Fall 8-24-2018

Laboratory Investigations on Creep Behavior of Grouted Tensioned Rebar

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LABORATORY INVESTIGATIONS ON CREEP BEHAVIOUR OF GROUTED TENSIONED REBAR

By

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B.Tech, Karunya University, 2013

A Research Paper

Submitted in Partial Fulfillment of the Requirements for the

Master of Science

Department of Mining Engineering

in the Graduate School

Southern Illinois University, Carbondale

December 2018

RESEARCH PAPER APPROVAL

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Approved by:

Dr. A.J.S. (Sam) Spearing, Chair

Graduate School

Southern Illinois University, Carbondale

December 2, 2015

AN ABSTRACT OF THE RESEARCH PAPER OF

Naga Sai Yeshwanth Tirumalaraju for the Master of Science degree program in Mining Engineering presented on December 2nd, 2015 at Southern Illinois University Carbondale.

TITLE: LABORATORY INVESTIGATIONS ON CREEP BEHAVIOUR OF GROUTED TENSIONED REBAR

MAJOR PROFESSOR: Dr. A.J.S. (Sam) Spearing

Rock bolts constitute over 80% (Mark C., 2002) of the primary roof support systems in underground coal mines. An active rock bolt is tensioned during the installation process, while passive rock bolt is not and needs subsequent rock movement to develop a reactive force. The fully grouted passive rock bolts are widely used in the underground mines as they provide adequate support under most conditions and are easier to install than active rock bolts and less expensive. Active rock bolts are used as they can limit movement of rock by pre-tensioning on installation. In situ monitoring of instrumented active versus passive rock bolts were conducted at two room and pillar coal mines in the Illinois basin and a longwall mine in Colorado. These indicated that fully grouted active rock bolts appear to creep (load shed over time), significantly (Spearing et al., 2011). This research was conducted, assuming that the load loss in the active rock bolts is due to slippage of the resin column in contact with the weak rock surfaces and that the use of an expansive anchoring material will reduce this adverse effect significantly.

The study used sodium bicarbonate as the expansive agent added to a standard anchoring resin grout. Resin mastic is mixed with the catalyst to form a solid resin column for the rock bolts. Laboratory based experiments were conducted to observe the load loss behavior of fully grouted tensioned rebar using five types of resin formulations with different percentage expansions—,0.0% expansion 0.5% expansion, 1% expansion, 2.5% expansion, and 5% expansion

Creep was observed in all the simulated lab tests, thus concluding that creep does occur in active bolts underground. In the simulated lab tests torque wrench was used to provide tension to grouted rock bolts and with the slow loading (torqueing) methodology that had to be used, the average measured creep in tests varied from 6 to 12% over the two-hour monitoring period. Creep observed in situ is significantly more than creep measured in lab tests possibly because of the slow torqueing of the rock bolts in the lab as opposed to in situ where rock bolts are installed and tensioned rapidly by the rock bolter before the resin had reached it maximum strength. The concept of reducing the effect of creep using an expansive resin with foaming action, even though foam does significantly reduce the strength of grouts, in weak strata the improved mechanical key (between rock and grout) appears to be more critical. Foaming action with 0.5% expansion formulation appears to have merit, as it outperformed the standard resin.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

Roof falls have been a major concern in the field of ground control in underground coal mines. Many improvements have been made in ground control to prevent roof falls since the 20th century (Gardner, 1971). The study covered in this paper falls under the area of ground control, which is essential to stabilize and prevent the failure of mine openings.

Figures 1 and 2 show the historical data of critical rock fall injuries and fatalities in US coal mines from 2002. The number of fatalities resulting from roof and rib falls have declined from 12 in 2007 to 3 in 2015, due to constant efforts and concern of mine owners and due to regulations and audits undertaken by the US Mine Safety and Health Administration (MSHA), as covered by the Miner Act of 2006.
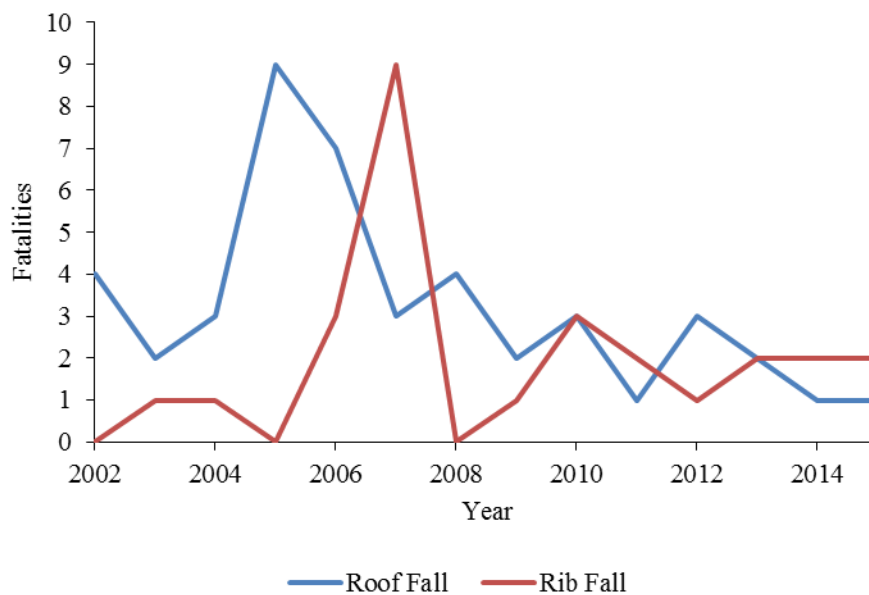
Figure 1: Rock fall fatalities from 2002 to 2015 (MSHA, 2015)

However, injuries resulting from roof and rib falls increased from 439 in 2010 to 484 in 2011 and roof fall injuries appear to be increasing. The ultimate goal for everyone in the field is

to achieve mining conditions without any fatalities or injuries. Therefore, comprehending and improving the roof support systems to provide safe mining environments is a necessity.
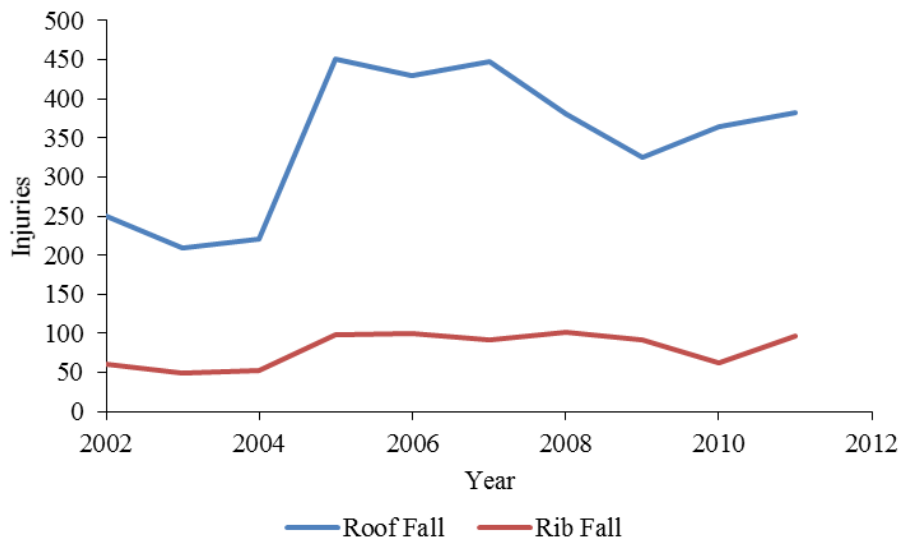
Figure 2: Rock fall injuries from 2002 to 2011 (MSHA, 2012)

Roof support systems in US underground coal mines can be divided into primary, secondary, and supplementary support systems. Primary roof support acts as the first line of defense to prevent rock falls in underground mines and to create a stable roof. Primary roof supports consist of resin grouted rock bolts installed immediately after excavation. Secondary roof supports installed as additional supports, which typically consists of cable bolts are generally installed in intersections. Supplementary roof supports are installed as additional supports to secondary supports due to poor roof conditions and typically consists of cribs and truss bolts.

Supporting the skin of rock around excavations is the main function of rock bolt systems. Primary roof support mechanism provided by the rock bolts varies with the type of ground and the types of bolts installed. Figure 3 shows the four simplified types of support mechanisms, the use of which depend mainly on the geology of the roof layers. The four types are as follows:

- Skin Control: In a self-supporting massive and strong roof, stress levels could be low. However, cracks or joints can cause occasional hazardous loose rock (key blocks). Therefore, spot bolting using relatively short bolts is adequate to prevent local loose rock from falling.

- Suspension: In mines where a much stronger roof layer overlies a weak immediate roof layer, roof bolts are anchored into the stronger overlying layer and act to suspend the weaker layer in a traditional dead weight loading design.

- Beam-Building Support: When there is no self-supporting layer in reach to create a suspension support, bolts installed tie the roof together to create a beam and the bolts act by maintaining friction on bedding planes and keying together blocks of fractured rock and controlling dilation of failed roof layers. To create an effective beam mechanism, multiple roof bolts need to be installed per area.

- Supplementary Support: When the roof is extremely fragmented, and stresses are high, roof bolts may not be able to prevent roof failure. In these cases, cable bolts and cable trusses may be necessary to carry the dead-weight load of the fragmented roof, and roof bolts act primarily to prevent the collapse of the immediate roof.

