured into the borehole close to the top section, as shown in Figure 42. Then the cable bolt was inserted into the borehole and rotated to mix and ensure good coverage between the cable bolt and grout as shown in Figure 43.
The alignment clamps were then added to fasten the cable bolt and make sure that the cable was installed properly in the middle of the borehole as is shown in Figure 44. After the grout within the borehole set for at least half an hour, half of the clamps could be removed and one metal block was used to grip the cable bolt, as shown in Figure 45. After curing for 12 hours, the clamps were removed and used to grout another cable bolt as shown in Figure 46.
After the Stratabinder grout had set for at least 24 hours, the anchor tube was installed over the remaining exposed cable bolt. It should be noted that top section of the anchor tube was wrapped with a plastic tape to prevent the threads around the top of the anchor tube being fouled by the grout as shown in Figure 47. The w:c ratio of the Stratabinder used in the anchor tube section was slightly less at 0.38 to achieve a higher strength of 70 MP.

As the cable bolt is a flexible tendon, special attention was required to ensure the cable bolt was located in the centre of the anchor tube. A small wood wedge was installed between the anchor tube and cable bolt after pouring of the Stratabinder grout into the anchor tube as shown in Figure 48.
Similar to the method to secure the cable bolt in the test sample, clamps were used to secure the anchor tube as illustrated in Figure 49.

It should be noted that the MW9 cable bolt has a hollow tube in the middle seen in Figure 50 and considering this, the Stratabinder grout was poured into the middle hollow tube using a funnel as shown in Figure 51. The Superstrand had no middle tube and no special treatment was required.
With the cable bolt grouted into the test sample and anchor tube, the assembled samples were left for 28 days to fully cure as shown in Figure 52.
3.3.3 Hydraulic power pack and data logging system

The bearing plate was placed on the top surface of the test sample with the anchor tube in the centre. A key locking nut coupled outside surface of the bearing plate to the split steel containment cylinder while a second keyway on the inside of the bearing plate locked the bearing plate to the anchor tube. The hydraulic cylinder was seated on the bearing plate followed by the distribution plate, load cell, abutment plate and finally the reaction plate. An LVDT was attached to a frame to measure displacement during the pull-out process. At the same time, a Micro Pulse magnetostrictive non-contact linear position transducers was attached to measure the axial displacement of the top of the cable bolt. The arrangement of the different elements is shown in Figure 53.

![Figure 53 Front (left) and side (right) views of the testing rig showing three types of displacement transducers](image)

It should be noted that the reference point for the LVDT was the reaction plate rather than the cable bolt. Since the reaction plate is threaded and attached to the top of the anchor tube, the LVDT can only measure displacement of the anchor tube. Therefore, if there is no slippage between the anchor tube and the cable bolt, the measured value is the pull-out displacement of the cable bolt. However, if any slippage does occur between the anchor tube and the cable bolt, the measured value does not reflect the true displacement of the cable bolt. Considering this issue, a Micro-Epsilon displacement sensor which is a non-contact laser radiation instrument as shown in Figure 54 was fixed on the top area of the test frame. The measuring point of this laser radiation is on the cable bolt and hence measures the pull-out displacement of the cable bolt.
One item discussed at the March 2014 meeting of the ACARP Industry Monitors was the topic of control systems, an important factor in developing a standardised testing method. Two possible options were considered of force control and displacement control. It was recommended that displacement control be used as had been done earlier in the Canadian research and because it is the simpler of the two options. It was recommended to target a constant displacement rate of 0.3 mm/sec so that failure should occur within an approximately 15 minute period.

Consideration has been given to various hydraulic system designs. At this stage, the simplest and least expensive design entailed a constant speed pump unit. The other more complicated and expensive option is a servo-control system incorporating a feedback loop between hydraulic cylinder and pump control. A special hydraulic cylinder would also be required for this option that incorporates a displacement transducer. The constant displacement pump and controller unit are shown in Figure 55. The system includes a valve in the return line that acts as a hydraulic dampener since during the preliminary cable bolt test, slight oscillations in the load were detected that were probably due to a lack of back pressure in the hydraulic cylinder circuit when under load.
resultant load on the cable bolt was recorded together with the displacement. The LabVIEW software package was used to record the measurements during tests.

### 3.4 Testing process

#### 3.4.1 Strength determination of anchorage test sample materials

During the casting process of the test samples, additional specimens were made for strength determination. Two cement products were selected based on recommendations made by Hanson Construction Materials that would match the two desired rock types having equivalent strengths of 10 and 30 MPa – designated as low strength material (LSM) and medium strength material (MSM) respectively. Details of the two products are listed in Table 3.

<table>
<thead>
<tr>
<th>Nominal strength</th>
<th>10 MPa - LSM</th>
<th>30 MPa - MSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete grade</td>
<td>Non-standard</td>
<td>32</td>
</tr>
<tr>
<td>Product code</td>
<td>YN1.5MPA</td>
<td>GS32250</td>
</tr>
<tr>
<td>SAP number</td>
<td>10056269</td>
<td>10007731</td>
</tr>
<tr>
<td>Type</td>
<td>Grout CHT/FS/FLW35S</td>
<td>Grout PMP 32/SND/250</td>
</tr>
<tr>
<td>Nominated slump</td>
<td>Flow 35 s</td>
<td>250 mm</td>
</tr>
</tbody>
</table>

Two shapes of test specimen were prepared, these being cylinders and cubes. The cylinders had dimensions of 54 mm diameter and height of 134 mm consistent with the ISRM requirements for UCS testing of rock core sample as shown in Figure 56a. The cubes had equal dimensions of 50 mm consistent with Australian Standard testing of soil samples as shown in Figure 56b. Five specimens were prepared for each combination of specimen type and strength, in all a total of 20 specimens.

As in the case of the test samples, all the strength test specimens were submerged in tap water during the 28 day curing period prior to the strength tests. All tests were conducted using an MTS 815 Universal Compressive Test machine as shown in Figure 57a and Figure 58b at a constant displacement rate of 3 μm/s.

The stress-strain graphs for the two sets of LSM specimens are shown in Figure 59 and a summary of test results provided in Table 4 and Table 5 for the cube and cylindrical
specimens respectively. The results were more consistent in terms of the stress-strain graph for the cube specimens that also registered a slightly higher average strength value of 11.4 MPa compared to that achieved with the cylindrical specimens of 9.2 MPa. This higher strength result is consistent with previous comparisons between the two specimen shapes. The tests confirm the material is within the ballpark range of strength required for cable bolt testing of the weak or soft material of 10 MPa.

Figure 57 Testing of the cube specimens

Figure 58 Testing of the cylindrical specimens
Table 4 Strength test results for LSM cube specimens

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
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<tbody>
<tr>
<td>1</td>
<td>28.82</td>
<td>11.5</td>
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<tr>
<td>2</td>
<td>29.69</td>
<td>11.8</td>
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<tr>
<td>3</td>
<td>28.54</td>
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<tr>
<td>4</td>
<td>30.61</td>
<td>12.1</td>
</tr>
<tr>
<td>5</td>
<td>28.12</td>
<td>11.1</td>
</tr>
</tbody>
</table>

*mean* 11.4

Table 5 Strength test results for LSM cylindrical specimens

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
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<tbody>
<tr>
<td>1</td>
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<td>9.77</td>
<td>4.28</td>
<td>0.15</td>
</tr>
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<td>2</td>
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<td>8.82</td>
<td>3.54</td>
<td>0.12</td>
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<td>3.42</td>
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<td>3.19</td>
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<td>20.19</td>
<td>8.93</td>
<td>2.97</td>
<td>0.12</td>
</tr>
</tbody>
</table>

*mean* 9.2 3.5 0.12

The stress-strain graphs for the two sets of MSM specimens are shown in Figure 60 and a summary of results provided in Table 6 and Table 7 for the cube and cylindrical specimens respectively. For this material, the opposite was observed with the cylindrical specimens displaying more consistent results for the stress-strain curves. Again, the average strength of the cube specimens of 64.5 MPa was slightly higher compared to the cylindrical specimens of
62.8 MPa. In this case, the material is found to be of much higher strength than was originally intended for the medium strength material.

![Stress-strain graphs](image)

a) Stress-strain graph for the cube MSM specimens  

b) stress-strain graph for the MSM cylindrical specimens

Figure 60 Stress-strain graphs of the MSM specimens

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>142.38</td>
<td>62.3</td>
<td>11.57</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>145.10</td>
<td>63.5</td>
<td>11.99</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>143.21</td>
<td>62.3</td>
<td>11.91</td>
<td>0.27</td>
</tr>
<tr>
<td>4</td>
<td>144.71</td>
<td>64.7</td>
<td>12.46</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>139.98</td>
<td>61.2</td>
<td>12.14</td>
<td>-</td>
</tr>
</tbody>
</table>

**mean** 62.8 12.0 0.27

3.4.2 Strength determination of cable grout material

Stratabinder was selected as the grout material for embedment of the cable bolt in the borehole and anchor tube due to its low shrinkage and low viscosity. Hence, it has a greater
propensity to flow between the cable strands improving the bond between cable and test specimen. Two different strengths of Stratabinder grout were used having different w:c ratios.

As the cementitious grouts used in Australian underground coal mines commonly has a strength of about 60 MPa, this was chosen as the grout strength of the embedment length in the test sample. To ensure strong bonding of the cable in the anchor tube, the grout strength was slightly higher at 70 MPa.

Data provided by Orica (2014) shows the variation in strength of Stratabinder with water ratio as shown in Figure 61. A w:c ratio of 0.45 should equate to a strength of 60 MPa. In order to confirm this value, strength tests were conducted on specimens with different w:c ratios to determine the w:c ratios to be used.

Figure 61 Variation in strength of the Stratabinder grout with water content (after Minova, 2014)

Based on the grout strength variation relationship indicated in Figure 61, four different w:c ratios were tested, namely 0.35, 0.38, 0.42 and 0.45. Cube and cylindrical specimens were prepared with the Stratabinder material as shown in Figure 62 and Figure 63 respectively. All specimens were cured under similar conditions as previous strength tests fully submerged for 28 days. Dimensions for both cube and cylindrical specimens are shown in Table 8 and 9.

