Quantifying Creep Behaviour in Polyester Resin and Grout

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ABSTRACT

This report entails the findings of a current final year research project which aims at quantifying the creep behaviour in polyester resin and cement grout through the results gathered from laboratory testing. An extensive review into existing literature related to the project was undertaken to gain knowledge in the area of bolting and time-dependent deformation of materials. It was decided that two separate tests would provide the data needed to fulfil the scope and objectives. The tests chosen were:

- UCS Machine deformation testing; and
- Laboratory Short Encapsulation Pull Test (LSEPT).

Based on past research in the scope of the project, a methodology was developed along with measuring techniques to accurately monitor the deformation. Some hazards and risks associated with the project were identified as part of a risk management plan. These hazards were then ranked and control measures were developed to control each of the identified hazards. The results obtained from each of the laboratory experiments were analysed and evaluated in excel. A series of graphs and tables were produced to showcase the rate of creep, shear strength and strain for each of the test subjects. Based on the analysis, the main conclusions and recommendations were:

- The rate of creep for from the pull test suggested that water based resin deforms the most under an induced load whereas grout tends to deform the least;

- Long term creep testing on water and oil based resin yielded a peak strain of 1.11% and 0.72% respectively. The trend of creep in this case did not conform to a standard creep curve since stress relaxation was introduced due to loading and unloading of the samples over the duration of the test;

- The highest shear strength was recorded for the oil based resin at 8.47 MPa. This compared to the 5.5 MPa for grout and 4.51 MPa for water based clearly shows that the oil based resin resisted the highest load; and

- Further testing be done on each of the materials to acquire consistent results. This would increase the accuracy and validity of the data related to each material.
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1. PROJECT INTRODUCTION

1.1 BACKGROUND

Rock bolts and cables bolts have become one of the main forms of support for most geotechnical excavations in the modern age. It is used due to the high level of successful implementation over the past few decades. Rock bolts consists of a steel rod inserted into a drill hole with an anchor at one end and face plate and nut at the other. Once in the hole, the void around the bolt is filled with a bonding material which bonds the bolt to the surrounding rock mass. The bolt is then tensioned to a specific load to support the excavation. Cable bolts are installed in the exact same manner, however the cable consists most commonly of 7 wire strands woven together to form a strong steel cable (Hem, 2014).

Various studies and tests have been done to evaluate and test the performance of bolts in the underground environment. Limited tests however, have been conducted on the specific subject of bolt creep. Creep is defined as a measure of deformation due to an induced stress that is less than the yield stress (Mirza, 2016). The key area associated with creep within the bolting process is the bonding interface between the bolt and the surrounding rock mass. Since the bolts are pretensioned to a specific load, they can experience some deformation sometime after the installation. The creep in roof bolts leads to the loosening of bolt caps which can result in localized instability of the roof.

1.2 SCOPE

The scope of this project is to establish the creep behaviour of products used in bonding rock bolts to the surrounding rock mass. Two common bonding products used in the industry were identified for further testing. The first product is a cement grout which is mostly used as a post-installation adhesive that bonds the bolt to the surrounding strata after the bolt is tensioned. The second product is a polymer based resin, which is either mixed with an oil based or water based hardening agent (catalyst) to bond the bolt to the rock mass during installation. The resin usually has a very quick set time, which allows for more efficient bolting since the bolt can be tensioned after a short period of time. Two tests would be carried out in order to determine the creep experienced by the materials. A deformation test would be done on the samples when cured along with pull out tests to determine the creep within a more practical application.
1.3 **AIMS AND OBJECTIVES**

The sole aim of this project is to quantify the creep behaviour in polyester resin and grout. To achieve this, some objectives have to be satisfied and include:

- Conduct research on bolting support used in the mining environment with special attention given to bolt anchoring;
- Review of past trials and similar tests which supports the current project and provides guidelines for creep testing;
- Develop a test procedure for data collection based on conducted trials and requirements of the proposed project;
- Outline and identify the key task and activities associated with the project;
- Conduct a risk analysis on the overall project and determine the best control measures to manage the identified risks;
- Analyse the difference in creep experienced between the two resin products and the grout sample;
- Produce a graphical representation of the deformation experienced by each test sample; and
- Analyse key factors that has the possibility of influencing the results.

1.4 **EXPECTED OUTCOMES**

Based on the literature review, it is expected that:

- Deformation experienced by the resin samples are higher than the grout samples;
- Test results would quantify the creep experienced due to industry related pretensioning;
- The difference in creep between the two resin samples are minimal; and
- Resin samples fail at higher loads than grout samples.
2. LITERATURE REVIEW

2.1 ROOF BOLTING ADVANCEMENTS

2.1.1 Overview

Rock bolts are extensively used throughout the mining industry for supporting underground excavations. Roof bolting is an efficient and effective technique for strata control and has undergone significant changes over the past 40 years. Most of these changes were driven by the need for mine safety, productivity and cost reduction. Bolting in general controls strata by applying confinement to a specific region. It confines through a friction force, suspension effect or a combination of both (Kristjansson, 2014). The bolt is generally anchored in a unit of high strength such that it transfers pressure through an unstable face to prevent unit separation. Bolting also aims to control failure along major and minor geological structures within the rock mass. These structures can be in the form of bedding planes, fracture networks, joints, discontinuities and faults. Figure 1 below shows the general effect of a roof bolt. As seen in the figure, the bolts help prevent failure of the weak layer by applying pressure through the bolt, which is anchored in the stronger unit.