(a)   (b)

(c)   (d)
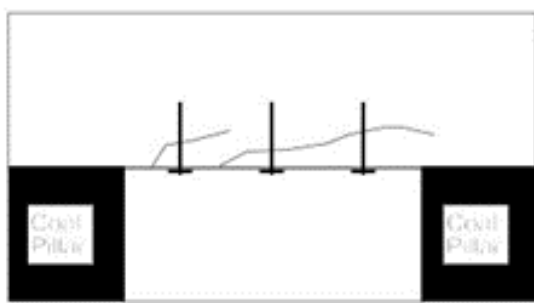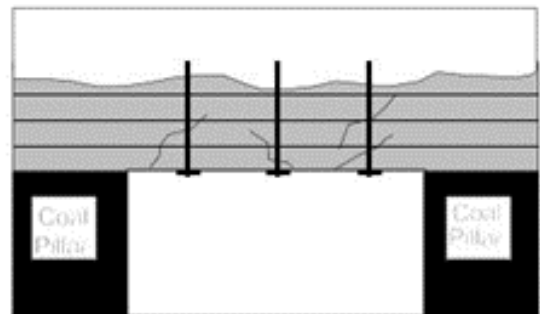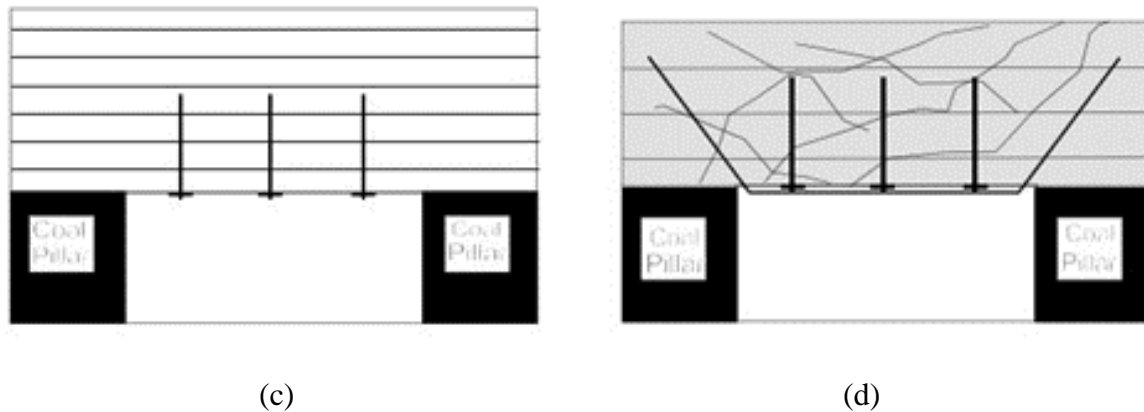
Figure 3: Rock bolt support mechanisms: (a) Simple skin support (b) Suspension (c) Beam-building mechanism (d) Keying effect of bolting (Mark C. , 2001)

Rock bolts are categorized as active or passive, based on load upon installation. Active bolts are tensioned upon installation; passive bolts tend to develop tension upon ground movement. Upon tensioning the active bolts, stabilizing immediately and under some conditions can improve the stability. Passive bolts develop tension only in response to ground movement. This research paper intends to focus on studying the load loss behavior of active rock bolts.

During normal installation of fully grouted passive bolts without any tension, the loads generated are comparatively small—up to approximately three tons (Minova, 2006). Bolts with forged heads cannot be tensioned in a conventional way and usual practice has been to use the installation drilling boom to push them against the roof as the resin cures. The drill thrust of the rock bolting machine pushes the bolt end and compressible plate against the roof as the resin sets. When point anchor or partially encapsulated bolts are tensioned, a compression zone is formed in the rock above the bolt plate which ultimately results in the tightening of discontinuities, augmenting the shear strength on discontinuity planes and increasing bolt effectiveness (Mark C., 2000). This paper focuses on the aspect of improving the effectiveness of the resin used in the installation of particularly active rock bolt system.

Resin was first introduced in United States underground coal mines during 1971, and commercial production started in 1973 (Minova, 2006). Polyester resin cartridges are the most commonly used and consists of two compartments separated by thin plastic film: one compartment consists of resin mastic, which is a mixture of polyester resin, limestone filler and additives and other compartment consists of benzoyl peroxide and fillers. The resin system uses the polymerization of polyester and styrene under the influence of the cross-linking catalyst agent benzoyl peroxide to secure roof and wall bolts (Convery, 2001). Neither mastic nor catalyst react with rock or rebar and also, offer protection to the steel rock bolts from corroding by the underground water. During the roof bolts installation, bolt is typically spun upward into the hole and this ruptures and shreds the cartridge material and initiates an exothermic chemical reaction, as the resin hardens.

To speed up the rockbolt installation of active rock bolt systems, the use of two-speed resin system has been common practice for some years (Minova, 2006). Two-speed resin cartridges typically have two distinct resin gel times— "fast" and "slow" resins— in the same cartridge, usually by modifying the catalyst strength. This saves time as the rock bolter only has to install a single cartridge and not two. In a full column anchor with two-speed resin cartridge, the upper portion of the anchor consists of fast-setting resin and the lower portion consists of a slow-setting resin. Torque delay mechanism is used while installing the bolts with two-speed resin system, the bolt is inserted and spun in the resin, when the fast resin in upper portion is set, the nut is rotated up against the plate, tensioning the system before the slow resin sets. Generally, the slow resin sets after tensioning, and this could result in tension being "locked in" so that it cannot easily dissipate like partially encapsulated rock bolt systems (Unrug & Thompson, 2002).

In situ monitoring of active versus passive bolts in coal mines has indicated that active resin grouted rock bolts could creep significantly (Spearing, 2014). It was speculated that load loss in active rock bolts is caused by slippage of resin columns from failing along the weak rock surfaces. Using an expansive fast setting resin anchoring material or active confinement could reduce or even eliminate this effect (Spearing et al., 2015). High pretension loads reduce the open joints and fractures, which significantly increases the shear strength of the discontinuities while minimizing the load loss over time (McHugh, 1999). Therefore, the tests were conducted on the different formulations of the expansion resin to achieve and retain high pretension loads.

CHAPTER 2

LITERATURE REVIEW

The extensive use of roof bolts can be dated back to early 1920's, when St. Joe Lead

Company's mine near Bonne Terre, Missouri used them (Mark C, 2002). Roof bolts act as the

first line of defense to reduce the occurrence of unplanned falls of roof and ribs. Roof bolts are

more advantageous than standing supports, such as timber posts and wood cribs used in the very

earliest days of mining, because roof bolts utilize the inherent strength of the strong rock mass

unlike standing supports (Mark C, 2001) and don't impede ventilation or the movement of men

and material. Due to the complex nature of rock stresses, various design methods for roof bolt

support system have been proposed over the years. Main design methods that are currently in use

are; experiential design, analytical design, empirical design, numerical modelling and

observational design.

Mechanical point anchors were the first used roof support system in the case of weak

laminated roofs in US underground coal mines (Mark C, 2000). The major disadvantage of the

mechanical point anchor bolts in weak strata is that they are prone to loosen as the weak rock is

crushed by the point anchor and, therefore, are limited in their application to mainly the stronger

strata. The movements in the roof allowed slippage of the mechanical anchor, causing the

delamination of the roof layers. This prompted the introduction of resin to encapsulate the bolt in

the borehole to reduce the load loss caused by mechanical point anchor.

Original polyester resin grouts were very expensive, when it was first introduced. This

limited the application of the polyester resin and it was confined to very difficult and weak

ground conditions. Resin industry has evolved over the years by putting up constant effort in

design improvements and this led to more consistent product, with wide range of applications at 30% below 1974 resin sales price (Belvins & Campoli, 2006).

The objective of using rock bolts is to provide hazard-free environment from roof falls in mines, and the usage of resin in anchoring the rock bolts increased the performance significantly. Research on tensioned point anchor systems versus non-tensioned grouted rebar was carried on in two different mining scenarios having laminated immediate roof conditions. Stankus (1990) conducted the study in a longwall mine at a 1,200 ft. depth and in a room and pillar coal mine at a depth of about 300 ft. In both mining scenarios, the performance of the tensioned rock bolts was better than non-tensioned rock bolts, and modifications conducted in both mines by installing the tensioned point anchor resin bolts improved the roof control system significantly.

Signer et al., conducted studies on active and passive bolts in a bedded mine in 1993. The load on the bolts was monitored at four locations in the tailgate roadway of a mine, with two of the locations using tensioned bolts and the other two using resin-assisted mechanical anchor bolts. The study used the passive instrumented bolts of grade-60 #6 rebar. Installed tensioned bolts were grade-60 #7 rebar with a mechanical expansion shell; resin grout was used to reduce the anchor creep. The load in the tensioned bolts was monitored using a load cell. The amount of load seen in the instrumented bolts is much greater than what the simple suspension of the rock from the main roof would produce. The additional bolt loading could have been caused by the stiffness of the fully-grouted bolts. Signer and the others concluded that the active bolts exhibited a slightly superior performance than the grouted passive rebar. However, overall analysis of the bolt loads indicated that except in some localized conditions, the performance of the active bolts and passive bolts did not differ significantly (Signer et al., 1993).

Unrug et al.(2004) conducted studies on the selection of active and passive rebar. They concluded that load transfers between the rock bolt and rock through the bearing plate while tensioning the active bolts. Tensioned bolts elongate within the elastic range and load due to tension, is effective until the bolt relaxes to its original length. When 10,000 lbf of tensile load was applied to a 4ft long and 3/4 inch in diameter steel bolts, total dissipation of the tension was experienced with 0.04 inch of ground movement. The hole diameter was not specified in the paper. Immediate roof surface might fail due to the weakening of rock properties by moisture in the mine air, resulting in movement of bearing plates, nut and dissipation of tension in the bolt (Unrug et al., 2004).

In 2011, Spearing et al., conducted studies in underground coal mines to evaluate fully grouted passive rebar (FGPR), resin-assisted mechanical anchor (RMAB), and the fully grouted tension rebar (FGTR). The team chose three different mines known as A, B, and C, with Mines A and B being room and pillar mines in the Illinois basin and with Mine C being a longwall mine in Colorado. Instrumented bolts were used in all the mines to conduct the performance differences. In Mines A and B, roof bolts were installed as a primary support, whereas in Mine C (the longwall mine), roof bolts were installed as secondary support. All the installed roof bolts were #6 grade 60 rebar (grade 60 rebar refers to a minimum yield strength of 60,000 pounds per square inch) with 0.75-inch diameter and 6 ft. long.