Figure 62 Cube specimens
Table 8 Dimensions of the cube specimens

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
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<td>49.91</td>
<td>49.92</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50.32</td>
<td>50.01</td>
<td>50.04</td>
</tr>
<tr>
<td></td>
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<td>50.48</td>
<td>50.05</td>
<td>50.01</td>
</tr>
<tr>
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<td>50.23</td>
<td>50.26</td>
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<td>50.49</td>
<td>50.17</td>
<td>50.16</td>
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<td></td>
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<td>50.37</td>
<td>50.25</td>
<td>50.35</td>
</tr>
<tr>
<td></td>
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<td>50.22</td>
<td>50.18</td>
<td>50.23</td>
</tr>
<tr>
<td></td>
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<td>0.42</td>
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<td>50.39</td>
<td>50.12</td>
<td>50.34</td>
</tr>
<tr>
<td></td>
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<td>50.28</td>
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</tr>
<tr>
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<td>50.19</td>
<td>50.15</td>
<td>50.17</td>
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<td>50.39</td>
<td>50.12</td>
<td>50.34</td>
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<td>5</td>
<td>50.50</td>
<td>50.17</td>
<td>50.23</td>
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</table>
Table 9 Dimensions of the cylindrical specimens

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Length (mm)</th>
<th>Diameter (mm)</th>
<th>L/D ratio</th>
</tr>
</thead>
<tbody>
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<td>0.35</td>
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<td>139.90</td>
<td>53.85</td>
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</tr>
<tr>
<td></td>
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<td>140.96</td>
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</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<td>141.08</td>
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<td>2.64</td>
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<td>2.65</td>
</tr>
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<td>2.64</td>
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<td>53.29</td>
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<tr>
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<td>53.65</td>
<td>2.61</td>
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<td>53.98</td>
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<td>53.87</td>
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<tr>
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<td>140.72</td>
<td>53.30</td>
<td>2.64</td>
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<td>139.55</td>
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<td>53.69</td>
<td>2.61</td>
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<td>5</td>
<td>141.12</td>
<td>53.85</td>
<td>2.62</td>
</tr>
</tbody>
</table>

Water:cement ratio of 0.35

The stress/strain relationships of both cube and cylindrical specimens are shown in Figure 64 while the corresponding values are given in Table 10 and Table 11 respectively.

![Figure 64 Stress/strain curves for specimens with w:c ratio of 0.35](image)

a) cube specimens  
b) cylindrical specimens
Table 10 Stress/strain values of cube specimens with w:c ratio of 0.35

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Area (mm²)</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>1</td>
<td>2512.47</td>
<td>179.76</td>
<td>71.55</td>
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<tr>
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<td>3</td>
<td>2526.52</td>
<td>175.83</td>
<td>69.60</td>
</tr>
<tr>
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<td>5</td>
<td>2526.57</td>
<td>163.38</td>
<td>64.67</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td>68.6</td>
</tr>
</tbody>
</table>

Table 11 Stress/strain values of cylindrical specimens with w:c ratio of 0.35

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>1</td>
<td>145.56</td>
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<tr>
<td></td>
<td>2</td>
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<td>62.81</td>
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<tr>
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<td></td>
<td>63.1</td>
<td>11.8</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Water:cement ratio of 0.38

Figure 65 Stress/strain curves for specimens with w:c ratio of 0.38

Figure 65 illustrates the stress/strain relationships of both cube and cylindrical specimens with a w:c ratio of 0.38. As for the corresponding values, they are given in Table 12 and Table 13 respectively.

Table 12 Stress/strain values of cube specimens with w:c ratio of 0.38

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Area (mm²)</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>1</td>
<td>2531.09</td>
<td>153.62</td>
<td>60.69</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2527.58</td>
<td>161.56</td>
<td>63.92</td>
</tr>
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<td>170.70</td>
<td>67.79</td>
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<tr>
<td>mean</td>
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<td></td>
<td></td>
<td>64.1</td>
</tr>
</tbody>
</table>
Table 13 Stress/strain values of cylindrical specimens with w:c ratio of 0.38

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
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<td>130.14</td>
<td>58.46</td>
<td>11.57</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>117.74</td>
<td>52.87</td>
<td>9.95</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>145.47</td>
<td>64.57</td>
<td>11.01</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>58.6</td>
<td>10.8</td>
<td>0.20</td>
<td></td>
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</tbody>
</table>

Water:cement ratio of 0.42

When w:c ratio is 0.42, the stress/strain relationships of both cube and cylindrical specimens are shown in Figure 66 and the corresponding values are given in Table 14 and Table 15 respectively.

Table 14 Stress/strain values of cube specimens with w:c ratio of 0.42

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Area (mm²)</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
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<td>2527.58</td>
<td>143.40</td>
<td>56.73</td>
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<td>2533.59</td>
<td>152.73</td>
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<tr>
<td></td>
<td>mean</td>
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<td></td>
<td>60.2</td>
</tr>
</tbody>
</table>

Table 15 Stress/strain values of cylindrical specimens with w:c ratio of 0.42

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
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</thead>
<tbody>
<tr>
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<td>55.37</td>
<td>10.40</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>119.25</td>
<td>53.51</td>
<td>10.01</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td></td>
<td>54.3</td>
<td>9.94</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Water:cement ratio of 0.45

Finally, the stress-strain relationships of both cube and cylindrical specimens are shown in Figure 67. Following that, the corresponding values are given in Table 16 and Table 17 respectively.
Figure 67 Stress/strain curves for specimens with w:c ratio of 0.45

Table 16 Stress/strain values of cube specimens with w:c ratio of 0.45

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Area (mm²)</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
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<td>2525.55</td>
<td>133.01</td>
<td>52.66</td>
</tr>
<tr>
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<td>2533.59</td>
<td>118.30</td>
<td>46.69</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
<td></td>
<td><strong>49.8</strong></td>
</tr>
</tbody>
</table>

Table 17 Stress/strain values of cylindrical specimens with w:c ratio of 0.45

<table>
<thead>
<tr>
<th>w:c</th>
<th>Specimen</th>
<th>Force (kN)</th>
<th>Strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
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<td>96.14</td>
<td>42.18</td>
<td>8.45</td>
<td>0.38</td>
</tr>
<tr>
<td>0.45</td>
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<td>93.14</td>
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</tr>
<tr>
<td>0.45</td>
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<td>46.39</td>
<td>8.49</td>
<td>0.37</td>
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<td><strong>43.4</strong></td>
<td><strong>8.7</strong></td>
<td><strong>0.34</strong></td>
<td></td>
</tr>
</tbody>
</table>

As expected strength of the material varied with w:c ratio as shown in Figure 68 and summarised in Table 18. The graph shows the results from testing the cube and cylindrical specimens together the published data. Generally, the strength data was consistent with Orica’s technical data but was found to be slightly lower for both specimen shapes. The main reason for this may be due to differences in specimen size. The cube moulds used by Orica have a reported side lengths of 40 mm whereas the moulds used in this project were larger at 50 mm.
From Figure 68, it is found that a w:c ratio of 0.42, would result in strength of the Stratabinder grout of approximately 60 MPa. As for the anchor length section, a w:c ratio of 0.35 would be sufficient. Since the grout within the anchor length should have a larger strength compared with that within the embedment length, the selected w:c ratio for anchor length is 0.35, as shown in Table 19.

Table 19 Selected water:cement ratio when grouting a cable bolt

<table>
<thead>
<tr>
<th>Component section</th>
<th>w:c ratio</th>
<th>UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>embedment length</td>
<td>0.42</td>
<td>60.2</td>
</tr>
<tr>
<td>anchor length</td>
<td>0.35</td>
<td>68.6</td>
</tr>
</tbody>
</table>

Note 1: based on UCS testing of cube samples

3.4.3 Initial testing with new cable bolting facility

In order to confirm the workability of the newly established test rig, a Superstrand cable bolt was installed in the test sample. After the test, the pull-out load and advancing displacement of the tested Superstrand cable bolt were plotted together, this is given in Figure 69.
It can be seen that, within the initial 3 mm, the pull-out force increased quickly to around 120 kN. After that, there is a small decrease of the pulling load due to the crack within the concrete sample. Then, load increased with displacement until a peak load of 158 kN at a displacement of 64.7 mm. Beyond the maximum value, the pull-out force decreases gradually to 80 kN. As for the residual behaviour, there is no apparent oscillation.

After the test, the bearing plate was removed and it was found that the whole cable bolt was pulled from the grout column, as shown in Figure 70, indicating the shear failure occurred at cable/grout interface, which is consistent with previously published results.

In order to further check the failure behaviour of this Superstrand, the sample holder tube was removed and the concrete sample was split into two pieces, one piece is shown in Figure 71. It can be seen that there was even contact between the cable and grout and between the grout
and test sample. The grout column had firmly adhered to the test sample while slippage was evident along the cable/grout interface.

![Figure 71 Shear failure along the cable/grout interface](image)

During the whole experiment, the anchor tube performed well with no slippage detected in the anchor tube. A comparison of the anchor tube before and after the test is shown in Figure 72. Figure 73 shows the top and underside of the coupled cable bolt grouted in the anchor tube with no sign of failure or slippage.

![Figure 72 View of cable bolt at top of anchor tube](image)

![Figure 73 View of the intact cable bolt grouted in the anchor tube after a test](image)

It can be seen that there is a relatively good bonding contact between the anchor tube, grout column and cable bolt. Hence, displacement of the reaction plate at the top of the anchor tube as measured by the LVDT reflects the displacement at the test sample/anchor tube interface. Also as no slippage was evident, there was no need for use of the barrel and wedge or any other termination mechanism to secure the free end of the cable bolt to the anchor tube.
3.4.4 Displacement measuring transducers

Three displacement transducers namely an LVDT, MicroPulse and Laser were initially used to record displacement. In order to compare performance of these three transducers, a test using an MW9 cable bolt was undertaken. During the test, pull-out load versus displacement curves were recorded for each transducer that are shown in Figures 74 to 76.