![Figure 1. General roof bolting set-up (Kristjansson, 2014).](image)

2.1.2 Principles of bolting

As mentioned earlier, the main aim of bolting is to reinforce strata by binding structured and fractured rock units together to form a larger, more stable unit. It is believed that the bolt’s binding effect aim to accomplish (Kristjansson, 2014):

- Skin control;
- Suspension;
Skin control refers to bolting of localised hazardous loose rock. Often in an excavation even with a strong and self-supporting roof, local joints, fractures or slickensides creates planes of weaknesses in the near roof or skin of the excavation. Generally short bolts are implemented in these area as prevention for a major collapse would not be necessary (Christopher, Gregory and Dennis, 1996). The suspension bolting mechanism works by joining a strong self-supporting unit to a weaker immediate roof layer. The bolt, which is in tension, then acts to suspend the weaker layer and control the likelihood of a roof collapse. Suspension has proved to be very efficient but can become harder to implement if the weak units increase in thickness (>1 m).

In the two discussed mechanisms, both relay on a strong unit to support the underlying strata. If no strong unit exists, bolting can still be implemented but in the form of stitching (beam building). This involves binding together a number of weak layers in the roof such that they form a single beam. This mechanism is still effective in resisting horizontal movement of strata and vertical movement induces further tension in the bolts that forces the layers together. However, a higher density of bolts is required in a scenario like this as the bolts have to work much harder (Christopher, Gregory and Dennis, 1996). For truss building (supplement support), the bolts alone may not be able to prevent roof failure as the immediate roof may be extremely weak. In this case, additional support which extends past the usual bolting horizon must be implemented. Support systems capable of this is include cable bolts, standing support or truss systems that is able to carry any induced load from the highly fractured roof. In most of these situations the roof bolts are primary just for preventing localised failure of the immediate roof (Kristjansson, 2014).

2.1.3 Transition from mechanical to chemical anchoring

Bolts can be anchored in a couple of different ways. Mechanically anchored bolts comes in two forms, slot and wedge bolts or expansion shell bolts, both of these anchor themselves in the strata by the means of expanding when installed. These bolts however, had many problems that led to lost efficiency from anchoring in weak sedimentary layers and a considerable amount of creep was experienced especially when blasting took place. In an attempt to overcome some of these problems, chemically anchored bolts were introduced. The main objective of these bolts
was to improve overall bolt performance. The performance was greatly improved as early tests demonstrated an increase in support stiffness (Mieczyslaw, 2000). The stiffness of the chemical supports was improved due to the increased anchorage length and bond strength between the bolt and rock interface. Polyester resin is mostly used as the chemical anchor for rock bolts. Resin relies on its shear strength to resist bolt movement within the bore hole. It is important for the bolt-resin and the resin-rock interface to bond properly as this would affect the stiffness of the support (Hem, 2014). Figure 2 shows the difference in displacement experienced by mechanically and chemically anchored bolts.

![Figure 2. Difference in deformation experienced by anchoring system (Hem, 2014).](image)

As seen in Figure 2, polyester resin anchors experienced much less displacement when compared to mechanically anchored bolts. For this reason, chemical anchorage in rock bolting became very popular. Further development in support stiffness was made with the use of fully encapsulated resin systems.

2.1.4 **Installation of fully encapsulated resin bolts**

A fully encapsulated resin bolt is one of the most sophisticated anchoring systems in current use. It is mostly used as it incorporates most of the advantages from other bolting systems. Installing a resin bolt however, is not very straight forward. It requires precision and great operator skills to install bolts effectively (Hoek, 1987). There are many aspects of bolt
installation that can affect bolt performance. One of the most important aspects is the resin to catalyst mixture which has to be precise. Catalyst is a compound added to the resin which speeds up the rate of a chemical reaction and causes the resin to set. Different catalyst compounds exist, water based or oil based. The mixture of resin to catalyst must be perfect to ensure proper setting and to achieve maximum strength.

Another aspect which affects bolt performance has to do with the installation itself. In most cases a two-stage resin capsule is used to install a fully encapsulated bolt. A fast setting resin at the top part of the capsule and a slow set resin at the bottom end. The aim of the fast set is to anchor the bolt, which is being installed, fairly quickly. Once the fast resin is set, the bolt can be tensioned which thereafter the slow set resin holds the tensioned bolt in place. It is crucial to ensure the correct RPM is used when spinning the bolt as this insure proper mixing and reduces the risk of the plastic cartridge affecting the bond interface. The bore hole should also not be over drilled as this will affect the anchoring length of the bolt (Ferreira and Franklin, 2008). Shown in Figure 3 below is the general fully encapsulated bolting set-up with a two-stage resin capsule.

![Figure 3. Fully encapsulated resin bolt set-up (Hoek, 1987).](image-url)
2.2 ADVANTAGES AND DISADVANTAGES OF BOLT SYSTEMS

As mentioned in section 2.1.3, resin anchorage incorporated most of the advantages from other bolting systems, hence why the resin system is such an effective method of ground control. Table 1 below compares the advantages and disadvantages of a resin anchored system to both cement grout and mechanical bolt systems.