Initial readings in Mines A and B were delayed as the data loggers—instruments that collect data— were not intrinsically safe, so readings were taken after substantial delay (6-10 days) of bolts installation, when the rock bolts were in fresh air. Figure 4 compares the initial load data on all three types of bolts (FGPR, FGTR & RMAB) in Mine A. Initial readings from all the three mines were not significantly different. Although, readings from Mine A and Mine B

were obtained after a long delay when compared to readings from obtained from Mine C (1-2 days), they exhibited no significant difference in pre-load. Tensioned rebar exhibited loss of initial load; the exact reasons for the load loss were not investigated in this study (Spearing et al., 2011).
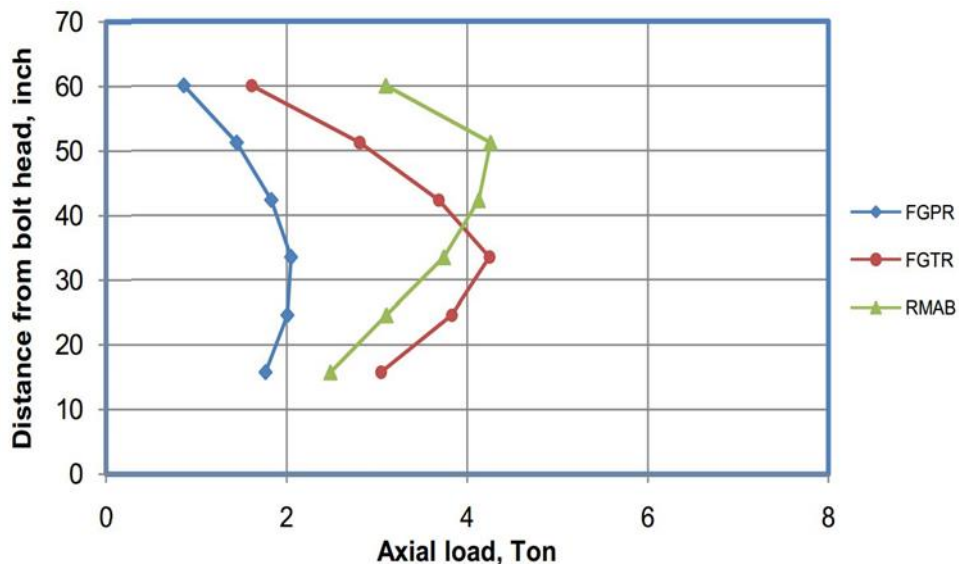
Figure 4: Average initial loads for each bolt type in Mine A *(Spearing et al., 2011)*

Spearing et al. (2015), conducted laboratory studies on #6 grade-60 active rebar encapsulated with a pourable resin with an unconfined compressive strength of 10,000 psi in a concrete block to understand the axial load on a bolt with time (i.e. creep). From the tests, it was determined that creep occurs in weaker rock due to the mechanical key failure or, stick-slip between the resin column and the rock surface. Figure 5 shows the creep with respect to time in #6 rebar tensioned to 200 lb-ft. Readings were monitored every 10 seconds; from these observations, it was determined that load loss was typical "stick-slip" which is load dropped from 8.45 to 8.25 tons and followed by a flat portion of curve. Figure 5 displays this data. The bolts could only be torqued slowly with a torque wrench and creep behavior while torqueing the bolts could not be monitored, there could have been a possibility of sudden stick-slip or load loss

while torqueing. In situ conditions could possibly have more load loss because the unconfined

compressive strength (UCS) of typical coal roof layer is 1,700 psi which is less than concrete

used of UCS 4,300 psi in the lab tests (Spearing et al., 2015).
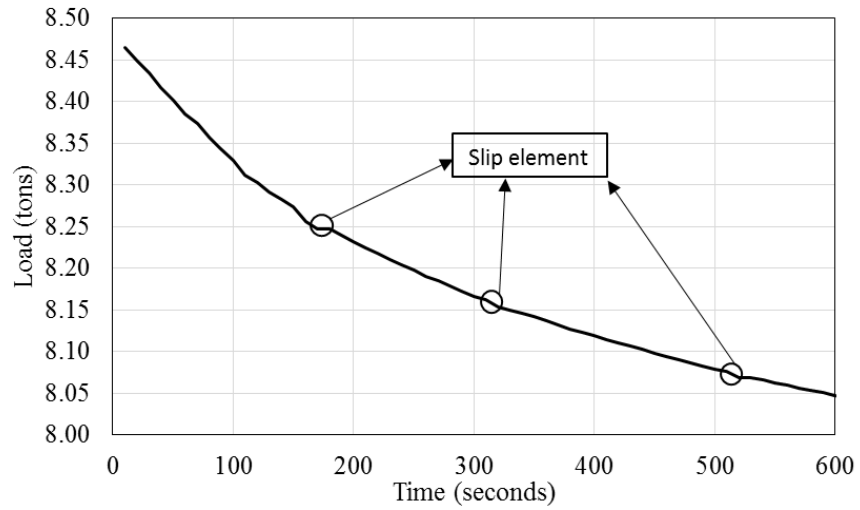
Figure 5: Occurrence of slip as creep progresses

CHAPTER 3

RESEARCH OBJECTIVES

Creep can be defined as the tendency of any solid material to deform under the influence of mechanical stress as a function of time (Brooks, 2014). Shear stresses occur between rock, resin and rock bolt, when the horizontal layers are subjected to vertical stresses. From the ground movement occurred due to these stresses, load is transferred to the bolt as grout interface (grout-rock & grout-bolt) shears. From the previous studies performed by Ray et al., comparisons between active and passive grouted rock bolts concluded that the load loss was prominent in the active rock bolts, and, therefore, the active bolts had no advantage upon the passive bolts (Ray et al., 2012). The main objectives of this study are to understand and measure the performance of grouted tensioned rock bolts in lab conditions and to test proposed ways to reduce the creep phenomenon. The research objectives listed below can help provide more insight on creep effect in tensioned rebars.

- Conduct study on the factors affecting the load loss behavior in the active rock bolt systems.

- Test the performance of the proposed expansive resin— achieved by aeration of better crystal growth— in tensioned rebar to reduce the load loss effects when compared to the standard resin.

- Conduct a performance analysis of the new proposed expansive resin with different encapsulation lengths.

CHAPTER 4

EXPERIMENTAL PROCEDURE

In this study, small-scale laboratory tests were conducted, to understand and measure the creep behavior of fully grouted tensioned rebar. #6 grade 60 rebars, which are commonly used for rock bolting in underground coal mines, was encapsulated using pourable resin (expansive and standard resin from Minova) in concrete blocks at the ground control laboratory at Southern Illinois University Carbondale to understand the behavior of creep. Test were conducted using five types of resin formulae comprising of standard formulation and 0.5%, 1%, 2.5%, and 5% expansion resins— as proposed to reduce the effect of creep. Figure 6 shows a hydraulic load cell with a capacity of 50 tons that was used to measure the pre-load and the load loss percentage on the tensioned rebar with time.

Hydraulic load cells consist of a liquid medium in a confined space connected to a dial gauge. When force is applied to the load cell, the pressure of the liquid increases and can be read directly on the calibrated dial gauge. Hydraulic load cells are sensitive to temperature changes, and they need to be calibrated to validate the manometer reading. Calibration is necessary to obtain accurate and comparative load readings and thus determine the creep effect.

Figure 6: Hydraulic load cell

The study used four hydraulic load cells with a capacity of approximately 50 tons. A hydraulic press with a capacity of 60 tons was used to calibrate the hydraulic load cells (Figure 7).
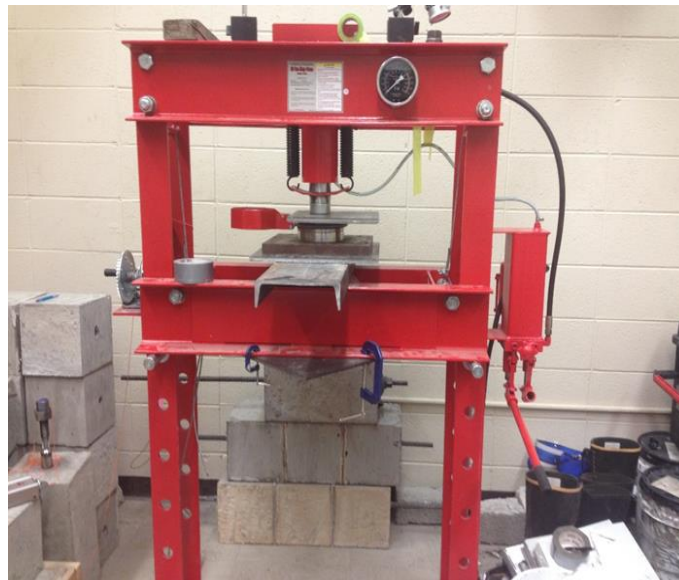

Figure 7: Calibration test of hydraulic load cell

Calibration of the hydraulic load cells took place using the following procedure:

- A hydraulic load cell was mounted onto the hydraulic press frame. For uniform distribution of the load on the load cell, flat plates were placed either side of the load cell.

- Load cells were loaded to 5 tons at regular intervals of 1.25 tons and any load applied above 5 tons is at a regular interval of 1 ton, as the smallest division on the hydraulic press manometer is 1.25 tons from 1–5 tons. and 1 ton from 5–60tons.

- The maximum load applied to a load cell was 6 tons, which is approximately equal to the tensile load produced by the 200 lb-ft. of torque on the rebar.

- Load cells are sensitive to temperatures, so the temperature control unit in laboratory was used to maintain the ambient temperature at during the calibration tests.