All three graphs show pull-out load increased with displacement reaching a peak load of 378 kN at a displacement corresponding to 10 mm. In the post-failure region, load gradually reduced to 140 kN at a displacement of 100 mm. It should be noted that the full range of the LVDT was only 100 mm.
Figure 74 indicates more noise when using the LVDT likely due to vibration from the hydraulic cylinder. This compares unfavourable with the more consistent results measured with the MicroPulse and Laser transducers. Although there was less vibration in the signal with the MicroPulse, like the LVDT it was physically tied to the apparatus that limited its measurement range. The laser being a non-contact unit was both unaffected by vibration and also had a much larger measurement range making it more suited in this application. Despite these differences there was reasonable correlation between the three displacement measurement systems as indicated in Figure 77.

Figure 77 Comparison in resolution between the LVDT, MicroPulse and Laser displacement transducers

3.4.5 Effect of borehole roughness and rifling

In order to better replicate the borehole roughness occurred in the field, spiral boreholes were created in the test samples. In order to validate this rifled borehole effect, a series of tests were conducted between rough and smooth boreholes. Both the MW9 and Superstrand cable bolts were used. Each test was replicated five times and results shown in Figure 78.
It can be seen that the load transfer performance with the MW9 cable bolt in a rifled borehole was better than in a smooth borehole. In the case of the Superstrand there was a slight improvement in performance with the rifled borehole.

The main reason for this difference is due to the fact that for the MW9 cable bolt, during the pull-out process, under both rifled and smooth borehole conditions, failure occurred along grout/rock interface, as evident in Figure 79 and Figure 80. As a consequence, the rifled borehole can enhance the load transfer capacity of MW9 cable bolts since more contact area occurs along the grout/rock interface.

On the other hand with the Superstrand, different failure modes occurred. As seen in Figure 81 and Figure 82, failure always occurred at the cable/grout interface no matter independent of borehole roughness. This indicates that for the plain strand under smooth borehole conditions, the bond strength on grout/rock interface was stronger than that at
cable/grout interface. Thus, there was no relative slippage along the grout/rock interface in both a rifled and smooth borehole. As a result, the load transfer capacities of Superstrand cable bolts under those two borehole roughness conditions are almost identical.

![Figure 81 Failure of Superstrand cable bolt in a rifled borehole](image1)

![Figure 82 Failure of Superstrand in a smooth borehole](image2)

It can be concluded that the borehole roughness can influence the load transfer performance of cable bolts particularly when failure does not occur at the cable/grout interface. Furthermore, if failure occurs at the grout/rock interface, the rifled borehole will improve the load bearing capacity of a cable bolt.

Hence the recommendation is to use a rifled borehole in the anchorage tests.

### 3.4.6 Further study of cable termination methods

In order to ensure there was no relative slippage between the anchor tube and grout, different ending methods on the top section of the anchor were tested.

Generally, the barrel and wedge system is commonly used in cable bolting as shown in Figure 83. Thus, this method was used to grip the cable bolt at one end of the anchor tube. In the case of the MW9 cable bolt, there is a special ending plate as shown in Figure 84. Three different ending methods were tested these being no termination mechanism, a barrel and wedge ending system and finally a special ending plate is selected. The pull-out performances of the cable bolts under these three different conditions were compared.
In the first series of tests, pre-confinement of the test sample was set to 40 N·m and results obtained from three different ending methods mentioned above were compared, as shown in Figure 85. It can be seen that the pull-out displacement behaviour of MW9 cable bolts from those three different ending methods are similar, indicating that different ending method has little significant effect on the behaviour.
A second round of tests was undertaken at a higher level of confinement with a torque setting of 80 N•m. Considering fully grouted cable bolts rely on the friction-dilation mechanism, more pre-confinement force may result in a larger load transfer capacity. After the test, the comparison among those corresponding three ending methods is depicted in Figure 86. It can be seen that the load transfer capacities of the MW9 cable bolts under three different ending methods were almost the same.

Based on these tests, it is recommended that the long length of internally threaded anchor tube be adopted as it can work just as effectively in firmly gripping the cable bolt as any of the other mechanisms.

3.4.7 Influence of pre-confinement of the test sample

A large diameter steel cylinder was adopted as a means of providing passive confinement to the test sample. The cylinder is formed by bolting together a pair of half-circular plates. Before each test, a foam pad was inserted between the face plates of each half cylinder to create and a flexible gap of approximately 5 mm thickness. The test sample was place within
the assembled cylinder and grout added to fill the small annulus between the sample and cylinder. After the grout cured, the bolts were tightened using a torque wrench. This effectively provided confinement to the sample as shown in Error! Reference source not found. The level of confinement being a function of the torque applied. This ensured a consistent level of contact between the sample and cylinder.

In order to study the effect of this pre-confinement on the pull-out behaviour of cable bolts, a series of tests was undertaken at torque values ranging from 0 to 200 N\cdot m. The pull-out load versus displacement characteristics were recorded and compared as shown in Figure 88 with values of the maximum load tabulated in Table 20. The graph shows that torque had little or no impact on the stiffness of the grouted cable bolt system but did influence the load transfer capacity of cable bolts. In order to illustrate this effect, the peak loads for each level of torque are shown in Figure 90.

![Figure 87 Tightening the bolts joining the two halves of the steel cylinder to a constant torque ensures a consistent level of test sample confinement](image)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Pre-confinement torque (N\cdot m)</th>
<th>Peak load (kN)</th>
<th>% Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>218</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>381</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>440</td>
<td>85</td>
</tr>
<tr>
<td>4</td>
<td>135</td>
<td>513</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>507</td>
<td>100</td>
</tr>
</tbody>
</table>
The graph shows the maximum pull-out load increased with the pre-confinement torque up to approximately 150 N\(\cdot\)m beyond which there was little further change. The likely reason for this is that the grout in the annulus yields and undergoes plastic deformation.

Hence pre-confinement has an appreciable effect on the load transfer capacity of cable bolts. In order to ensure a constant testing environment while minimizing any potential impact on performance, it is recommended the bolt torque joining the two halves of the cylinder be set to the lowest reproducible level of 40 N\(\cdot\)m which achieves approximately 75% of maximum peak load.

### 3.5 Summary

A new design of an axial test rig based on the original LSEPT design has been developed. In order to better reflect the load transfer situation of reinforcement tendons in the field, the design incorporates two sections, namely the embedment and anchor sections.
A series of single embedment pull tests was conducted to determine the optimum test sample size with diameters ranging from 150 mm to 508 mm. The tests used a high capacity cable bolt that would induce the largest dilation. It was found that load increased with sample size up to around 300-350 mm with little change thereafter. As a consequence, the sample used in this design has a maximum diameter of 330 mm including the cement annulus. Further, a split steel cylinder is used to contain the test sample providing the ability to lock the test sample to the anchor tube preventing rotation during the pull-out process.

As for the anchor section, this consists of an internally threaded anchor tube designed to grip the cable bolt, preventing it from rotating and stretching during a test. Various mechanisms were investigated to prevent slippage between the anchor tube, cable bolt and grout. It is found that grouting the cable bolt in the anchor tube can provide sufficient bond strength to prevent any slippage.

The strength of the two test materials was determined, a strong material and weak or soft material to be 68 MPa and 10 MPa respectively.

Stratabinder grout was used to bond the cable bolt in the test sample and anchor tube. Tests found a Stratabinder mixture with a water to cement of 0.42 had a strength of 60 MPa that was used in the embedment section while a w:c ratio of 0.35 used to create a slightly strong grout of 69 MPa for use in the anchor tube.

The influence of borehole roughness was investigated. It was found in cases when failure of the cable bolting occurred at the cable/grout interface, the borehole roughness had little effect on performance. However, under weak rock conditions, when the high capacity MW9 cable bolt was used, failure occurred at the grout/rock interface. In this case borehole roughness did have an effect on the load transfer capacity. Consequently the test design incorporates a manufactured rifled borehole to ensure consistent testing conditions. The rifled borehole is also a better reflection of the field situation compared with a smooth borehole.

It was found that changes in the level of torque of the test sample cylinder can significantly alter cable bolt performance. On the other hand, little or no pre-confinement can result in poor or inconsistent contact between test sample and cylinder and may even result in rotation of the test sample during loading. In order to ensure a consistent testing environment, prior to a test the bolts of the split cylinder should be tightened to a torque level of 40 N•m.


4 PERFORMANCE TESTING OF TWO CABLE BOLTS

4.1 Introduction

The primary objective of this project was to build a laboratory-scale axial-loading cable bolt testing facility capable of assessing the anchorage performance of different types of cable bolts. In addition, the facility must include a capability to vary installation and ground conditions such as rock type, grout and borehole diameter.

One of the major benefits of a laboratory test facility is to undertake repeated tests under controlled conditions with certainty of what variables have been changed between each test so that results can be compared. This ability to control the test environment thereby provides more certainty in any analysis of test results and subsequent conclusions that are made; for example conclusions that there may or may not be any difference in performance due to a change in a parameter.

In the context of this project, there were questions as to what difference, if any, there is in the maximum load bearing capacity, stiffness, post-failure load bearing capacity and, of rock type etc. Efforts have been made in the past to develop a suitable test methodology and facility to examine these differences. Overall, they have been successful taking into account the environment at that time.

Nevertheless, as cable bolting technology has evolved over the past sixty years to meet the new challenges as mining conditions change and the increased demands in terms of performance, there has also been a need for changes in testing. This is no better illustrated than the current British Standard for cable bolts. The foundation for this test was developed over a decade ago and was based on the cable bolting practice in the UK at that time. With subsequent new cable bolts such as plain-strand cables, work reported by Thomas (2012) found deficiencies with the Laboratory Short Encapsulation Pull Test (LSEPT) developed by RMT Ltd such as twisting of the cable as it unwinds under load. Similarly, in the 1970s and 1980s with the use of 25 mm diameter cables, the testing facilities had much lower load capacities than that needed today with 31 mm diameter modified cables for example.