<table>
<thead>
<tr>
<th>Anchor Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin</td>
<td>• High strength and stiffness</td>
<td>• Higher cost $/kg</td>
</tr>
<tr>
<td></td>
<td>• Convenient to use</td>
<td>• Requires proper installation</td>
</tr>
<tr>
<td></td>
<td>• Used in a variety of rock masses</td>
<td>• Consistent mixing is required</td>
</tr>
<tr>
<td></td>
<td>• Early pretension can be applied</td>
<td>• Limited shelf life</td>
</tr>
<tr>
<td></td>
<td>• Installation is quick</td>
<td>• Requires accurate drilling</td>
</tr>
<tr>
<td></td>
<td>• Provides immediate support</td>
<td>• Needs skilled operators</td>
</tr>
<tr>
<td></td>
<td>• Shorter critical bond length</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td>• Simple system</td>
<td>• Drill hole diameter is critical</td>
</tr>
<tr>
<td></td>
<td>• Quick to install</td>
<td>• Corrosion is a problem in long term supports</td>
</tr>
<tr>
<td></td>
<td>• Least expensive for materials</td>
<td>• Many mechanical parts</td>
</tr>
<tr>
<td></td>
<td>• Inexpensive system</td>
<td>• Relatively low stiffness</td>
</tr>
<tr>
<td></td>
<td>• If properly installed can be durable and competent</td>
<td>• Experiences high creep</td>
</tr>
<tr>
<td></td>
<td>• Provides good corrosion resistance</td>
<td>• Requires special installation for tensioning</td>
</tr>
<tr>
<td></td>
<td>• Requires special installation for tensioning</td>
<td>• Has to cure for several days before applying load</td>
</tr>
<tr>
<td></td>
<td>• Provides good corrosion resistance</td>
<td>• Generally not applicable in area in need of immediate support</td>
</tr>
</tbody>
</table>

Source: Ferreira and Franklin (2008); Hoek (1987)
2.3 BOLT PERFORMANCE

2.3.1 Overview

Since bolts are so widely used within the ground support industry, the measurement of performance is essential in further developing and improving current systems. Many standards of measurement have been established for a variety of performance parameters. The parameters found to effect bolt performance, as outline by Holden and Hagan (2014), the most are:

- Borehole diameter;
- Embedment length;
- Improper Installation;
- Confinement conditions;
- Bolt geometry and configurations; and
- Quality of bond material.

2.3.2 Testing of bolt performance

The mechanisms that lead to the failure of bolts is complex and relies on the interaction between the bolt, the rock mass and the bonding material. The four main failure mechanisms are; bolt-resin interface, resin column failure, rock-resin interface and rock failure surrounding the borehole. The most common mechanism is the failure along the interface between the resin and the bolt. This occurs as a result of insufficient frictional resistance between the bolt edges and the bond material.

A wide range of testing methodologies has the potential to test the performance of bolts. The most common and mostly used is the pull test. For this testing method however, there is no universally accepted method which is suggested for testing bolt performance (Holden & Hagan, 2014). It was found that the most appropriate method for pull out testing is the Laboratory Short Encapsulation Pull Test (LSEPT). This test is designed to be simple and quick, and can be conducted with the use of limited specialized equipment. Although the LSEPT provides data on the strength and deformation of the encapsulation is cannot be used for quality control as it does not generally provide a measure of resin mixing which forms part of the full bolting system in field.
2.4 TIME-DEPENDENT DEFORMATION

2.4.1 Overview

Time-dependent deformation undergone as a result of an induced load which is less than the yield point of that material can be referred to as creep. Materials seldom recover from creep-strain which means the deformation is largely plastic. Creep can be experienced by various types of ground support and it reduces the effectiveness of the support to hold up the roof. If heavy creep is experienced by a bolt it can lead to localised sagging of the roof. Therefore, it is important to ensure the performance of the bolts are maximised since this will lower the chances of excessive creep. A graphical representation of creep relates strain to time. There are three stages within the creep curve as detailed by Brantut et al (2013): primary or decelerating creep, secondary or steady-state creep and tertiary or accelerating creep. Figure 4 shows a typical graph for creep.

![Creep Graph](image)

Figure 4. Typical creep graph showing the three stages of creep (Brantut et al 2013).

2.4.2 Creep in rock

Time-dependent deformations in hard rock can be referred to as creep. These deformations can be described as creep of the intact rock, which results from micro fracturing and leads to volumetric and shear strain, or as creep along joints which results in normal shear and compression movements along the discontinuities. Factors that govern creep rates in intact rock is stress, confinement and moisture content. In joint structures, creep is mostly governed by the geometry, extent of the fractures and their relative orientation with respect to the excavation. In most cases creep rates along fracture systems are more common since the shear strength of the fractures are less than that of intact rock (Glamlheden and Hokmark, 2010).
Creep deformations in joint systems are more common if the networks are filled with material. The movements in this case would be where the most unfavourable conditions exist in terms of joint geometry with respect to the excavation. Although the study of long-term displacements is limited for hard rock, some tests have been done to show that rock units do experience creep under stress conditions. The extent of the displacement is governed by the underground conditions. In-field testing showed that near-field creep can affect excavations over the long term but with the limited study, rates and implications have not been established (Glamheden and Hokmark, 2010).
2.5 Creep in Chemical Bonding - Similar Trials

2.5.1 Overview

Research on chemical bonding deformation showed that, a limited amount of tests has been done to quantify the time-dependent deformation for materials such as resin or grout. Most completed studies looked at the deformation over the short term and only focused on either resin or grout. Some of these studies also looked at overall bolt displacement to help quantify bolt performance. The studies that proved to be of importance were assessed for their relevance to the proposed project and some of the limitations were identified.

2.5.2 Creep testing on grout

As part of a time-dependent deformation project, the University of Wollongong (UOW) undertook testing using two commonly used cement grout products. The project was aimed at testing the uniaxial compressive strength (UCS), elastic modulus and creep of each sample. All the samples were tested in the lab using a standard test developed by the UOW. This particular test was found to be relevant to the proposed project since it sets a standard procedure for the testing of creep using different materials.