- Calibration can be defined as the set of operations performed to establish the relationship between the values of load applied and the corresponding values of the weighing system output. A 5-step method was followed, where load cells were loaded with five substantial equally-spaced loads, repeatedly to check repeatability, linearity and determine the accuracy of the load cell.

Figure 8 shows the calibration of one load cell; the Appendix contains the remaining calibrations. The graph was plotted with applied hydraulic press loads on the y-axis against the readings of the load cell on the x-axis. The hydraulic press is used as a load testing machine, and each load cell is a dependent variable on the hydraulic press. The graph clearly indicates that the applied load is not equal to the load measured on the load cell, representing the error in the manometer readings. To eliminate this error, calibration factor (slope) is obtained by plotting a linear regression line from data obtained on load cell against applied load. The calibration factor of load cell 1 is 1.09; this explains that the load measured on the load cell is 9% percent less than the actual applied load.
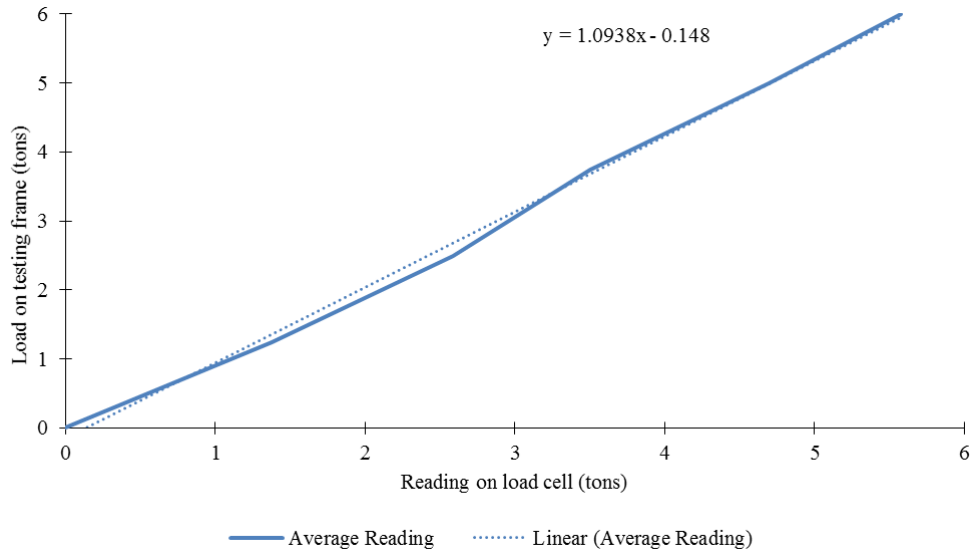
Figure 8: Calibration of load cell – 1

Table 1 represents the calibration factors of each load cell obtained from its respective graph. Calibration factors were obtained from the load cells to avoid errors.

Table 1: Calibration factor of load cells

Load Cell	Correction Factor
Load Cell – 1	1.09
Load Cell – 2	1.16
Load Cell – 3	1.20
Load Cell – 4	1.20

Three sizes of concrete blocks— having dimensions of 9×9×9", 9×9×12", and 9×9×18"— were used to perform the lab tests. The rebar was grouted with the pourable resin

into these concrete blocks with 1 inch in diameter hole (1 inch in diameter, steel rods are used

while casting the concrete blocks); 48-inch rock bolts that were threaded on both sides were cut

accordingly to test encapsulated bolt lengths of 9, 12, and 18 inches. Rock bolts used in these

experiments were already cut to an additional 6 inches more than the required encapsulation

length to be used in U-cells. Figure 9 illustrates the set-up of the hydraulic load cells. Hydraulic

load cells were placed against the flanges and thick load distribution plates were placed on the

load cells to distribute the load more evenly. Bearing plates, with 0.25 inches thick were placed

on the load distribution plate of the load cell and nuts were threaded onto bolts to tension them.

A torque wrench provided tension to the resin-encapsulated bolt (see Figure 10).

Figure 9: Experimental setup for a single test
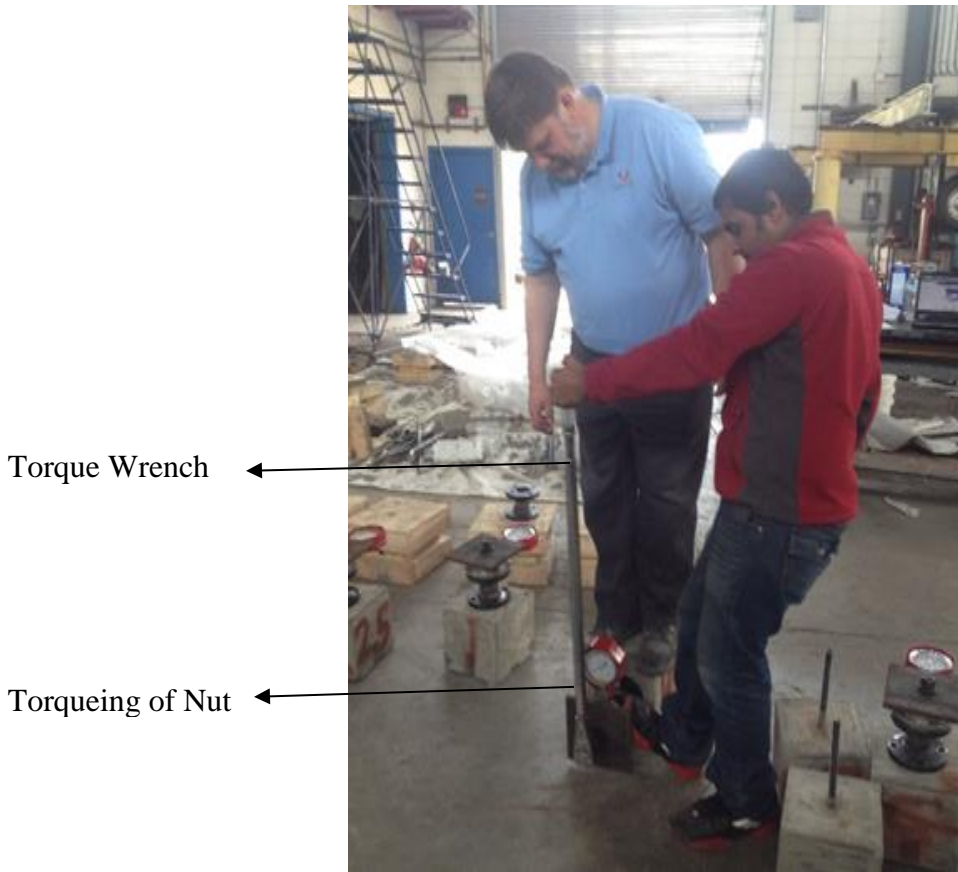
Figure 10: Torque wrench used to tension the rock bolts

Using a torque wrench, bolts were tensioned up to 200 lb-ft., and the load loss was

observed for two hours at regular intervals of 15 seconds for the first 10 minutes and at intervals

of 5 minutes for the remainder. Various parameters influencing the load loss behavior include:

- Rock/Substrate Strength: As UCS of typical shale ranges from 1410 psi (weathered shale)

  to 9064 psi (coherent shale), tests were conducted on stronger concrete with an

  unconfined compressive strength of 6380 psi and a weaker concrete with an unconfined

  compressive strength of 3480 psi. Ideally an even weaker concrete should have also been

  utilized.

- Resin Expansion Percentage: Five types of resin expansion formulae— standard, 0.5%,

  1%, 2.5%, and 5% expansions— were used to test their individual performances in trying

to reduce the creep effect. A few tests were performed with the fast setting resin on both the ends, which acts as the confinement to the slow setting resin to investigate if this had an effect on the creep.

- Encapsulation length: Tests were conducted to observe the load loss in tensioned rock bolts, using 9, 12, and 18-inch encapsulation lengths.

- Ambient temperature: Tests were conducted at 68°F and 82°F to observe the load loss at different ambient temperatures.

CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

The following experiments were conducted and analyzed as part of the research

objectives.

Effects of Rock Substrate:

Initial tests were conducted on stronger concrete (6381.66 psi) and weaker concrete (3480.91

psi) and Table 2 represents the average pre-load and load loss percentage.

Table 2: Average pre-load (t) and load loss (%) on the rebar in stronger concrete (6381 psi) and

weaker concrete (3480 psi) with 9-inch encapsulation length at 82º F (200 lb-ft. torque)

Formulation	Average (6381 psi)		Average (3480 psi)	
	Pre-load (t)	Load loss (%)	Pre-load (t)	Load loss (%)
Standard	4.6	6.6	5.5	6.9
0.5 % Expansion	5.8	5.4	6.5	5.6
1.0 % Expansion	6.0	8.2	3.1	6.4
2.5 % Expansion	8.0	10.7	3.7	6.4
5.0 % Expansion	6.2	13.4		

Figure 11 represents comparison of the pre-load attained in the rebar by encapsulating it

in the weaker and stronger blocks of concrete using five types of expansive resin formulae.

Higher pre-load in stronger concrete was attained by using 2.5% expansive resin and lower pre-

load was attained by using standard resin formulae, whereas higher pre-load in weaker concrete

was attained by using 0.5% expansive resin and lowest pre-load cannot be determined as there is

no data using 5% expansive resin in weaker concrete. 0.5% expansive resin exhibited higher pre-

load than standard resin in both weak and strong substrates. Results using Standard and 0.5% expansive were compelling as they follow a trend when compared with 1%, 2.5% and 5% expansive resin, however more data is required before a definitive result can be obtained.