Having said that, there are limitations of the laboratory test unit and this is mainly due to scale. There are constraints on the range of test parameters chiefly to do with modelling the response of the rock mass and the length of encapsulation. These effect on size and hence mass of test samples that can be safely produced and handled in a general laboratory setting as well as cost to conduct a test. Larger-scale tests are possible to simulate in-field conditions but this requires funding to build, operate and maintain a dedicated large laboratory facility.

With respect to rock mass, varying approaches have been taken over the years such as the adoption of steel tubes and biaxial cells in order to overcome the effects these can have on masking performance. The current facility is a hybrid design incorporating a near doubling in
the diameter of the test rock sample placed within a rigid fixed frame. This design combines both confinement as would be seen in a rock mass in the field but while allowing interaction to occur between the cable, grout and rock mass.

In terms of the length of encapsulation and aside from the double-embedment tests, which has its own limitations, most test designs have a limited encapsulation length and importantly a short range of displacement. The total length of cable bolt encapsulation in the new test design is 360 mm, slightly longer than the LSEPT used at the RMT Ltd test facility.

The new test allows for a much longer controlled pull-out length of 100 mm. Previous facilities have typically displayed a capability of controlling and measuring the load/displacement behaviour up to around 40 mm to 50 mm when testing plain strand cables but much less with high capacity cable bolts.

The longer length of displacement control allows for a more extensive assessment of the behaviour in the post-failure region. Thomas (2012) reported there were indications of significant differences between the various types of cable bolts beyond the point of peak anchorage load. For example, in testing modified bulb cables with high anchorage loads, little data was measured in the post-failure region resulting in total measured displacements of typically less than 30 mm. It is postulated that this might have been due to the large sudden and uncontrolled release of the strain energy on anchorage failure. The displacement control mechanism in the current facility has been shown to allow for full measurement over the full range of displacement of 100 mm independent of cable type.

The advantage of displacement control and the extended range of measured displacement is that it allows a study of post failure behaviour. This could range from a cable bolt having:

- little or no load bearing capacity as was evident in some instances with the use of modified bulb cable;
- to a cable offering some level of resistance and hence support such as plain strand cables;
- to the phenomena described as “slip/lock” mechanism. This has previously been observed in some tests with indented wire cable bolts and 25 mm diameter bulbed cables but to date has not been shown to occur with larger diameter modified cable bolts.

As discussed earlier, the constraints on the scale of a laboratory test facility limit the amount of post-failure behaviour that can be measured. While such a facility can provide information regarding post failure behaviour, a more extensive picture of what actually happens over a wider range of displacement can only be realistically determined from in-field tests. It is likely that there are instances where cable bolts do provide some load bearing capacity after anchorage failure but what is not known is how much it reduces after a displacement of 0.2 mm or more. This research was proposed in Stage 3 of the modified full proposal for the current project that is “to assess and compare the in situ performance with those measured in the field confirming the recommendations in terms of alignment between a certain set of ground conditions and optimum cable bolt selection.”
In other words, while laboratory-scale tests cannot provide the complete picture of cable bolt behaviour, the tests can provide information on the maximum load bearing capacity, initial stiffness and immediate post failure behaviour. It is recommended that further field-test research will fill any remaining gaps in knowledge. A list of all the tests in the preliminary evaluation of two cable bolts is shown in Table 21.

<table>
<thead>
<tr>
<th>Cable</th>
<th>Borehole condition</th>
<th>Rock strength (MPa)</th>
<th>Borehole diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW9</td>
<td>smooth</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>rifled</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>rifled</td>
<td>68</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>rifled</td>
<td>11</td>
<td>52</td>
</tr>
<tr>
<td>Superstrand</td>
<td>smooth</td>
<td>11</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>rifled</td>
<td>11</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>rifled</td>
<td>68</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>rifled</td>
<td>11</td>
<td>37</td>
</tr>
</tbody>
</table>

4.2 Load transfer behaviour of MW9 cable bolt

4.2.1 Effect of test sample strength

The performance of MW9 cable bolt in strong material was first studied. Figure 91 shows the resultant load versus displacement graph.

![Figure 90 Repeatability in the behaviour of an MW9 cable bolt embedded in strong material](image)

The strong material provided a higher level of resistance, resulting in a stiff tendon having a large pull-out load of nearly 380 kN after a displacement of only 10 mm. After the peak load was reached, the load bearing capacity in the post-failure region fell away quickly. After 100 mm displacement, the capacity of the cable bolt reduced to less than 80 kN.
After testing, the test sample was split to check the failure mode in the embedment section with the cable bolt and remains of the embedment grout shown in Figure 91 and Figure 92 respectively. These indicate good contact at the interface between the rifled borehole and surrounding rock material. And during the pull-out process, failure initially occurred at the free end of cable/grout interface. Failure then propagated to the far end when the whole cable/grout interface was broken.

![Figure 91 MW9 cable bolt after extrusion from the grout column](image1)

![Figure 92 Shear failure occurred at the grout/rock interface](image2)

The performance of the cable bolt in a weak material was also studied. The graph in Figure 94 indicates much more variability in behaviour in the weak material particularly in the post-failure region. The graph shows a similar peak load of the cable bolt of approximately 170 kN, which is nearly half that achieved in the strong material.

![Figure 93 Performance of MW9 cable bolt embedded in weak material indicating a similar maximum load but with differences in post-failure behaviour](image3)
It should be mentioned that the failure mode of the cable bolt is also largely different from the failure mode in the strong material. As can be seen in Figure 94, a plug of material consisting of the cable bolt, grout column and test sample material was extracted from the borehole in the weak material. This is also evident in Figure 95, which was taken after the test sample failed.

The likely reason for this is the high strength of Stratabinder grout of around 60 MPa compared to the weak test material of 10 MPa. In this case, the grout adjacent to the rifled surface is sufficiently strong to extract the surrounding material.

As a comparison, the load versus displacement curve of MW9 cable bolt in both weak and strong material is plotted together in Figure 96 with a summary of results in Table 22. It can be seen that the material strength has a significant effect on the axial performance of the cable bolt. Although the stiffness is almost the same, the peak load is largely different. Significant differences can be seen in the mean peak load achieved in weak and strong test materials.
4.2.2 Effect of borehole diameter

In order to evaluate the effect that a larger borehole may have on the performance of a cable bolt, test samples with a borehole diameter of 52 mm were prepared in a weak material with a strength of 10 MPa. The results obtained from an oversized borehole are shown in Figure 97. Table 23 illustrates the specific values obtained from pull-out tests for both standard and oversized boreholes.
A comparison of the effect between standard and an oversized boreholes is shown in Figure 98. It would seem that in this instance, an oversized borehole can improve the axial performance of MW9 cable bolts in soft rock conditions. A contributing factor to this difference is the high strength of the Stratabinder used to grout the cable bolt relative to the strength of the test sample. As discussed earlier, failure of MW9 reinforcing system for a standard borehole situation occurs at grout/rock interface. However with a larger borehole, failure occurs at the cable/grout interface as shown in Figure 99. In this situation, no slippage occurred at the grout/rock interface in the oversized borehole. As a result, both the grout annulus and rock material can be regarded as an intact confining medium. Since in this case the Stratabinder grout had a strength of 60 MPa, being much larger than the test material of 11 MPa, then with the bigger surface area of the larger borehole increased the effective strength and hence greater resistance to pull-out. Consequently, large boreholes in weak rock conditions improve the load transfer performance of cable bolts.

Table 23 Comparison of MW9 cable bolt in standard and oversized boreholes

<table>
<thead>
<tr>
<th>Borehole diameter</th>
<th>Peak load (kN) mean</th>
<th>Peak load (kN)</th>
<th>Initial stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>208</td>
<td>208</td>
<td>52.2</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>206</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oversized</td>
<td>257</td>
<td>250</td>
<td>51.0</td>
</tr>
<tr>
<td></td>
<td>252</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>242</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 98 Comparison of performance between standard and oversized boreholes with an MW9 cable bolt
4.2.3 Effect of embedment length

As illustrated in Figures 97 and 99, there was some oscillation observed in pull-out load with the MW9 cable bolt post-failure. This is likely to be what is described as slip-lock or interlocking as the cable bolt slips along the cable/grout interface before re-gripping. This occurred within a short range of displacement between 10 to 60 mm as highlighted in Figure 101 for the MW9 cable bolt in strong rock. Beyond this zone there was a uniform reduction in load up to 100 mm which was the limit of measurement.

The reason for this is attributed to the bulb within the embedment length. Initially at the outset of the pull-out test starts, the chemical adhesion between the cable bolt and surrounding grout column is easily broken. Mechanical interlock between the cable and grout then comes into play which holds firm until it too fails and the bulb slips at which time the peak load occurs. The mechanical interlock is damaged but not altogether broken. After being drawn 13 mm, the leading edge of the bulb re-engages with the intact grout annulus with a repeat of mechanical interlock. Consequently, the resulting resistance leads to an increase in pull-out load though not as great as earlier. Once this newly built mechanical interlock system is broken, the pull-out load decreases. This cycle repeats itself several times until eventually the bulb is drawn out from the borehole.
The total borehole length in the standard LSEPT is 320 mm. The bulb was placed mid-length at 160 mm from the free surface. The overall length of the bulb section is approximately 120 mm or a half-length of 60 mm. Over this section the outer diameter of the cable gradually increases to a maximum and then decreases again. Hence the distance from the free surface to the start of the bulb is 100 mm.

A further series of tests was undertaken at embedment lengths of 340 mm, 360 mm and 380 mm, the latter being the limit before interaction begins to occur between the end of the cable bolt and the end of the test sample. The results of this series are shown in Figure 102.