Both samples were loaded to 100 kN in constant compression for 15 min. It was found that the samples did not experience any significant creep in the short term with the highest recorded strain value being only 0.27%. The difference in creep experienced between the two samples was found to be only 0.04%, which is a very insignificant value. The main limitation of this test, as outlined in the paper, is that the creep was measured over a very short period of time, 15 min. With the current objectives of the proposed project, the time frame for which measurements are taken would need to be extended to show the effects of long-term creep. Therefore, the standard test procedure in this paper would be used in the proposed research project but would be adjusted to test the long-term creep effects of various grouts and resins (Mirza, 2016).

2.5.3 Resin anchored bolt performance

The International Journal of Rock Mechanics and Mining Sciences posted an article which discussed the performance testing of fully encapsulated resin bolts. A test was developed to quantify performance of these bolts based on some field-testing and mostly laboratory load-displacement results. The bolts were installed in an underground environment and were overcored to retrieve samples ready for laboratory testing. Testing of overcored samples gives
a good indication of the geological characteristic within the study area and it provides an indication of stiffness, peak load and residual loads. Overcoring also provides other important information regarding the bolt system such as resin mixing effectiveness, problems with gloving, resin migration and over drilling of holes. Some very fractured samples were recovered from the study area however, short samples of 300 mm, in sections where the rock is less fractured, was prepared for laboratory testing. Each sample was tested until failure.

The paper concluded that the weakest region in the bolt encapsulation is the toe area. Results proved that bolts experienced more deformation at this location due to poor mixing and it suggested that the performance of a bolt is highly dependent on the resin mix quality and bolt plating. By knowing this, special attention should be given to these areas when preparing samples for testing in the proposed project. The journal overall has relevant information which supports aspects of the project however, test were done using the same resin. This means that different types of resins could not be compared which is one of the objectives in the proposed project (Villaescusa, Varden, and Hassell, 2007).

2.5.4 Summary and relevance of trials

In summary, both these trails on grout and resin samples were found relevant to the project since they address key areas to which special consideration should be given. The experimental investigation on grout proved that it should behave brittle and subsequently experience small amounts of creep. It also provided insight to an experimental procedure for creep testing. The trail on resin performance concluded that the strength is highly depended on the mix quality and thus by knowing this, poor mixing quality can be minimised to ensure maximum strength when testing is conducted as part of this project.
3. METHODOLOGY

3.1 OVERVIEW

As discussed in section 2.5.2, the University of Wollongong published a paper on creep in 2016 in which some industry standard test procedures were used to test creep effects in grouts. Wollongong established a method in which 50 mm cube samples are loaded in a UCS machine at a 100 kN load over a time period of 15 min. The 100 kN or 62.5 MPa load was induced within the first minute of loading meaning the loading rate is very fast. The disadvantage of this procedure is that it tests creep over a very short-term period. Thus, in order to test creep over a longer time period, the test method used as part of this project was based on the test from Wollongong but adjusted to a time period of one month. The test procedure would be repeated three times with two resin and one grout sample in each test.

Based on a review of deformation testing, a second procedure was developed as part of this project to test the total amount of creep experienced by an encapsulated bolt. Past studies by Aziz et al (2014) concluded that strength increases with curing time thus, the second procedure aims to quantify the amount of creep experienced if load is applied early after bolt installation. The LSEPT, as mentioned in section 2.3.2, was chosen to evaluate creep using a pull out load which is based on an industry pretension of 8 t. Samples would be encapsulated such that the bond length is 100 mm. This test would be carried out over a period of one week with regular measurement intervals.

3.2 METHODOLOGY FLOW CHART

3.2.1 Overview

As part of the methodology, a flow chart, as seen in Figure 5, was designed to show the various aspects of the project and how it all ties in together to produce a final result. A flow chart provides a good visual representation of the whole project. The project title was used as the start of the chart followed by objectives, scope and background information, which provided insight into the required tasks and type of testing that needs to be done. The pull test is for testing the effect of pretension on an encapsulated bolt relative to time and total displacement whereas, the UCS test is for testing deformation of the bonding material itself. In this test, the aim would be to measure total displacement over a period of one month. Both these tests produce results which can be used to identify the creep behaviour of chemical bonding products.
Quantifying Creep Behaviour in Polyester Resin and Grout

Aims, Objectives and Scope

Background Information

Methodology

- UCS Test
  - Testing at 75KN for 1 month period
  - 3 Samples of each type

- Pull Test
  - Pre-load to 8 ton for a week period
  - 6 Resin and 3 Grout samples cured.

Data Recording

Deformation results, graphs and discussion of outcomes

Figure 5. Flow chart of project methodology.
3.3 DEFORMATION TESTING

The deformation testing was conducted using a UCS machine with strain gauges attached to each sample. Test samples are 50 mm cube in size. The testing procedure is as follows:

1. Prepare three samples of the same type (resin or grout) in a 50mm cube mould and make sure they are the same dimensions.

2. Attach two strain gauges to each sample that feeds back to a data logger.

3. Set up the samples in the UCS machine one above the other. Ensure that the samples are directly aligned vertically.

4. Set up the data logger to start recording data.

5. Set the UCS machine to a 75 kN load with a loading cycle of 10 kN/min.

6. Leave samples loaded for up to a month to record long-term creep effects.

7. Repeat the above steps once for each material type.

Figures 6 and 7 display the set-up relating to the test.