Figure 11: Comparison of pre-load (t) between 9-inch encapsulation lengths in a stronger concrete (6381 psi) and weaker concrete (3480 psi) at 82° F (200 lb-ft. torque)

Figure 12 represents that the percentage of load loss in weaker and stronger concrete is the same when 0.5% expansive resin is used. Load loss percentage on the weaker concrete for 1% and 2.5% is less when compared to load loss percentage on stronger concrete; this may be due to the lower pre-loads obtained while tensioning the weaker concrete. Overall, it represents that the least load loss percentage was observed when 0.5% expansion resin was used.
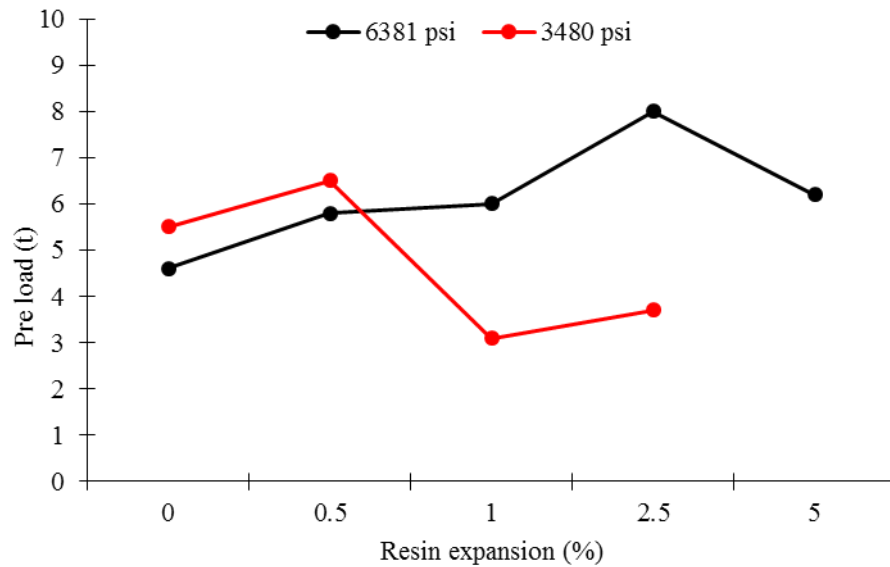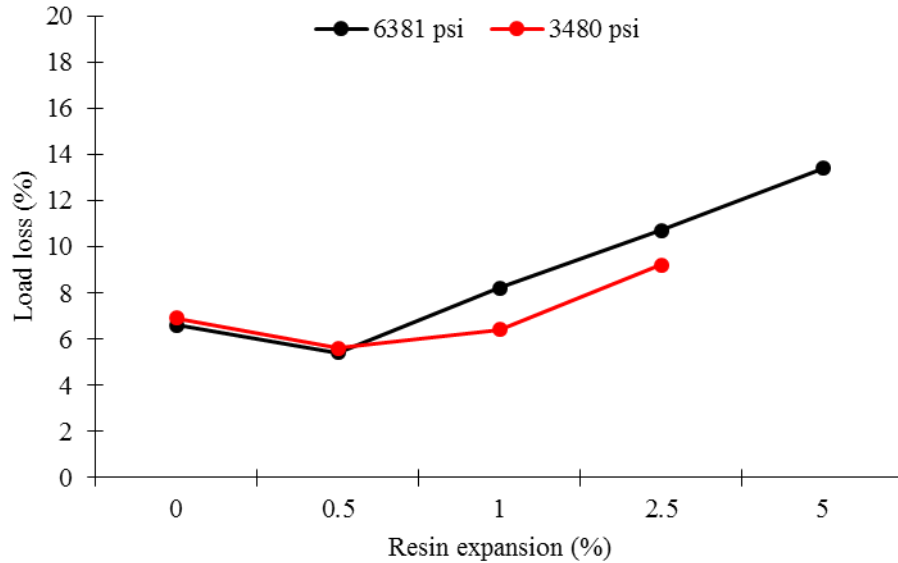
Figure 12: Comparison of load loss (%) in 9-inch rebar encapsulated in a stronger concrete (6381 psi) and weaker concrete (3480 psi) at 82°F (200 lb-ft. torque)

Effects of Confined and Unconfined Resin Columns:

To try and achieve the goal of retaining the maximum pre-load attained after tensioning of the rock bolts using expansive resin types as the grouting material; fast setting, standard resin is used as a confinement at both ends of the expansive grouting material. Generally, fast setting resin sets as soon as the bolt is tensioned, and expansive resin sets slowly by expanding between the confined fast setting resin, there by restricting any loss in pre-load or stiffness of the bolt. Weaker concrete with a desired 9-inch encapsulation length, torqued to 200 lb-ft., was used at the same ambient temperature (82°F) to observe the load loss. Five sets of tests were done using the five types of resin formulae. Table 3 represents the average pre-load and load loss percentage of the five tests for the confined and unconfined resin columns.

Table 3: Average pre-load (t) and load loss (%) on rebar in weaker concrete (3480 psi) with a confined encapsulation length and an unconfined encapsulation length (200 lb-ft. torque)

Formulation	Unconfined Resin Column Average		Confined Resin Column Average	
	Pre-load (t)	Load loss (%)	Pre-load (t)	Load loss (%)
Standard	5.5	6.9	5.7	11.0
0.5 % Expansion	6.5	5.6	5.0	6.9
1.0 % Expansion	3.1	6.4	6.4	8.2
2.5 % Expansion	3.7	6.4	6.6	12.5
5.0 % Expansion			6.2	13.4

Figure 13 represents the comparison of pre-load obtained with the confined resin column against the unconfined resin column. Confined resin formulae of 1%, 2.5%, and 5% expansion have outperformed the unconfined resin column in regards to attaining the preload. Pre-loads attained by the unconfined resin column are approximately identical. The 0.5% expansive resin, however, in the case of the unconfined resin column achieved higher pre-load. Figure 14 represents the comparison of load loss % between the confined resin column and the unconfined resin column. Expansive resins at 1%, 2.5% and 5% exhibited higher load loss percentage in the confined resin column, similar to that of the unconfined resin column. However, the 0.5% expansive resin has shown merit with lower load loss percentage in both the cases of confined and unconfined resin columns. Overall, results for the confined resin column bolts are contrary to the assumptions made based on the literature of using fast and slow setting resin for active bolts. Not having a defined length of confined (fast setting) resin column and the additional time to install it at the ends of grouting material could be explanations for inconsistent results.
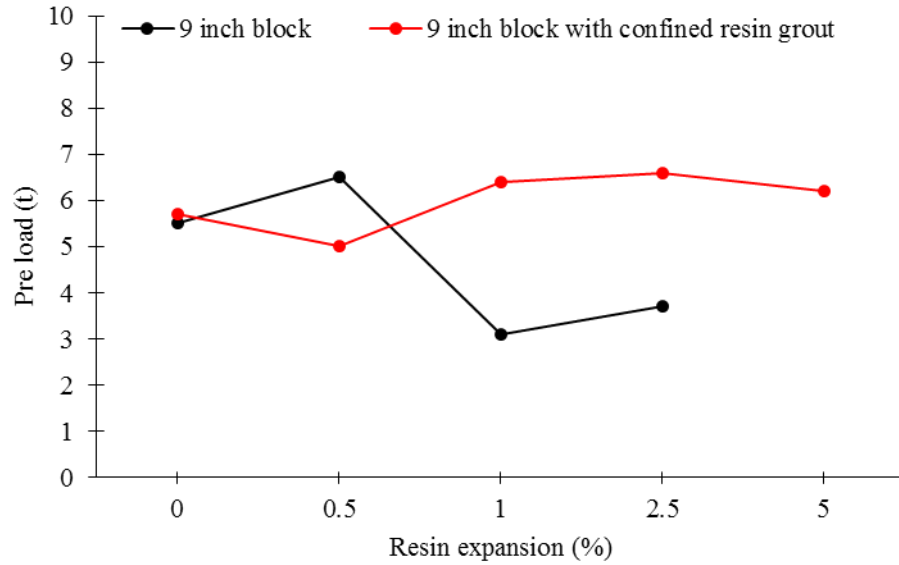
Figure 13: Comparison of pre-load (t) between unconfined (standard) and confined resin

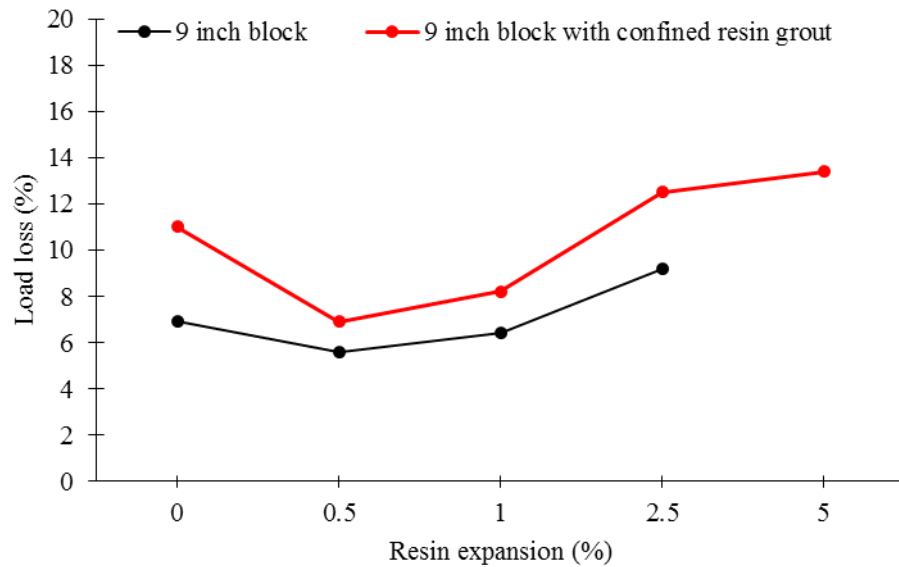columns in weaker concrete (3480 psi) (200 lb-ft. torque)

Figure 14: Comparison of load loss (%) between unconfined (standard) and confined resin

columns in weak concrete (3480 psi) (200 lb-ft. torque)

Effects of Temperature:

Tests were conducted to compare the load loss performance of a 9-inch encapsulation length torqued to 200 lb-ft. in stronger concrete (6381 psi) at 68ºF and 82ºF. Five sets of tests were done using the five types of resin formulae. Table 4 represents the average pre-load and load loss of the five tests.