As would be expected, embedment length had little if any effect on the initial elastic behaviour up to the peak pull-out load. However the peak load was sensitive at the shorter embedment lengths increasing up to 360 mm when it reached a constant pull-out load of approximately 480 kN as shown in Table 24 and in Figure 103.

<table>
<thead>
<tr>
<th>Embedment length (mm)</th>
<th>Pull-out load (kN)</th>
<th>Limit of slip-lock (mm)</th>
<th>Residual stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320</td>
<td>380</td>
<td>60</td>
<td>-4.2</td>
</tr>
<tr>
<td>340</td>
<td>443</td>
<td>65</td>
<td>-4.3</td>
</tr>
<tr>
<td>360</td>
<td>478</td>
<td>75</td>
<td>-2.7</td>
</tr>
<tr>
<td>380</td>
<td>481</td>
<td>90</td>
<td>-2.5</td>
</tr>
</tbody>
</table>
There were also differences in the post-failure region. As Figure 105 indicates, the length of the slip-lock zone increased with embedment length though not in direct proportion. Whereas the embedment length increased from 320 mm to 380 mm or, 60 mm, the slip-lock zone extended by only half this or 30 mm. The residual stiffness also tended to increase with embedment length.

### 4.3 Load transfer behaviour of Superstrand cable bolt

#### 4.3.1 Effect of test sample strength

The performance of the Superstrand cable bolt in strong material was studied with the results shown in Figure 104.

It can be seen that all the cable bolts had a similar peak load and behaved in a similar fashion post-failure with a gradual reduction in load bearing capacity. A typical failure mode is shown in Figure 105, showing failure at the cable/grout interface.
By contrast, the performance of Superstrand in weak material is shown in Figure 106 and the nature of the failure mode illustrated in Figure 107 with the cable bolt extruded from the bore borehole leaving behind the grout. This differs to that noted earlier with the MW9 cable bolt in weak material. A comparison of the values of Superstrand pulled from strong and weak materials is shown in Table 25.
A comparison of the behaviour of the Superstrand in weak and strong test materials is shown in Figure 107. It is apparent that material strength has a significant impact on the axial performance of the Superstrand cable bolt. In weak material, the peak strength of Superstrand was around 112 kN compared to 265 kN when embedded in strong material, that is almost 240% higher. Also the initial stiffness of Superstrand reinforcing system in strong material is slightly higher than that in weak material as seen from the data in Table 25.

### Table 25 Comparison of Superstrand cable bolt embedded in strong and weak materials

<table>
<thead>
<tr>
<th>Rock strength</th>
<th>Peak load (kN)</th>
<th>Mean load (kN)</th>
<th>Initial stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong rock</td>
<td>275</td>
<td>265</td>
<td>68.6</td>
</tr>
<tr>
<td></td>
<td>258</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>262</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak rock</td>
<td>109</td>
<td>112</td>
<td>51.2</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.2 **Effect of borehole diameter**

Similar to tests with the MW9 cable bolts, the borehole size effect was studied in this case with a borehole diameter of 37 mm. It is found that resistance to load initially rose sharply with displacement in the larger borehole as shown in Figure 109. After approximately 6 mm displacement, the load decreased temporarily but rose again steadily with displacement to around 60 mm displacement when load bearing capacity reached its maximum of around 150 kN. After this there was a sharp reduction in load capacity.
A comparison of the performance in the larger and standard borehole diameters is shown in Figure 109. The larger borehole resulted in a larger load bearing capacities for the Superstrand. The main reason is similar to the MW9 cable bolt as failure of the Superstrand in this condition always occurred at the cable/grout interface, as shown in Figure 110. In this case, the grout annulus and surrounding rock material can be regarded as the intact confining material. A larger borehole results in more strong material surrounding the cable bolt, improving the load transfer capacity of the Superstrand.
4.4 Effect of sample strength on cable bolt performance

4.4.1 Strong test material

The effect of cable surface geometry on the axial performance of rock tendons can be studied by comparing results obtained from MW9 and Superstrand cable bolts, the differences in the performance can be observed in Figure 111. In the case of the MW9 cable bolt, the bearing capacity rose very quickly to the peak load with little displacement. Subsequently the load transfer capacity reduced quickly until after approximately 100 mm there was little bearing capacity. By contrast, the Superstrand achieved a much lower peak load after some 30 mm after which it gradually decreased with displacement. Table 27 shows that the modified bulb increased the pull-out load by up to 143% compared to the plain strand Superstrand.

Figure 111 Effect of surface geometry on the performance in strong material
Table 27 Performance of MW9 and Superstrand in strong material

<table>
<thead>
<tr>
<th>Cable bolt type</th>
<th>Peak load (kN)</th>
<th>Mean peak load (kN)</th>
<th>Initial stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW9</td>
<td>381</td>
<td>380</td>
<td>69.4</td>
</tr>
<tr>
<td></td>
<td>379</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>381</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superstrand</td>
<td>275</td>
<td>265</td>
<td>68.6</td>
</tr>
<tr>
<td></td>
<td>258</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>262</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.4.2 Weak test material

In a lower strength test material, the influence of cable surface geometry can show some significant difference as shown in Figure 112. To be more specific, the MW9 cable bolt achieved a peak load of around 200 kN, after a small displacement of 6 mm while the Superstrand achieved a maximum load of near 100 kN after a displacement of nearly 25 mm. Further details are shown in Table 28. Again, the MW9 cable bolt lost load bearing capacity very quickly after the peak strength. Whereas with the Superstrand the bearing capacity remained almost constant over a large displacement of around 90 mm.

Figure 112 Effect of surface geometry on the performance of cable bolts in weak material

Table 28 Comparison of performance of MW9 and Superstrand in weak material

<table>
<thead>
<tr>
<th>Cable bolt type</th>
<th>Peak load (kN)</th>
<th>Mean peak load (kN)</th>
<th>Initial stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW9</td>
<td>257</td>
<td>250</td>
<td>51.0</td>
</tr>
<tr>
<td></td>
<td>252</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>242</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superstrand</td>
<td>109</td>
<td>112</td>
<td>51.2</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 27 and Table 28, it can be seen that the performance of MW9 cable bolts was always better than that of Superstrand, indicating the specific surface geometry of MW9 can
improve the load transfer capacity of cable bolts to a great extent, especially in weak rock situations.

4.5 Post-failure behaviour

The post-failure behaviour was continuously monitored under controlled conditions over a total displacement of 100 mm. This compares to other tests where only displacements of 40 to 50 mm have been measured for plain strand cables and considerably less for modified cable bolts as reported by Thomas (2012). Interestingly there were differences in post-failure behaviour between the two cable types.

4.5.1 Superstrand cable bolt

For the Superstrand cable bolt, there was some appreciable and sustained level of load bearing capacity after the maximum load was achieved as shown in Figure 113. The average peak loads were 265 kN and 112 kN for the strong and weak rocks respectively in a rifled borehole at the standard recommended borehole diameter.

After 100 mm displacement, the cable bolt could still maintain a load bearing capacity of nearly 80 kN in weak rock. Interestingly, the post-failure load was consistently maintained over the full range of controlled displacement compared to that observed in strong rock where there was a near 25% reduction in load bearing capacity of the latter over the final 60 mm displacement to 100 mm. Even so, the load bearing capacity after 100 mm displacement in the strong rock was nearly 200 kN.

![Comparison of performance of the SuperStrand cable bolt in strong and weak materials](image)

4.5.2 MW9 cable bolt

In earlier test work reported by Thomas (2012) undertaken by RMT Ltd in the UK, measurements were truncated soon after the peak load was reached. This was typically within a total displacement of 10 to 15 mm as shown in Figure 114. Little if any post-failure behaviour of the cable bolts was able to be determined in each case.
Significantly, with this new test facility the post-failure behaviour for the MW9 cable bolt could be determined well beyond the peak load. As shown in Figure 115, the post-failure behaviour over a displacement range of 100 mm was consistently achieved.

The average peak loads were 380 kN and 208 kN for the strong and weak rocks respectively in a rifled borehole at the standard recommended borehole diameter.

![Figure 114 Load/displacement curves for bulbed cable bolts indicating truncation of readings soon after the peak load value is reached with little indication of post-failure behaviour (after Thomas, 2012)](image)

There was a mirror image in behaviour between the strong and weak rock for the MW9 cable bolt with a near equal stiffness of ~3.7 kN/mm as reflected in the constant difference observed in the post-failure load-bearing capacity of approximately 100 kN.

![Figure 115 Comparison of performance of the MW9 cable bolt in strong and weak materials](image)

Thomas (2012) noted what appeared to be the slip/lock mechanism being observed with some cable bolt types namely the Hilti spirally indented cable and plain strand Megastrand as
shown in Figure 116. This was not observed with bulbed cables and it has been speculated it might be due to the sudden high strain energy release on failure as seen in Figure 114. The mechanism occurred over a displacement range of 10 mm to 33 mm beyond which no further measurements were recorded.

![Figure 116 Load/displacement curves for the Hilti spirally indented cable and plain strand Megastrand indicating slip/lock mechanism (after Thomas, 2012)](image)

There was evidence of slip/lock mechanism with the MW9 modified cable bolt using the new test facility within a similar narrow range of displacement of 15 mm to 30 mm as previously observed with the Hilti spirally indented cable. This was observed in both the strong and weak rocks as shown in Figure 116 and the three test replications shown in Figure 117. As seen in Figure 115, beyond a displacement of about 30 mm to 40 mm there was a near-uniform reduction in load with displacement signifying little effective bond strength or resistance between the cable and grout that might indicate it had irretrievably been damaged. By the 100 mm mark in soft rock, there was little significant load bearing capacity. In strong rock, this state was reached after a total displacement of nearly 125 mm.