![Figure 6. UCS test schematic.](image1)

![Figure 7. Actual test set-up.](image2)
3.4 ROCK BOLT PULL OUT TEST

The rock bolt pull out test was carried out over a period of one week and the interest in this test is to quantify creep of the bond materials relative to each other. The test procedure is as follows:

1. Prepare a 100 mm long threaded steel cylinder of 27 mm diameter and a rock bolt, 440 mm in length, for each test material.

2. Mix the bonding material according to industry guidelines and standards.

3. Centre the rock bolt in the cylinder and pour mixture for the full length of cylinder. Wait until resin/grout is fully set before proceeding to load the sample.

4. Set sample in load rig. Apply a constant load of 8 t (80 kN).

5. Measure drop in pressure and deformation daily for a week at a time.

6. Record data in a table for each of the samples.

7. Repeat this test three times for each material type to acquire consistent data.

Figures 8 and 9 displays the set-up relating to the test.
4. PROJECT RISK MANAGEMENT PLAN

4.1 OVERVIEW

Hamilton (2011) stated that a project risk can be defined as an uncertain event or condition that, if it occurs, will influence the project’s objectives in either a negative or a positive way. Risk management is an important aspect of any project or development. It analyses the specific hazards and risks associated with the particular project. This help all personnel involved in the undertaking to understand and be able to manage specific risks if the need arises. Risk management plans should be in place before starting a project since this will help raise awareness of the possible risks and hazards and reduce the likelihood of an event impacting the project. The risk management plan, as shown by Figure 10, for this particular project was developed in the following manner:

![Risk management process](image)

Figure 10. Risk management process Altered from (Chapman, 2014).

4.2 IDENTIFIED RISKS AND HAZARDS

The risks and hazards for the proposed project has been divided into two sections. The first section lists the hazards associated with the practical laboratory testing whereas the second section lists the hazards associated with the technical part of the project. The hazards for section one and two are listed in Table 2 and 3 respectively.

### Table 2

<table>
<thead>
<tr>
<th>Task</th>
<th>Associated Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Preparation</td>
<td>Spilling of resin and grout while preparing samples</td>
</tr>
<tr>
<td>Materials Handling</td>
<td>Possibility of dropping some materials causing harm/damage</td>
</tr>
<tr>
<td>Resin Mixing</td>
<td>Possibility of the resin setting before it is poured in the moulds</td>
</tr>
<tr>
<td>UCS Test</td>
<td>Limbs getting trapped, machine failure and sample chip projectile</td>
</tr>
<tr>
<td>Pull Test</td>
<td>Mechanical failure of pump, hose or bolt mechanism</td>
</tr>
<tr>
<td>Laboratory Space</td>
<td>Chemical spills, sharp objects and possible projectiles</td>
</tr>
</tbody>
</table>
### Table 3

Identified hazards for technical aspects.

<table>
<thead>
<tr>
<th>Task</th>
<th>Associated Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Document Write-up</td>
<td>Computer failure leading to loss of work</td>
</tr>
<tr>
<td>Research</td>
<td>Internet connection failure</td>
</tr>
<tr>
<td>Missing Due Date</td>
<td>Misunderstanding of assessment due dates</td>
</tr>
<tr>
<td>Study Commitments</td>
<td>Spending too much time on other subjects</td>
</tr>
<tr>
<td>Transport</td>
<td>Car breakdown, unexpected traffic or other transport problems</td>
</tr>
<tr>
<td>Communication</td>
<td>Misunderstanding something said by supervisor or academic</td>
</tr>
</tbody>
</table>

#### 4.3 Qualitative Risk Analysis

As part of the risk management process, the identified hazards has to be analysed. The analysis is based on the likelihood of the event taking place and if it took place, what would the severity of the impact be. Figure 11 shows the risk analysis rating used for the project.

![Risk rating system](image)

Figure 11. Risk rating system (Iowa, 2016).

As seen in Figure 11, the rating gives a qualitative measure to an identified hazard by analysing the likelihood and related impact of the specific event. The identified risks have been analysed and are shown in Table 4 in order of severity, from high risk to low risk.
Table 4
Qualitative analysis of hazards.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Likelihood</th>
<th>Impact</th>
<th>Risk Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misunderstanding of assessment due dates</td>
<td>Possible</td>
<td>Severe</td>
<td>High</td>
</tr>
<tr>
<td>Mechanical failure of pump, hose or bolt mechanism</td>
<td>Likely</td>
<td>Significant</td>
<td>High</td>
</tr>
<tr>
<td>Possibility of the resin setting before it is poured in the moulds</td>
<td>Very Likely</td>
<td>Significant</td>
<td>High</td>
</tr>
<tr>
<td>Limbs getting trapped, machine failure and sample chip projectile</td>
<td>Possible</td>
<td>Significant</td>
<td>Moderate</td>
</tr>
<tr>
<td>Possibility of dropping some materials causing harm/damage</td>
<td>Likely</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Chemical spills, sharp objects and possible projectiles</td>
<td>Likely</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Car breakdown, unexpected traffic or other transport problems</td>
<td>Very Likely</td>
<td>Minor</td>
<td>Moderate</td>
</tr>
<tr>
<td>Spilling of resin and grout while preparing samples</td>
<td>Likely</td>
<td>Minor</td>
<td>Moderate</td>
</tr>
<tr>
<td>Spending too much time on other subjects</td>
<td>Possible</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Computer failure leading to loss of work</td>
<td>Possible</td>
<td>Significant</td>
<td>Moderate</td>
</tr>
<tr>
<td>Internet connection failure</td>
<td>Unlikely</td>
<td>Minor</td>
<td>Low</td>
</tr>
<tr>
<td>Misunderstanding something said by supervisor or academic</td>
<td>Possible</td>
<td>Minor</td>
<td>Low</td>
</tr>
</tbody>
</table>

As shown in Table 4, the hazards were ranked from the highest risk to the lowest risk. This gives a good indication of which hazards have the potential to impact the project significantly. Special attention should be given to the response measures of these risks since controlling them are essential for the successful execution of the project.