Table 4: Average pre-load (t) and load loss (%) on rebar in stronger concrete (6381 psi) with 9-inch encapsulation length at 68ºF and 82ºF (200 lb-ft. torque)

Formulation	Average at 68ºF		Average at 82ºF	
	Pre-load (t)	Load loss (%)	Pre-load (t)	Load loss (%)
Standard	5.5	11.8	4.6	6.6
0.5 % Expansion	5.3	11.4	5.8	5.4
1.0 % Expansion	5.8	9.4	6.0	8.2
2.5 % Expansion	4.0	12.8	8.0	10.7
5.0 % Expansion	4.5	14.9	6.2	13.4

Figure 15 reveals that pre-loads are approximately identical at both temperatures for the first three types of expansion resins. As the percentage of expansion of the resin increased above 1%, a considerable amount of difference was noted in the pre-loads obtained at the two different temperatures. Higher pre-loads were attained at higher temperatures, due to the foaming action of the 2.5% and 5% expansive resin. Figure 16 shows that higher load loss percentage was attained with the 2.5% and 5% expansive resin at both temperatures. Lower load loss percentage was attained with 1.0% expansive resin at 68ºF and with 0.5% expansive resin at 82ºF. At 68ºF and 82ºF all the expansive resin types exhibited the same load loss percentage trend except with 0.5% and 1% expansive resin type.

Figure 15: Comparison of pre-load (t) between 9-inch encapsulation lengths in a stronger

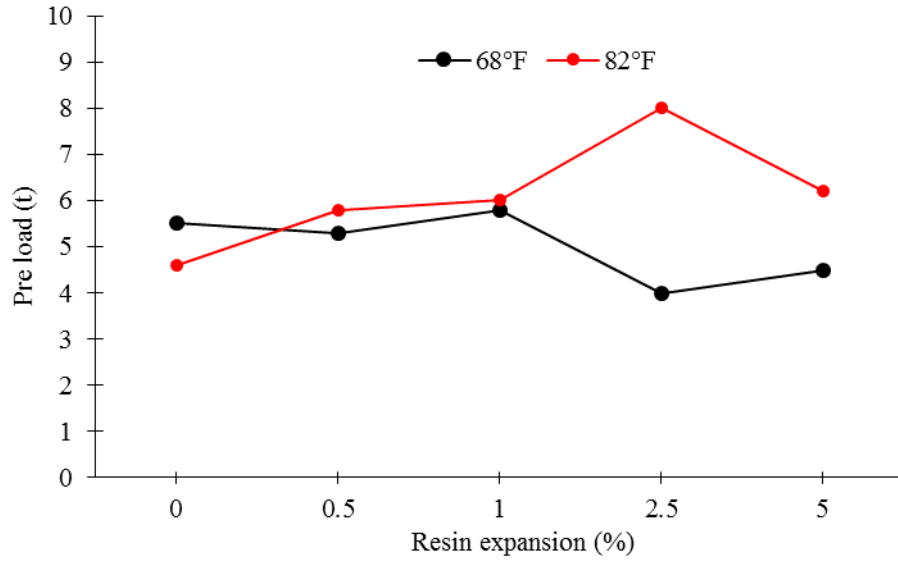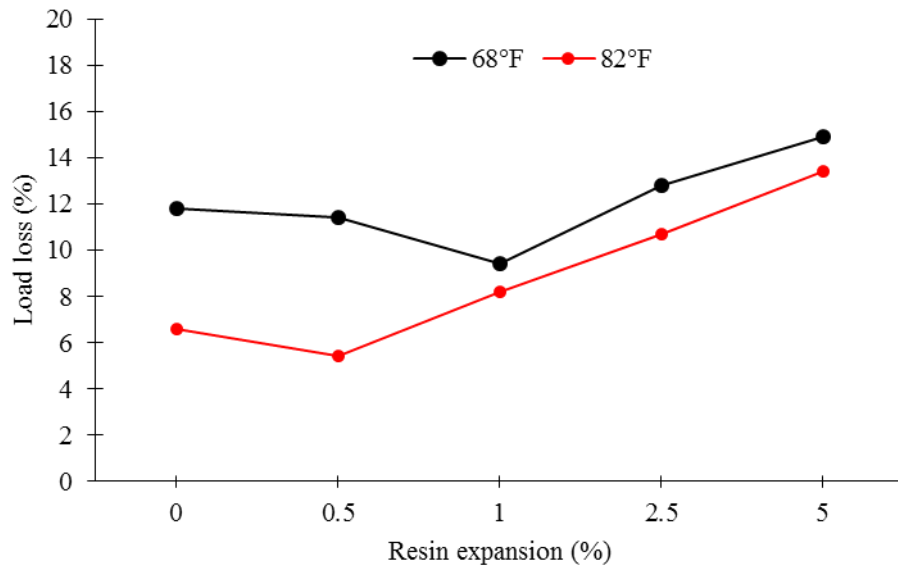concrete (6381 psi) at 68ºF and 82ºF (200 lb-ft. torque)

Figure 16: Comparison of load loss (%) between 9-inch encapsulation lengths in a stronger

concrete (6381 psi) at 68ºF and 82ºF (200 lb-ft. torque)

Test were conducted using 12-inch encapsulation lengths torqued to 200 lb-ft. in a

stronger concrete (6381 psi) at 68ºF and 84ºF to evaluate the effects of ambient temperature on

load loss. Five sets of tests were done using the five types of resin formulae. Table 5 represents the average pre-load and load loss of the five tests.

Table 5: Average pre-load (t) and load loss (%) on rebar in stronger concrete (6381 psi) with 12-inch encapsulation length at 68ºF and 82ºF (200 lb-ft. torque)

Formulation	Average at 68ºF		Average at 82ºF	
	Pre-load (t)	Load loss (%)	Pre-load (t)	Load loss (%)
Standard	3.7	7.4	5.1	8.0
0.5 % Expansion	6.6	5.7	5.4	5.6
1.0 % Expansion	4.5	7.5	4.8	11.2
2.5 % Expansion	4.8	11.2	6.8	10.2
5.0 % Expansion	5.4	14.5	2.9	21.5

Figure 17 represents pre-load of 12-inch encapsulation length rebar in stronger concrete at 68ºF and 82ºF. At lower temperatures, pre-load is higher at 0.5% expansive resin and lower in all other types of expansive resin. At higher temperatures, higher pre-loads were observed at 0.5% and 2.5% when compared to all other types of resins.

Figure 17: Comparison of pre-load (t) between 12-inch encapsulation lengths rebar in a stronger

concrete (6381 psi) at 68ºF and 82ºF (200 lb-ft.) torque

Figure 18 represents the percentage of load loss in 12-inch rebar encapsulated in stronger

concrete at 68ºF and 82ºF. At both temperatures, the trend of load loss is almost the same. Higher

load loss is observed with the 5% resin expansion in the cases of both higher and lower

temperatures. Expansive resin at 0.5% exhibits the lower load loss percentage at higher and
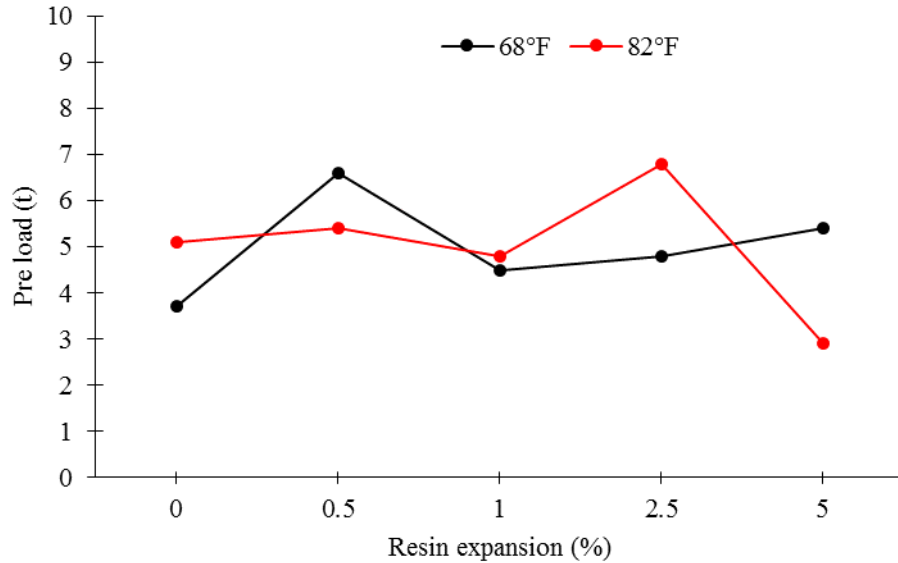
lower temperatures.

Figure 18: Comparison of load loss (%) between 12-inch encapsulation lengths rebar in a

stronger concrete (6381 psi) at 68ºF and 82ºF (200 lb-ft. torque)

Pre-load and load loss can be compared using the available data of experiments

conducted on 9-inch and 12-inch encapsulation lengths torqued to 200 lb-ft. in a stronger

concrete at 68ºF. Figure 19 represents the comparison of pre-load between 9-inch and 12-inch

encapsulating lengths at 68ºF. Higher pre-loads were attained in 12-inch encapsulated rebar

using 0.5 % expansive resin. Figure 20 represents the load loss percentage behavior in 9-inch and

12-inch encapsulating lengths at 68ºF.