It might be speculated that some load bearing capacity could be evident in a longer borehole. This highlights the deficiency in a laboratory test arrangement, as there are designed working limits in the test parameters that can be examined. The long borehole and hence length of encapsulation together with displacement control has meant more information can be collected post failure than in other testing facilities. While further increasing the scale of the laboratory test might be possible, there are practical limits and this must be weighed against the possibly more meaningful results that could be obtained from full-scale field tests.
4.6 Summary

Two types of cable bolts, namely the high capacity, modified bulbed MW9 and the plain strand Superstrand cable bolts were tested in the laboratory with the newly established axial cable bolt test facility. Relevant testing parameters including the test sample strength and borehole size were studied. After a series of tests, the following conclusions can be made.

- Rock strength was found to have a significant effect on the axial performance of cable bolts. In the case of the MW9 cable bolt, a strong test sample can improve the maximum load transfer capability by up to 180%. Similarly in the case of the Superstrand, there was an increase of nearly 240%. Furthermore, the failure mode of MW9 was largely different between strong and weak test samples. To be specific, failure of cable bolting system always occurred at the cable/grout interface in the strong test samples, this is consistent with previous research. However, when testing in weaker material, failure always occur at the grout/rock interface. This is likely to be due to the relative high strength of the grout material. Hence it is important to consider the properties of the grout as well as those of the rock and cable bolt. As a consequence, the bond contact between the MW9 cable bolt and grout annulus is better than that at the grout/rock interface, altering the failure mode from cable/grout to grout/rock interface. However, it should be further mentioned that in the case of other cables such as the Superstrand, the failure mode is always at the cable/grout interface in both strong and weak rock situations. In part this is due to the lower stress and hence dilation caused by the Superstrand. This indicates that the confinement stress generated in the surrounding rock material has an important impact on determining the performance of a cable bolt.

- Slip-lock was observed in the post-failure region of the modified bulb MW9 cable bolt. A cyclic rise and fall in resistance and hence load occurred over a displacement of 60 mm in the standard LSEPT design having an embedment length of 320 mm. Increasing the embedment length by 40 mm from 320 mm to 360 mm significantly increased the peak pull-out load from 380 kN to 480 kN with little further benefit beyond 360 mm.
In weak rock conditions, borehole size influenced the load transfer behaviour of both cable bolts. For the MW9 cable bolt, when a larger borehole was used, failure occurred at the cable/grout interface, indicating there is a good bond contact between the grout annulus and surrounding rock material. In this case, the grout as well as the rock can be regarded as the intact confining medium. Therefore, in a larger borehole, more confining material with a relatively larger strength is involved surrounding the cable bolt, resulting in a larger confining pressure. As a consequence, the load transfer capacity of the MW9 cable bolt can be improved up to 120% in a larger borehole in weak rock. This behaviour was also replicated with the Superstrand. For instance, the maximum bearing capacity of the Superstrand increased by 135% compared with that obtained in a standard borehole.

The modified cable surface geometry, especially the single bulb of the MW9 cable bolt within the borehole section has an important effect in determining the load transfer capacity. The experimental results show that the MW9 cable bolt was always larger compared to the Superstrand in both strong and weak rock conditions. In relatively weak material, the MW9 cable bolt had a peak load bearing capacity more than twice than that of Superstrand, indicating the MW9 cable is more adaptable than the plain strand in severe situations. Also, the two types of cable bolts behaved differently. For example, the MW9 cable bolt was much stiffer up to the peak load but beyond that load reduced quickly with displacement. By contrast, the Superstrand while being less stiff was able to sustain its load bearing capacity well after the peak load was achieved. For example, the load bearing capacity of the Superstrand rose gradually with displacement up to 60 mm. Beyond this displacement, the load transfer capacity reduced gradually, indicating that even after a relatively large displacement, the Superstrand cable bolt is still capable of providing some level of appreciable support to the surrounding rock strata.
5 CONCLUSIONS

A review was undertaken of the methods used in the axial testing of cable bolts. It was concluded that a non-rotating, constrained test arrangement will provide a more useful assessment of cable bolting behaviour. The Laboratory Short Encapsulation Pull Test (or LSEPT) incorporated in the current British Standard is the latest development in this area of cable bolt testing. Recent work reported several deficiencies in this test design. For example, unwinding of a cable bolt during the pull-out process had an adverse impact on performance. The use of sandstone cores as a test sample not only limits understanding of behaviour in different rock types but also as the sample diameter is only 142 mm, it can directly impact performance of a cable bolt especially with high load transfer cable bolts.

A new modified cable bolt testing facility was designed and constructed that is capable of testing the various kinds of fully grouted cable bolts used in the Australian underground coal mining industry and that overcomes the shortcomings of the LSEPT in the current British Standard.

A series of tests were undertaken to confirm various test design parameters. In most test designs there are two main sections, namely an embedment section and an anchor section with the embedment section arguably the more significant. To determine the optimum size of test sample, a series of single embedment pull tests was conducted using cylindrical test samples having outside diameters ranging between 150 mm and 508 mm. A Sumo cable bolt was used in the tests as it has a large load transfer capacity. It was found pull-out load of the Sumo cable bolt varied with sample diameter up to 300 mm and remained largely unchanged thereafter; this result emphasises the sensitivity of sample size on anchor performance. As a result, a sample size of 300 mm is recommended for use in the embedment section.

A further modification from the LSEPT design has been the incorporation of a split steel cylinder rather than a bi-axial cell. The steel cylinder provides also passive confinement as opposed to the biaxial cell and it prevents any relative rotation between the cable bolt and test sample that can be induced during loading of some cable bolts.

As for the anchor length section of the test facility, an internally threaded steel anchor tube with a length of 600 mm is recommended to be used to grip the cable bolt. The threads enhanced the bond contact and mechanical interlock between the cable bolt and tube. To prevent the anchor tube from rotating during the pull-out process, a key slot couples the anchor tube to the bearing plate. The key slot can accommodate axial displacements of up to 100 mm while preventing any rotation between the test sample and anchor tube.

A bearing plate with an internal diameter of 70 mm provides an interface between the test sample and anchor tube to transfer and distribute the load. The hole in the bearing plate is larger than the borehole diameter in the test sample. Because of this, the top surface of the test sample surrounding the borehole is unconfined allowing different failure modes of a cable.
bolt, including slippage along the cable/grout interface, relative movement along grout/rock interface and failure within the surrounding material.

The steel cylinder test sample holder is comprised of two half cylinders that are bolted together. The effect of tightening the bolts to torque values ranging between 0 and 200 N-m on load transfer performance was examined. It was found that torque had a significant impact on the peak load of the cable bolt up to a torque of 135 N-m with little change thereafter. In order to ensure a consistent level of contact between the test sample and steel cylinder, it is recommended the bolts be tightened to a relatively low torque value of 40 N-m prior to each test.

To ensure a consistent level of borehole roughness, a technique was developed to manufacture a rifled borehole in the test sample. To gauge the effect of borehole roughness on the behaviour of cable bolts, pull-out tests were conducted in smooth and rifled boreholes. Two types of cable bolts, namely a plain strand and a modified cable bolt were used. The results showed borehole roughness had different effects with the two cable bolts. When the plain strand cable bolt was tested, borehole roughness had little impact with failure at the cable/grout interface and even in a smooth borehole there was sufficient bond strength to resist the grout column from slipping. However, with the modified cable bolt contact between the cable and grout was enhanced and as a consequence, failure occurred along the grout/rock interface. Consequentially as the effect can alter with the type of cable bolt, it is recommended the test design incorporates a rifled borehole in the test sample.

The effect of different cable termination mechanisms including using barrel and wedge and a special ending plate was studied. In the end, a slight redesign of the anchor tube without any cable termination mechanism was just as effective with no failure evident even at the highest load when using the high capacity modified cable bolt.

Results of the preliminary investigation in this ACARP funded project have shown the new laboratory-scale axial-loading cable bolt testing facility has the capability of determining the post-failure behaviour of a wide range of cable bolt types over a wide range of displacement up to 100 mm. Other testing facilities have a more limited capability, especially when testing modified cable bolts, for example the RMT facility in the UK was found to have a more limited range capacity of only 15 to 20 mm for some modified cable bolts.

Two cable bolts at either end of the design spectrum were tested under control conditions, including the Superstrand, or a plain strand type, and the MW9, or a high capacity, modified bulb cable bolt, together with test sample strength and borehole diameter. The tests were undertaken with a manufactured rifled borehole and a grout strength of 60 MPa.

The maximum pull-out load in a 10 MPa strength test sample with the Superstrand cable was 112 kN or nearly half that of the MW9 of 208 kN, a difference of 86%.

By contrast, with a six-fold increase in strength of test sample to 68 MPa, the maximum load of the Superstrand was 265 kN, representing an increase of 137% compared to that achieved in the weaker test sample. While for the MW9 cable bolt, the maximum load was 380 kN, that
is an increase of only 83%. Overall the difference between the two cable bolts reduced to just 43%. Hence, the Superstrand cable bolt was found to be more sensitive to changes in material strength.

The standard length of embedment in the LSEPT is 320 mm. Tests at longer embedment lengths of 340, 360 and 380 mm found pull-out load increased from 380 kN at 320 mm to 440 kN and 480 kN at 340 mm and 360 mm respectively. Beyond 360 mm there was no further increase in pull-load capacity. The phenomenon termed slip-lock was particularly evident with the modified MW9 cable bolt. It tended to increase with embedment length but at a lower rate. Based on these tests the recommended embedment length of a cable bolt in the test sample is 360 mm.

There were distinct changes in the stiffness of the cable bolts before and after the maximum pull-out load. For both cables, the initial stiffness was similar at approximately 51 kN/mm and 69 kN/mm in the weak and strong test samples respectively. However with the Superstrand, stiffness began to reduce once the load reached around 100 kN requiring a further displacement of 30 mm to achieve maximum load. In the case of the MW9 cable, stiffness remained constant up to the peak pull-out load within a displacement of only 7 mm, hence it is a much stiffer system.