4.4 Planned Risk Response

The planned risk response outlines the controls put in place for ensuring that the identified hazards does not significantly affect or delay the project. The controls have been developed based on past experiences with similar hazards. The response plan has been designed in such a way that makes it easy to read and simple to understand. This is a key aspect for any risk response plan. Table 5 shows the planned risk response for the proposed project based on the identified hazards. These measures should be implemented to ensure successful completion of the project.
<table>
<thead>
<tr>
<th>Hazard</th>
<th>Risk Rating</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misunderstanding of assessment due dates</td>
<td>High</td>
<td>Create an assessment schedule and use a calendar with set reminders</td>
</tr>
<tr>
<td>Mechanical failure of pump, hose or bolt mechanism</td>
<td>High</td>
<td>Do a thorough inspection of the equipment before use. Also ensure the test rig is securely set-up</td>
</tr>
<tr>
<td>Possibility of the resin setting before it is poured in the moulds</td>
<td>High</td>
<td>Ensure all moulds are ready for pouring before mixing. Weight mixture accurately</td>
</tr>
<tr>
<td>Limbs getting trapped, machine failure and sample chip projectile</td>
<td>Moderate</td>
<td>Take extra caution when loading sample. Ensure safety shield is on be starting test</td>
</tr>
<tr>
<td>Possibility of dropping some materials causing harm/damage</td>
<td>Moderate</td>
<td>Wear closed in shoes and take extra care when moving heavy items. Refrain from unnecessary moving of items</td>
</tr>
<tr>
<td>Chemical spills, sharp objects and possible projectiles</td>
<td>Moderate</td>
<td>Ensure any lids are properly closed and objects with sharp edges are removed from immediate working space</td>
</tr>
<tr>
<td>Car breakdown, unexpected traffic or other transport problems</td>
<td>Moderate</td>
<td>Leave an hour earlier than required. Check car oil and coolant regularly. Ensure services are up to date</td>
</tr>
<tr>
<td>Spilling of resin and grout while preparing samples</td>
<td>Moderate</td>
<td>Use proper mixing equipment and take care when mixing</td>
</tr>
<tr>
<td>Spending too much time on other subjects</td>
<td>Moderate</td>
<td>Effective time management</td>
</tr>
<tr>
<td>Computer failure leading to loss of work</td>
<td>Moderate</td>
<td>Use USB backup for files</td>
</tr>
<tr>
<td>Internet connection failure</td>
<td>Low</td>
<td>Submit early and have mobile internet as back-up</td>
</tr>
<tr>
<td>Misunderstanding something said by supervisor or academic</td>
<td>Low</td>
<td>Consultations with supervisor on weekly basis</td>
</tr>
</tbody>
</table>
5. EXPERIMENTAL RESULTS

5.1 OVERVIEW

The project methodology, discussed in section 3 of this paper, indicates that the data was recorded with a data logger as well as a laboratory logbook. All the results were imported into excel for deformation analysis through the means of calculations, graphs and tables. From the analysis, creep between each of the bonding materials could be quantified.

5.2 LONG TERM CREEP

The recorded data from the data logger and logbook was combined in the excel spreadsheet to produce a graph showing the deformation over the 28 days of the test. During the test it was noted that four of the strain gauges exceeded the maximum designed strain however, enough data for each sample was recorded to produce valid results. Figure 12 below displays the strain experienced by the oil and water based samples over the duration of the test.

![Graph showing strain over time for oil and water based samples](image)

Figure 12. Long term creep for oil based resin.

It can be seen from the graph that both the water and oil based samples experienced similar strain trends. After the initial loading of the samples, the strain increased to a peak value which thereafter, it reduced to a residual strain. The peak strain obtained for the water and oil based was 1.11% and 0.72% respectively. The nature of the graph shows that quite a significant
amount of strain is experience within the initial stages of loading on the sample. The strain experienced during first loading cycle is called initial elastic strain. The second phase in long term creep is known as primary creep. This can be seen in Figure 12 from day one till about day six. The rate of creep is high during the early stages of this phase but decreases with time. The third phase, called steady-state creep, is where the rate of deformation follows a near linear increasing trend. This can be seen from roughly day six till day nine for oil based resin and from day five till day 17 for water based resin. During this stage in the test a peak strain was reach. The final stage of creep was not showcased in Figure 12 and is known as tertiary creep. During this stage the rate of creep tends to increase rapidly as microstructural damage had sufficient time to propagate and generally culminates in failure. It is believed that the microstructural damage develops during the steady-state phase and once the rate of creep increases due to the interaction between the micro fractures, the material enters the tertiary creep stage (French, 1991).

During the test done as part of this project, the resin did not experience a tertiary stage which follows the standard trend. From Figure 12 it is evident that during the final stage the strain was steady for a few days which thereafter, the rate decreased to a final residual value. This can be seen as an error encountered during the experimental testing. Since the UCS machine could not sustain a constant load over the duration of the test, the load was reapplied to 75 kN before every measurement was taken. This partial unloading and loading influences the total strain experienced by the sample. Figure 13 gives a graphical representation of the concept behind loading and unloading of a sample.