Figure 19: Comparison of pre-load (t) between 9-inch and 12-inch encapsulation lengths rebar in a stronger concrete (6381 psi) at 68ºF (200 lb-ft. torque)
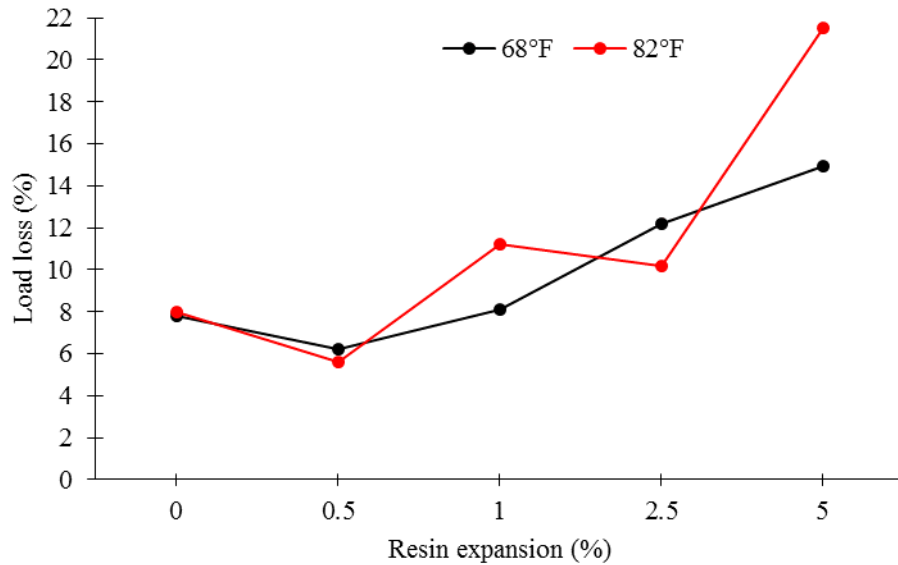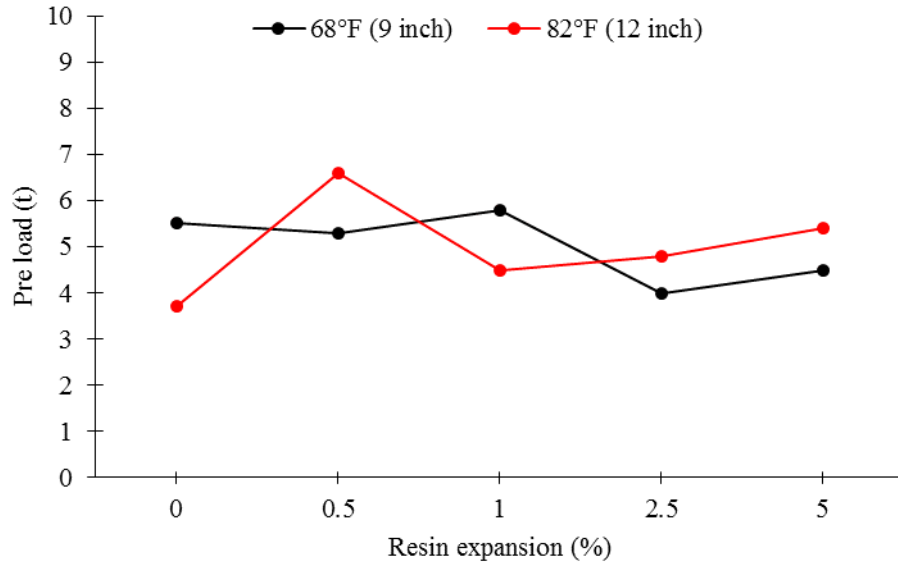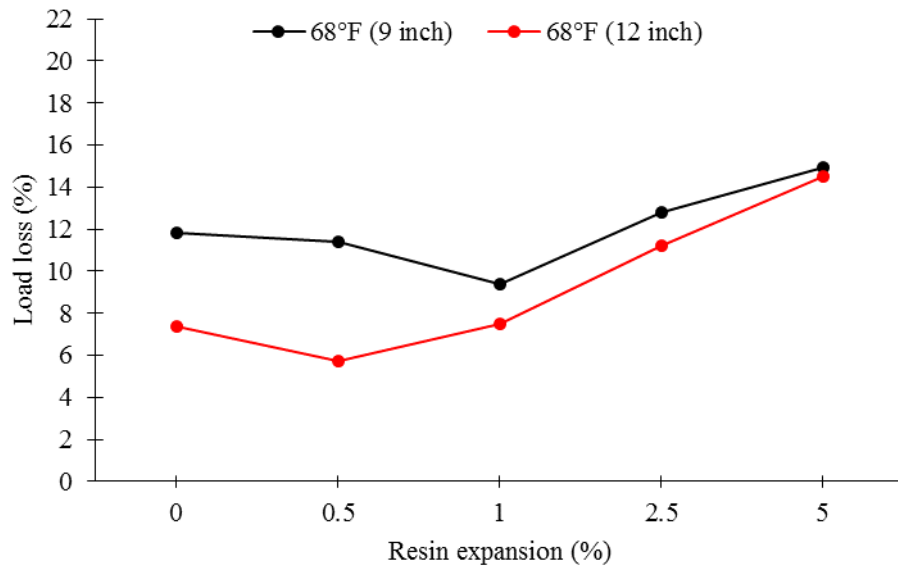

Figure 20: Comparison of load loss (%) between 9-inch and 12-inch encapsulation lengths rebar in a stronger concrete (6381 psi) at 68ºF (200 lb-ft. torque)

Higher load loss percentage occurred with the 5% expansive resin in both the cases. 9-inch and 12-inch encapsulated rebar with 0%, 2.5%, and 5% expansive resin has shown the same

trend. With the 12-inch encapsulation length, low load loss percentage was achieved with the 0.5% expansive resin.

Effects of Encapsulation Length:

For the comparison of load loss percentage with various encapsulation lengths, experiments were conducted with 9, 12, and 18-inch encapsulation lengths torqued to 200 lb-ft. in a stronger concrete (6381 psi) at 82°F. Five sets of tests were done using the five types of resin formulae. From Table 6 which represents the average pre-load and load loss of the five tests with different encapsulation lengths, it appears that stronger concrete using standard and 0.5% expansive resin exhibited lower creep when compared to other expansive resin formulations. However, in weaker concrete with 9-inch encapsulation length, it appears that only 0.5% expansive resin exhibited lower creep when compared to other expansive resin formulations.

Table 6: Average pre-load (t) and load loss (%) on stronger concrete (6381 psi) with 9-inch, 12-inch, and 18-inch encapsulation lengths at 82°F (200 lb-ft. torque)

Formulation	Average for 9-inch		Average for 12-inch		Average for 18-inch	
	Pre-load	Load loss	Pre-load (t)	Load loss	Pre-load (t)	Load loss
Standard	4.6	6.6	5.1	8.0	4.0	4.7
0.5 %	5.8	5.4	5.4	5.6		
1.0 %	6.0	8.2	4.8	11.2	4.5	4.7
2.5 %	8.0	10.7	6.8	10.2		
5.0 %	6.2	13.4	2.9	21.5		

Figure 21 represents a comparison of pre-loads in 9, 12, and 18-inch rebar encapsulated in a stronger concrete (6381 psi) at 82ºF. Pre-load appears to decrease marginally with increased resin encapsulation length and increased percentage of resin expansion. Higher pre-load is attained with the 2.5% resin expansion in the case of 9 and 12-inch encapsulation lengths. 0.5%, 1%, 2.5%, and 5% expansive resins exhibited the same trend with 9 and 12-inch encapsulation lengths. Pre-load of the 18-inch encapsulation increased from the 0% to the 1% expansion.
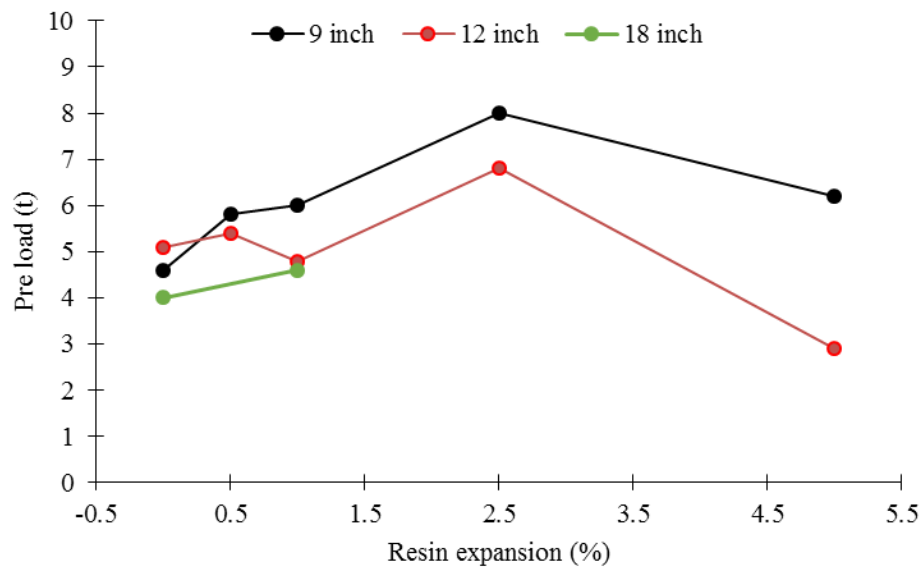

Figure 21: Comparison of the pre-load (t) between the different encapsulation lengths in a stronger concrete (6381 psi) at 82ºF (200 lb-ft. torque)