Post-failure, the Superstrand showed very little reduction in load-bearing capacity over the measured displacement range of 100 mm especially in weak material with only a 25% reduction from the peak load of 265 kN to a still significant load capacity of 200 kN with a stiffness of -1.1 kN/mm. In the weak material, failure occurred at the grout/rock interface resulting in a “plug” of grout and cable being extruded from the borehole. For the MW9 cable, the slip/lock behaviour was activated post-failure for up to a total 30-40 mm displacement in both the weak and strong test samples. Beyond this there was a similar stiffness measured in both the weak and strong materials of -3.8 kN/mm.

An increase in borehole diameter above the recommended standard borehole diameter of 10 mm was found to have a beneficial effect with both cable bolt types albeit the tests were conducted only in the weak test material.

Overall, the results of the preliminary investigation in this project have shown the new laboratory-scale axial-loading cable bolt testing facility has the capability of determining the post-failure behaviour of two different types of cable bolts over a wider range of displacement up to 100 mm. This extended range compares favourably with other testing facilities that have a more limited capability, especially for modified cable bolts, for example the RMT facility in the UK.
6 REFERENCES


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APPENDIX

Extract of published papers related to the project
The size effect of rock sample used in anchorage performance testing of cable bolts.  
Coal2014, February 2014

Matthew Holden and Paul Hagan

ABSTRACT. This paper outlines the results of a study into the effect of rock specimen size on the anchorage performance of a hollow strand bolted cable bolt. As part of the design of a Laboratory Short Encapsulation Pull Test (LSEPT) facility, a question arose as to the appropriate size of the rock sample in which the cable bolt is embedded and whether size might affect the pull out strength of the cable bolt. An analysis of previous research revealed little information regarding the rationale for the sample size used in previous test work. Many of pull out tests in the past had made use of either a rigid encasement such as steel, aluminium, or PVC casing or a biaxial pressure cell to apply a constant stress to model the in situ rock mass conditions.

A test arrangement was developed to assess whether there was any appreciable difference in anchorage performance with varying diameter of the rock sample. Cable bolts were embedded into the rock sample using a polyester resin grout having diameters of 150 mm, 215 mm, 300 mm and 450 mm with a constant embedment length of 280 mm. A hydraulic ram was used to load the cable bolts to failure.

The results indicate there was a size effect albeit only marginal whereby an increase in the diameter resulted in increased anchorage capacity of the cable bolt.

INTRODUCTION

Cable bolting is widely utilised in ground support of surface and underground excavations in both mining and civil engineering applications. Since they were first used in the 1970s, a wide variety of cable bolt configurations and geometries have been developed. The performance of cable bolts has been found to be affected by parameters that include:

- borehole diameter;
- embedment length;
- borehole radial confinement conditions;
- cable bolt configurations and geometry; and
- grout type and quality (Hutchinson and Diederichs, 1996).

The failure mechanism of cable bolted systems is complex and a function of loading conditions and the interaction between the cable bolt, grout and rock mass. There are four general mechanisms of cable bolt failure each of which is illustrated in Figure 1.

Failure at the cable-grout interface, indicated as Mode (ii) in Figure 1, is considered the most common failure mechanism identified in the field (Hyett et al., 1996; Hyett et al., 1995; Hutchinson and Diederichs, 1988; Rajaei, 1980; Singh et al., 2001). This usually results from insufficient frictional resistance between the ridges on the cable strands and the grout material. A combination of poor ground conditions and lack of quality control at the time of installation may also affect the bond strengths at the interfaces that in turn can lead to premature failure of the system before the capacity of the cable bolt is actually achieved. Hence a standardised testing methodology should be designed such that failure of the system is more likely to occur at the cable-grout interface (Rajaei, 1990; Hutchinson and Diederichs, 1996).

A comprehensive review of the testing methodologies revealed that while there are a number of testing methods that have the potential to become the standard for pull out tests, there is no standardised or universally accepted method with which to assess the strength of the wide range of cable.
The load transfer mechanism of fully grouted cable bolts under laboratory tests.

Coal2014, February 2014

THE LOAD TRANSFER MECHANISM OF FULLY GROUTED CABLE BOLTS UNDER LABORATORY TESTS

Paul Hagan, Jianhang Chen and Serkan Saydam

ABSTRACT: The load transfer mechanism of fully grouted cable bolts plays an important role in the performance of cable reinforcement systems. In order to better understand this behaviour, researchers have utilised a number of approaches including theoretical analysis, laboratory tests and numerical simulation. However, laboratory experiments are more often used because it offers a more direct and relatively accurate way to understand the physical and mechanical behaviour of cable bolts. This paper outlines the major developments and evolution in understanding the load transfer mechanism of fully grouted cable bolts under axial loading conditions through laboratory testing. The advantages and some of the shortcomings arising from previous tests are also presented. The major influencing factors that have been studied include embedment length, cable surface geometry and confinement of surrounding rock. A number of theoretical equations have been proposed based on these experiments. In conclusion, a roadmap for future research has been outlined that is necessary to better understand and improve the performance of cable bolts in stabilising underground excavations.

INTRODUCTION

A cable bolt is a flexible tendon consisting of a quantity of wound wires that are grouted in boreholes at certain spacings in order to provide ground reinforcement of excavations (Hutchinson and Diederich, 1996). They were first introduced into the mining industry in the 1960s (Thorne and Muller, 1964) and since the early 1970s have been used in both hard rock and coal mining operations. Over time, cable bolts have become the dominant form of ground support particularly in highly stressed ground conditions.

Originally, cables were only used as a temporary reinforcement element. This was due to the fact that many earlier cables were made from discarded steel ropes which had very poor load transfer properties as a consequence of their smooth surface profile. Over subsequent years a number of modifications have been made to the basic plain strand cable such as buttoned strand (Schmuck, 1979), double plane strand (Matthews, et al., 1983), epoxy-coated strand (Dorsten, et al., 1984), Fiberglas Cable Bolt (FCB) (Mahe, 1990), bincaged strand (Hutchins, et al., 1990), bulbed strand (Garford, 1990), and nucaged strand cable bolts (Hyett and Bavden, 1995). These changes to the cable surface geometry have been undertaken in an effort to improve the load transfer efficiency and anchorage capacity that has resulting in the more widespread use of cable bolts for permanent reinforcement.

Despite these development in design, failure of cable reinforcement systems still occur. Rupture of the cable strands rarely occurs as it requires the shear resistance between the cable strand and the grouted surface of the strand being larger than the cable's maximum tensile capacity (Moti and Rajaei, 1992). Potvin et al. (1989) stated that it is more likely for a cable bolt to fail at either of the cable/grout or grout/rock interfaces but more likely the cable/grout interface which is a function of the load transfer between the cable bolt and rock mass.

In order to evaluate load transfer efficiency, both peak shear stress capacity and system stiffness need to be determined. Although values for these can be estimated, most researchers tend to use the load versus displacement curves obtained from laboratory tests to study and compare the load transfer characteristics of cable bolts. More recently Thomas (2012) proposed the Load Transfer Index to evaluate the cable load transfer efficiency.

Hartman and Hebblewhite (2003) stated there are three sets of factors that have an impact on the cable load transfer, including the reinforcing element, rock mass and loading conditions. The following sections outline results of the effect of relevant parameters on cable load transfer together with the evolution in design of testing facilities showing the development in understanding the load transfer mechanism of cable bolts with respect to axial loading.
The load transfer mechanics of fully grouted cable bolts: a theoretical analysis.

Eurock2014, May, 2014

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ABSTRACT: Fully grouted cable bolts are widely used in underground excavations as a means of reinforcement to the surrounding rock mass and are regarded as one of the primary supporting tendons especially in deep and highly stressed rock conditions. Despite improvements in design over the past 40 years of cable bolting systems, slippage along the cable/grout interface is still a significant issue as it has an adverse impact on the load transfer between rock mass and cable bolts. In order to better understand this issue, a review was undertaken of previous theoretical analysis models of the load transfer mechanics. The results of this study are outlined in this paper highlighting the deficiencies, as well as the range of application for each model. Based on these constitutive models, the influence of relevant factors on the bearing capacity and stiffness of cables such as grout quality and borehole diameter are described. Furthermore, since theories in rock joints are always adopted by researchers to study the behaviour of cable/grout interface, the similarities and differences between them are discussed. According to these analytical models, reasons for different performances of standard and modified cable bolts together with two different bond failure modes are concluded. Finally, the authors indicate the gap in knowledge that needs to be focused in the future.

1 INTRODUCTION

Fully grouted cable bolts have been used in the mining and underground construction industries for more than forty years. With long tendon length compared to rock bolts they are effective in anchoring deep into rock mass and reinforcing large rock blocks by increasing the rock internal strength and preventing bed separation from occurring. Although there has been a dramatic increase in the use of cable bolts in underground mines, some incidents near the cable bolting area still happen; for instance, the falling of large rock blocks, which is led by the failure of cable bolt supports, especially the relative movement along the cable/grout interface (Hutchinson & Diederichs, 1996). This is related to the generic area of a load transfer issue and demanding modifications on the design of cables.

The engineering design of cable reinforcing is primarily dependent on load-displacement curves of strands, which are obtained from pull-out experiments on grouted cables. Since cables were introduced into mining, numerous laboratory and field tests have been conducted. Cox & Fuller (1977) conducted “split-pipe pull” tests on cables, suggesting that light rust on the strand could improve the bearing capacity of cables. Stillborg (1984) performed long embedment length pull tests, discovering that an increased embedment length resulted in a larger pull force. Beyond that, Maloney et al. (1992) undertook field tests and concluded that stress change evoked by mining resulted in bad performance of traditional strands. According to Satoku & Aroman (2003), who carried out double embedment length pull tests, the corrosion coating on the strand increased the bearing capacity. This was followed by Thomas (2012), who accomplished laboratory short encapsulation pull tests on nuteched cables with results that the nutech geometry improved the stiffness of cables up to two orders of magnitudes. These tests are successful in understanding the behavior of grouted cable bolts and helping engineers to modify relevant parameters in practice to improve the load transfer efficiency of strands.