![Figure 13. Strain effects of loading and unloading on a material (Tanaka, 2003).](image-url)
As seen in Figure 13, the steady unloading of a sample results in stress relaxation over time which leads to a reduction in strain. This reduction is known as strain restoration. Repeating the stress relaxation for a number of cycles would yield a peak and residual creep strain. The results from the long term creep test show exactly this, confirming that the effects of stress relaxation was the reason for the experimental creep graph only partly representing the trend from a standard creep graph. The residual strain was found to be 0.97% and 0.60% for water and oil based resin respectively.

5.3 Rock Bolt Pull Out Test

The results gathered from the pull test was analysed to show the difference in deformation, shear strength, peak load and strain experienced by each of the three materials. A total of three tests were completed on each of the materials. The total deformation for each sample was recorded during the seven days of testing. After each test, the samples were loaded until failure which was dictated by a rapid increase in deformation with no increase in load. To conclude the validity of the test the failure interface was identified. For the pull test to be valid, failure needs to occur between the material and bolt interface. Each of the test samples failed in this manner, thus ensuring the validity of the tests.

5.3.1 Oil Based Resin

None of oil based resin samples failed under the normal testing conditions. Each sample deformed for a full seven days without failure. Figure 14 displays the deformation results obtained for the three oil based resin samples.

![Figure 14. Pull test results for oil based resin.](image-url)
The results for each of the oil based samples, as displayed in Figure 14, were found to be fairly consistent. All three samples followed very similar deformation trends over the duration of the test and experienced a maximum displacement between 1.5-2.5 mm.

5.3.2 Water based resin

The samples for water based resin showcased a higher displacement when compared to the oil based. The trend for the samples were fairly consistent and were near linear. Figure 6 displays the displacement results for each of the water based samples.

As seen in Figure 15, the results from the water based samples were linearly increasing. Samples two and three showed very similar results with both trends being near linear. These two samples also experienced the highest displacement of all the tested samples from the pull out experiment. Initially, three water based samples from the pull test failed prematurely. After this, three additional samples were casted for testing and their results were used in the analysis. The premature failure in the water based samples could have been caused by the presence of air bubbles in the resin mixture. The water based resin blend was found to be more pasty than the oil based mixture which in turn makes it harder for air to escape the resin.

5.3.3 Cementitious grout

Two of the three samples tested for grout did not fail under the test conditions. The grout was found to behave more brittle than the resin samples. Figure 16 graphical shows the results.
Figure 16 shows the deformation experienced by each of the grout samples over the test duration of seven days. It can be seen that the rate of deformation is fairly linear for most of the samples. The third sample, which failed prematurely during the second day of the test, showcased the same trend as observed in the early stages of the second sample. The relative slow increase in deformation for the samples shows that the grout is quite brittle when compared to the resin samples.

5.3.4 Comparison

Figure 17. Averaged deformation trend for pull out test.
Figure 17 displays the average creep trend for each of the materials. From the graph it can be seen that the oil based resin and grout samples yielded very similar results and showcased a low creep rate. The water based samples had the highest rate of creep and produced a near linear increasing trend. These samples also experienced the highest displacement at failure. In contrast, the grout samples yielded the lowest creep rate and consequently had the lowest displacement at failure of the three materials.

5.3.5 Shear strength and strain

To further compare the test samples to one another, the shear strength and peak strain was calculated for each of the materials. To ensure accuracy, the peak strain was calculated by subtracting the elastic elongation of the bolt itself under the peak load. This ensured that the true displacement in the test material was used for the strain calculation. The shear strength was calculated based on the embedment length, bolt embedded surface area and the peak load experienced by the sample. It is know that failure from a pull test is largely caused by shear, but has some component of torsional unscrewing (Cao, 2012). Due to the complexity of analysing torsional unscrewing of the bolt, failure was assumed to be caused by shear only. Figure 18 below displays the averaged shear strength calculated for each of the materials.

![Shear strength of bonding materials.](image)

It is clear from the results that the oil based resin yielded the highest shear strength out of the tested materials. It experienced peak failure loads of 135 kN on average which is much higher than the 72 kN and 90 kN experienced by the water based resin and grout respectively. The grout samples yielded an average shear strength of 5.5 MPa, which was slightly higher than
the water based resin but lower than the oil based resin. Subsequently the water based resin yielded the lowest shear strength of 4.5 MPa. Figure 19 below displays the associated peak strain experienced by each of the materials.

![Figure 19. Shear strain of bonding materials.](image)

<table>
<thead>
<tr>
<th></th>
<th>Oil Based</th>
<th>Water Based</th>
<th>Grout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Strain</td>
<td>2.5%</td>
<td>3.2%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

The strain experienced by the samples are representative of the overall material stiffness. The rate of creep, as discussed in section 5.3.4 and outlined by Figure 17, was found to be highest for the water based resin and lowest for the grout. The calculated peak strain for each material suggests that the grout is most brittle, the oil based resin is more brittle than the water based but more ductile than the grout and the water based resin is most ductile. Therefore meaning that under an induced axial load, water based resin would experience the highest amount of deformation out of the three materials.

### 5.3.6 Results summary

In summary, the results found from the pull test suggests that the oil based resin has the highest shear strength and subsequently has the highest resistance to failure. The water based resin was found to be the weakest in terms of shear strength and behaved most ductile out of the three materials and the grout samples yielded the lowest creep rate and lowest peak strain.
5.4 Extended Analysis

As part of the data analysis, an extended investigation was conducted on the results to identify factors that had the possibility of influencing the outcomes of experiments. These factors were identified to be a combination of or be related to:

- Mixing practices;
- Mixing ratios;
- Ideal conditions; and
- Equipment limitations.