Figure 22 represents the load loss comparison of 9, 12, and 18-inch encapsulation lengths in stronger concrete (6381 psi) at 82ºF. Load loss percentage is higher with the 9 and 12-inch encapsulation lengths. All types of expansive resin exhibit the same trend with 9 and 12-inch, except for the 2.5% expansive resin of the 12-inch encapsulation length. The 18-inch encapsulation length has the same amount of load loss with the 0% and 1% expansive resins. The 0.5% expansive resin has displayed lower load loss percentage in all experiments.
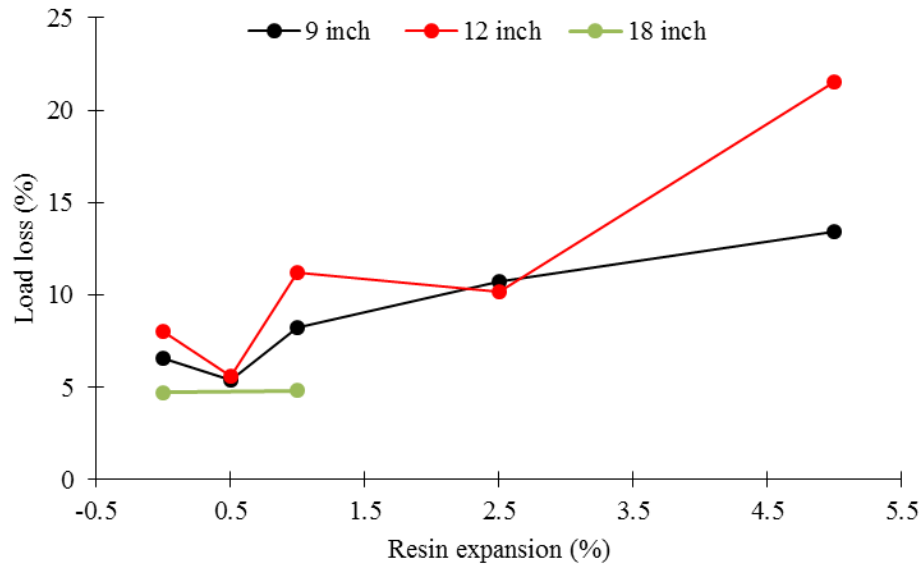
Figure 22: Comparison of the load loss (%) between the different encapsulation lengths in a stronger concrete (6381 psi) at 82ºF (200 lb-ft. torque)

Higher creep is observed in weaker concrete with standard and 0.5% expansive resin. However, with 1% and 2.5 % expansive resin creep is low in weaker concrete than stronger concrete, lower pre-loads attained in weaker concrete could be one of the reasons for this variance. Comparison could not be drawn for the usage of 5% expansive resin in weaker and stronger concrete due to insufficient data. Load loss is low in all the tests done in the laboratory with weaker concrete, when compared to the historical field data obtained from experiments undertaken in shale strata. It might be because shale is weaker than weak concrete.

CHAPTER 6

CONCLUSIONS

Based on these initial lab tests, the following conclusions can be drawn:

- Creep was observed in all the lab tests. With the slow loading (torqueing) methodology used, the average measured creep in tests varied from about 6% to 12% over the two-hour monitoring period, which is significantly less than what was measured underground (Spearing et al., 2011).

- Repetitive tests were performed on the concrete blocks by reloading the rock bolts repeatedly to observe the load loss/shedding. From these tests it was observed that grout-concrete and grout-rock bolt interfaces do not seem to lose their effectiveness to hold load even after shedding load and upon being reloaded. This is a similar performance to the mechanical key behavior of a Split Set when loaded.

- When the pre-loads of stronger and weaker concrete are compared using 1% and 2.5% expansion resin with a 9-inch encapsulation length, pre-loads attained for weaker concrete is less— which may be due to loss of torque during torqueing. However, standard and 0.5% expansive resins exhibited higher pre-loads in weaker concrete over stronger concrete.

- The concept of reducing the effect of creep using an expansive resin, even if only created by a foam, appears to have merit in the laboratory setting atmosphere as the 0.5% foamed expansion formulation outperformed the others consistently but much more tests are needed.

CHAPTER 7

FUTURE RESEARCH WORK

Clearly, the use of expansive resin to reduce the creep in active bolts has merit in laboratory setting atmosphere. However, it is hard to come to a firm conclusion with the limited number of tests done. A more comprehensive and controlled study should be done by carrying out the following tasks:

- UCS of weak shale is typically around 1410 psi, therefore using concrete cube strengths from 1000 psi, laboratory experiments need to be conducted to acquire a better understanding of active bolts in weaker strata.

- Different types of resin column experiments using slow and fast setting resin need to be carried out.

- Torque given in situ conditions is much higher when compared to the laboratory tests. Thus, to make a better comparison, bolts should be spun using a bolter even if done under controlled lab type conditions.

- Encapsulation length plays a major role in defining the active bolts strength. Fully grouted active rock bolts installed in situ conditions are typically 48 inches. To compare with in situ conditions, experiments should be carried out with encapsulation lengths up to 48 inches.

- Once comprehensive results from the lab tests are attained, in situ experiments can be carried out to determine the authenticity of lab tests and to evaluate the performance of expansive resin.

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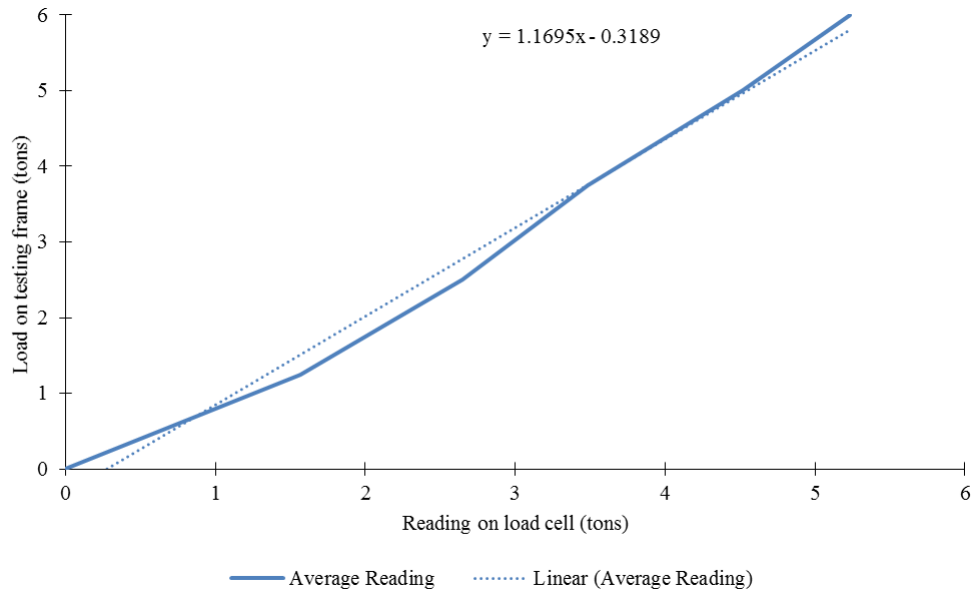**APPENDIX**

LOAD CELL CALIBRATION GRAPHS

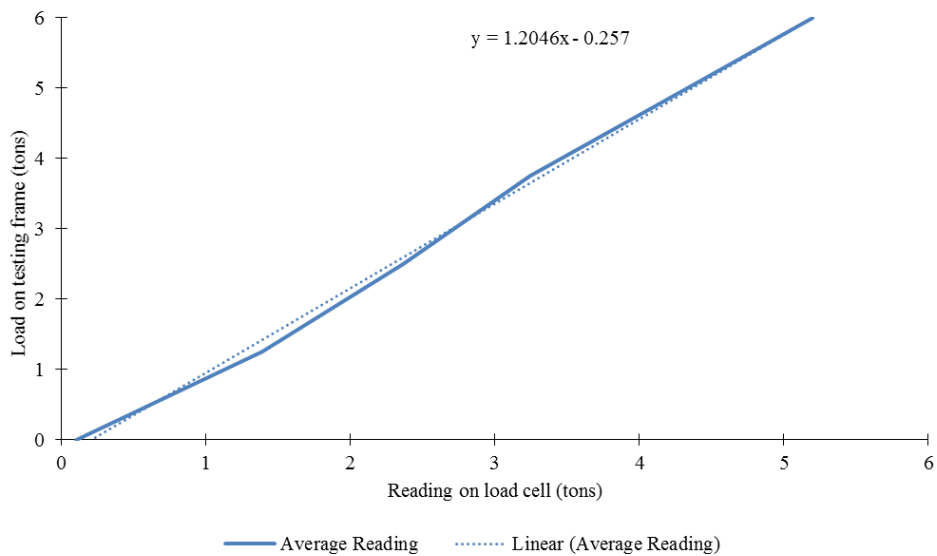Figure 23: Calibration of load cell – 2
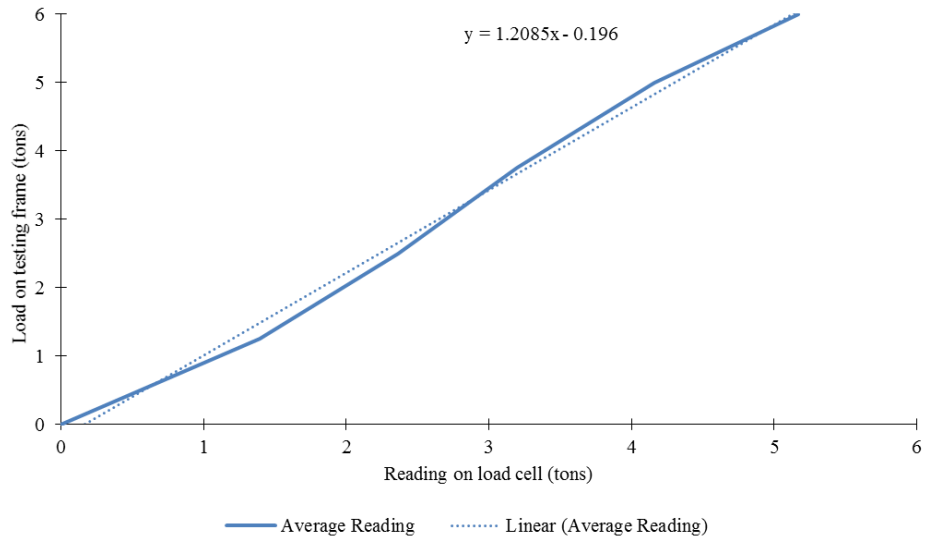

Figure 24: Calibration of load cell – 3

Figure 25: Calibration of load cell – 4

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