However, compared with physical experiments, limited research has been carried out on the theoretical analysis to explain the load transfer mechanics between rock mass and cables. This paper aims to present a review of previous theoretical study in this area. Relevant analytical models and their basic deducing process are given. Following that, some parametric studies relied on those models are referred to. The authors also provide the shortcomings and applied range of each model. Based on these shortcomings, the reasons for the different performance of plain and modified cables, as well as two different bond failure modes, are ultimately concluded.

2 LOAD TRANSFER MECHANICS

A conceptual model termed the “Bond Strength Model” or BSM was proposed by Yuziei & Kaiser (1992) to study load transfer mechanics of fully grouted cable bolts. The surface of a cable was simplified to be a zigzag geometry simulating a roughened joint which is illustrated in Figure 1.
Consideration of the factors impacting on the design of the laboratory short encapsulation test for cable bolts. 8th Asian Rock Mechanics Symposium, October 2014

8th Asian Rock Mechanics Symposium

Consideration of the Factors Impacting on the Design of the Laboratory Short Encapsulation Test for Cable Bolts


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Abstract

Fully grouted cable bolts were first introduced into the mining industry in the 1960s and they have played an increasingly important role in ground support particularly in both underground coal and hard rock mining. While there has been much research and development in cable bolt design, the failure of cable bolting systems especially slippage at the cable/grout interface is still a significant issue being reliant on the load transfer between surrounding rock mass and cable bolts. In order to better understand this mechanism and evaluate the influence of relevant parameters on the load bearing capacity of cable bolts, various methods have been devised over time including single embedment length test, double embedment length test, and the “split-pipe pull/push” test. The Laboratory Short Encapsulation Pull Test (LSEPT) is perhaps the most recent development in testing methods to assess the load transfer behaviour at the cable/grout and grout/rock interfaces. However, recent work has identified a number of issues with this method as outlined in this paper. Firstly, the diameter effect of the rock sample which is used to confine the grouted cable bolt is studied since the traditional LSEPT in the British Standard is only limited to a relatively small diameter of 142 mm being approximately only three times the diameter of some of the larger cable bolts. As well, the influence of bearing plate on anchorage performance due to similar dimensions of the hole size is considered, proposing an appropriate parameter dimension for the bearing plate. A modified version of the test method is proposed and is presented in this paper. This paper outlines the results of a study on some of the design parameters that formed the basis of the new modified test design.

Keywords: Modified LSEPT, Load transfer behaviour, Cable bolt, Cable/grout interface, Grout strength
Mechanical Properties of Cementitious Grout Serving in Fully Grouted Cable Bolting Systems

J Chen², P C Hagan² and S Saydam²

ABSTRACT

Fully grouted cable bolts have been used in underground mining industry for more than 40 years and are becoming more and more popular especially when severe geological conditions are encountered, such as high stresses and large cross-section excavations. The axial performance of cable bolts is mainly relied on the load transfer process between the cable itself and surrounding rock masses via grout annulus. Therefore, the selection of grout plays a significant role in determining the reinforcement quality for underground openings. In order to better understand the mechanical properties of StrataBinder HF grout, which is one type of cementitious grouts commonly used in Australian underground coal mines, plenty of unconfined compressive tests are conducted on it. Following diverse standards, two different kinds of samples are prepared and tested with the w/c ratio ranging from 0.35 to 0.45. During the test important mechanical properties including uniaxial compressive strength (UCS) values, Young’s modulus, Poisson’s ratio, and so forth are recorded. Based on experimental results, the effect of w/c ratio on the mechanical properties of StrataBinder HF grout is studied. Beyond that, influences of sample size on the failure mode, peak strength as well as residual strength of this kind of grout are summarised and analysed.

INTRODUCTION

The stability of underground excavations including drifts, open slope backs, permanent openings and so forth is always the most significant issue with which mining engineers are concerned due to the fact that any instability behaviour is likely to result in a loss of life and property. In view of this problem, most excavations in underground coal mines are always stabilised to guarantee the completeness of surrounding rock masses. In fact, Hoek and Brown (1988) suggested that: ‘The principal objective in the design of underground excavation support is to help the rock mass to support itself’. In order to realise this aim, fully grouted cable bolts are widely used in underground coal mines to sustain the dead weight of separated rock mass, reinforcing the bedded rock masses together.

According to the fundamental classification of rock reinforcement system defined by Windsor (1997), fully grouted cable bolts are involved in the continuously mechanically coupled (CMC) scheme. Therefore, the axial performance of fully grouted cable bolts is mainly relied on the load transfer between surrounding rock masses and bolts via the grout annulus (Fabjaneczyk and Tamrini, 1997). Although there are many different kinds of grout used in underground coal mines for rock reinforcement tendons, such as polyester resins, cementitious grouts and shotcrete, the cement-based grouts are more popular for cable bolt usage.

In this case, cementitious grout properties have a significant effect in determining the load bearing capacity of cable bolts. Initially, Stellborg (1984) conducted pull-out tests on 15.2 mm plain strand, using ordinary Portland cement with two different water/cement (w/c) ratios, namely 0.3 and 0.6. The results showed that both the ultimate as well as the residual pulling load were relatively larger when lower w/c ratio was adopted. However, it should also be mentioned that the chemical adhesion provided from those two different grouts on the cable bolt was the same, representing the pulling force at the general bond failure was not influenced distinctly by different w/c ratios. Similar results were also verified by later researchers under both static (Corsi, 1990; Hassani and Rajabi, 1990; Hassani et al., 1992; Diederichs et al., 1995; Chen and Mitri, 2005) and dynamic loading conditions (Fanah and Aref, 1986), while the only difference is that Hassani et al. (1992) and Chen and Mitri (2005) studied the effect of w/c ratio on the load bearing capacity of cable bolts at different embedment lengths. In the same period, considering the Portland cement grouts were commonly used in underground cable bolting systems, Heyet, Bawden and Coulson (1992) undertook a comprehensive study to evaluate the physical and mechanical properties of this grout. The w/c ratio ranges were ranged from 0.70 to 0.85 and corresponding parameters including density, UCS, Young’s modulus and so on were given. This kind of research provides an essential element to optimise

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AUSROCK 2014: THIRD AUSTRALASIAN GROUND CONTROL IN MINING CONFERENCE / SYDNEY, NSW, 3-6 NOVEMBER 2014

UNSW Mining Engineering
The influence of concrete sample testing dimensions on assessing cable bolt load carrying capacity. Coal2015, February 2015

2015 Coal Operators’ Conference
The University of Wollongong

THE INFLUENCE OF CONCRETE SAMPLE TESTING DIMENSIONS ON ASSESSING CABLE BOLT LOAD CARRYING CAPACITY

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ABSTRACT. This paper presents the results of a study into the influence of size of the test sample on the maximum load carrying capacity of cable bolts. As part of the design for the standardisation of the laboratory pullout test, it was previously found that the size of the sample in which the cable bolt is embedded can influence the behaviour of the cable bolt in terms of the peak load carrying capacity. This testing was done with a low capacity plain strand cable bolt with the sample in an unconfined state. Confinement of the sample during testing better simulates the in situ condition of the interaction between the cable bolt and surrounding rock mass. A test program was undertaken to assess whether there was any significant difference in the load carrying capacity with varying diameter of test samples and at different levels of confinement. A series of pull-out tests were conducted on cable bolts embedded into samples varying between 150 mm and 500 mm in diameter that were placed within a steel cylinder to provide confinement to the test samples. It was found maximum load varied with the test sample diameter up to some threshold diameter but that confinement pressure also had a significant effect on the load carrying capacity of a cable bolt.

INTRODUCTION

The application of cable bolt systems has advanced rapidly in recent years due to better understanding of the load transfer carrying capacity mechanisms and the advances made in cable bolt system technology. Cable bolts are used as part of temporary and permanent support systems in both civil tunnelling and mining operations throughout the world. In mining they are used for slope stability applications in surface mining and a variety of ground support purposes in underground operations such as stoping, roadway development and shaft sinking. Cable bolts are used to prevent the movement between discontinuity planes by transferring load across the discontinuity when relative strata layer movement takes place with separation.

The most common type of failure mechanism identified in the field is failure at the cable-grout interface (Hyett, Moussavi and Bawden, 1986; Singh et al., 2001). This type of failure is common due to insufficient frictional resistance between the cable strand and the nongrout material usually due to poor ground conditions and/or poor quality control at installation which leads to weak shear bond strength at the interface. This will often result in premature failure of the system before the steel capacity is mobilised. Due to the vast majority of failures being identified at the cable-grout interface, it can be concluded that a standardised testing methodology should focus on failures at the cable-grout interface (Rajaei, 1990; Hutchinson and Diederichs, 1996).

As reported by Hagan, Chen and Saydam (2014), a range of testing methods has been developed over the years including the double embedment and more recently the Laboratory Short Encapsulation Pull Test (LSEPT). The latter overcomes many of the deficiencies in the earlier tests. An issue with the LSEPT method highlighted by Thomas (2012) is the use of a small diameter test sample of approximately 142 mm placed within a pressurised Hoek cell arrangement and its inability to withstand the torsional loads generated during a pull-test. Rajaei (1990) reported a study on the anchorage strength of cable bolt and the effect of the diameter of the test sample. Nearly 300 pull-tests were conducted using test samples in an unconfined state in order to define the characteristic and behaviour of the cable bolt element using conventional grout and grout-aggregate. The cable bolt used was a plain strand cable with a diameter of approximately 15 mm in test samples having a constant embedment length and borehole diameter. Tests were conducted in test rock samples having diameters ranging between 100 mm and 300 mm. As the results in Figure 1 show, the load carrying capacity of the cable bolt varied with sample diameters up to 200 mm beyond which there was no change. This phenomenon was due to the stress generated with the test sample as a result of the load transfer between the cable bolt, grout and rock. Rajaei recommended that pull-out tests be standardised to test samples having a diameter of 250 mm.

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