5.4.1 Mixing practices

Research concluded that bonding material strength is greatly affected by the quality of mixture. As mentioned in the project methodology, section 3 of this paper, all the samples were mixed by hand. Each batch of material was mixed for at least 2 min before pouring it into the mould. In industry, the bonding material is mixed with high speed mechanical mixers to ensure that the components are properly blended together. Since mixing was conducted by hand during the sample preparation stage, some components might have not been thoroughly mixed resulting in a decreased material strength. This could have lead to some form of inaccuracy in the test results.

5.4.2 Mixing ratios

It is also important to note that the ratios used for mixing plays a vital role in the performance of the materials, especially in-situ. For example, grout is mixed beforehand with a large mechanical mixer and is then pumped into the borehole. This means that the mixture quality should be good which enhances material performance. The resin on the other hand is mixed inside the borehole for only a few seconds, which means the mixtures can vary quite significantly in terms of quality.

This varying quality in the mixing of resin is very hard to get consistent due to the amount of factors influencing the physical mixing. These include but are not limited to borehole diameter, borehole roughness, glove fingering and drill operator, to only name a few. The perfect ratio of mastic to catalyst for a consistent mixture would be 50:50. This means there is the same
amount of mastic as there is catalyst. However, the resins used in this project had a mix ratio of 93:7 for oil based and 80:20 for water based. From these mixing ratios, one would expect that given the same environmental conditions, the water based resin should have a better mix quality due to the ratio being closer to 50:50 when compared to oil based resin. This means that although the experimental results show that oil based resin, when perfectly mixed, might be stronger than water based, this might not be the case in-situ since the mixing quality has a higher chance of being good in the water based resin than in the oil based.

### 5.4.3 Ideal conditions

Another important factor to consider is that the results obtained from the experimental investigation was conducted in what is called an ideal environment. Most of the factors in an ideal environment can be controlled. This means that influencing factors such as improper mixing, glove finger and borehole inconsistencies has been minimised to obtain peak results for each of the materials. Further in-situ testing of the resins and grout could provide varying results due to the introduction of the other external influences.

### 5.4.4 Equipment limitations

Limitations in the available equipment for the experimental testing procedure had a big influence on the number of samples tested and also the accuracy of the results that were obtained. For the long term creep test, carried out in the UCS machine, only three samples of each type could be tested at a particular time. With this test having a duration of 4 weeks, it makes getting consistent results through repetition very time consuming. Having access to only one UCS machine limited the amount of tests that could be carried out during the timeframe of the project. Another aspect of the UCS machine that influenced the results is the fact that the load of 75 kN could not be sustained for the duration of the test. The load had to be reapplied before every measurement was taken. This introduced stress relaxation which lead to the test not following a standard creep curve.

For the pull test, the equipment was found to be performing well overall however, the load on the bolts were reapplied to the required load of 80 kN between measurements and since only one hydraulic ram was available for conducting the pull test, only three samples of each material could be tested in the project timeframe. In terms of measurements, load readings were conducted based on the hydraulic gauge attached to the ram. A load cell for more accurate measurement of the applied load was only acquired during the final stages of testing.
6. CONCLUSIONS AND RECOMMENDATIONS

Based on the aspects discussed in this report some conclusions could be made and include:

- Time-dependent deformation as a result of an induced load which is less than the yield strength of a material can be referred to as creep. The creep can be presented on a graph showing the amount of strain experienced over time.

- Resin bolt performance testing showed that the weakest region in the bolt encapsulation is the toe area. This is directly related to poor mixing practices thus, special attention should be given to mixing for sample preparation.

- As part of a risk management plan, risks associated with the project has been identified and ranked. The highest ranked risks are misunderstanding of assessment due dates, mechanical failure of testing equipment and the premature setting of resin. To control the risks a response plan was developed and its implementation is crucial for the successful completion of the project.

- Long term creep testing on water and oil based resin yielded a peak strain of 1.11% and 0.72% respectively. The trend of creep in this case did not conform to a standard creep curve since stress relaxation was introduced due to loading and unloading of the samples over the duration of the test.

- From the rock bolt pull test it was concluded that grout behaved most brittle while the water based resin behaved most ductile. The peak strain experienced by the samples were 2.5%, 3.2% and 1.9% for the oil based, water based and grout materials respectively.

- The highest shear strength was recorded for the oil based resin at 8.47 MPa. This compared to the 5.5 MPa for grout and 4.51 MPa for water based clearly shows that the oil based resin resisted the highest load.

- The peak average load at failure for each of the samples were 135 kN, 72 kN and 90 kN for the oil based, water based and grout respectively.

- The bonding material found to experience the highest amount of creep was the water based resin and the lowest amount was recorded for the grout.
Based on the conclusions drawn, it is recommended that:

- Further tests be done on each of the bonding materials to increase the consistency of the current results and especially for the water based resin. Obtaining multiple repetitions of the same test would ensure that the results gathered are accurate for the specific material.

- Improved equipment be acquired that overcomes the mentioned limitations. Especially the limitation of not being able to sustain a constant load.

- Bonding materials be tested in-situ. This will introduces a range of external factors not easily controlled and may produce different results. These results can then be used to directly relate to industry.

- When making cube samples, the moulds be vibrated to release any trapped air bubbles as this would reduce the amount of strain error encountered during the test.

- Mechanical mixers be used during sample preparation to ensure each of the resin and grout batches are blended thoroughly.

- The effects of industry install techniques on the shear strength of the material be analysed through borehole testing.
7. REFERENCES


