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MEMORANDUM

To: Technology Development Program Manager, Dam Safety Office
Attn: 84-44000 (LKrosley)

From: Evan Lindenbach, Civil Engineer
Concrete, Geotechnical, and Structural Laboratory (86-68530)

EVAN LINDENBACH
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Date: 2018.03.28 12:51:06 -06'00'

Subject: Dam Safety Technology Development Report DSO-2018-08 – Rock/Concrete Direct Shear Constant Normal Stiffness

A report on Rock/Concrete Direct Shear Constant Normal Stiffness, DSO-2018-08 from the Dam Safety Technology Development Program has been prepared by the Technical Service Center at the request of the Dam Safety Office. The report will be available in Adobe Acrobat Format on the Dam Safety website and will also be loaded into DSDAMS.

This transmittal concludes the work on the Technology Development Report. If you have any questions, please contact me at 303-445-2336 or at elindenbach@usbr.gov.

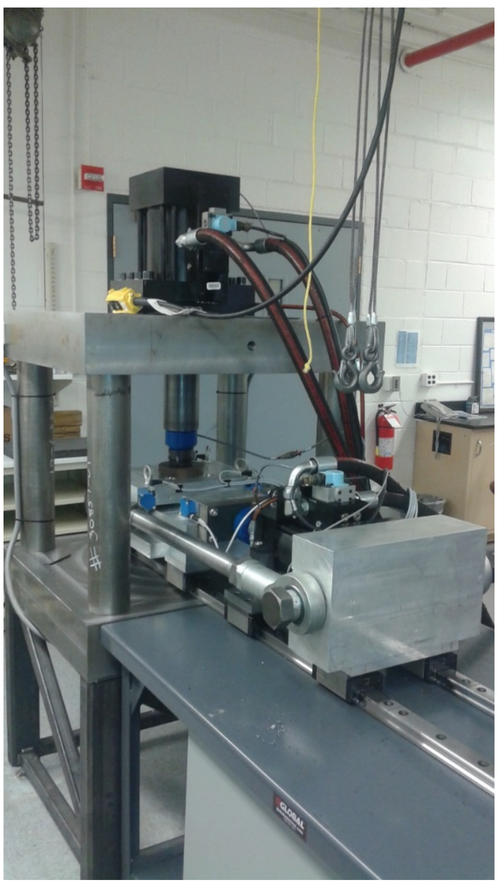
cc (w/att):
DSDaMS
Archives
86-68530 (Bearce, Rinehart)

Rock/Concrete Direct Shear Constant Normal Stiffness

DSO-2018-08

8530-2018-17

Dam Safety Technology Development Program



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, CO

March 2018

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This research developed the control software for a CNS boundary condition for an existing rock/concrete direct shear machine. After the programming was complete, a series of commissioning tests were performed, including a number of identical: a) 6-inch diameter concrete specimens, and b) sawtoothed hydrostone specimens to mimic rock discontinuities. Intact concrete specimens were tested for break-bond and sliding friction strengths while the hydrostone specimens were only tested for sliding friction strength. Both sets of tests were performed under both CNL and CNS conditions to investigate the effects on shear strength due to the different boundary conditions. This paper details the system upgrades and the results of the comparison testing under CNL and CNS boundary conditions, and provides examples of CNS data use in design.</td></tr>
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Bureau of Reclamation

Dam Safety Technology Development Program

Concrete, Geotechnical & Structural Laboratory, 86-68530

DSO-2018-08

8530-2018-17

Rock/Concrete Direct Shear Constant Normal Stiffness

EVAN LINDENBACH

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Contents

Tables

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Acronyms and Abbreviations

CC – Concrete

CNL – Constant Normal Load

CNS – Constant Normal Stiffness

HPU – High Pressure Unit

in – Inch

lbf – Pounds-Force

PID – Proportional-Inverse-Derivative

psi – Pounds per Square Inch

GRC – Ground Reaction Curve

LR – Large-Ridge

SCC – Support Confinement Curve

SR – Small-Ridge

TSC – Technical Service Center

UDEC – Universal Distinct Element Code

Symbols

φ – Friction Angle

° – Degree(s)

δ – Displacement

σ – Normal Stress

τ – Shear Stress

v_m – Rock Mass Poisson's Ratio

E_m – Rock Mass Modulus

f – Force

k – Stiffness

r – Influenced Radius

Executive Summary

Rock strength characteristics are typically determined using a suite of tests, including: uniaxial compressive strength, indirect tensile strength, ultrasonic pulse velocity, and rock direct shear tests on both existing discontinuities and sawcut specimens. Two other forms of the discontinuity-type testing are the rock to concrete interface encountered with some types of dams, and the shear strength of individual lift lines within a mass concrete structure. Discontinuities play a significant role in the behavior of a rock or concrete mass and can often be the critical strength used for design. Assessing the shear strengths of these discontinuities is performed by means of a rock/concrete direct shear test, in which both normal and shear loads are recorded and used to develop a shear strength envelope, later used in design.

The typical direct shear test involves holding a constant normal load (CNL) and shearing the specimen at a constant rate. While this is appropriate in situations where the normal load is relatively constant as sliding occurs along a discontinuity, there are instances where the shear strength is dilatancy controlled (i.e. underground excavations or rock-socketed piles) and the normal load is not constant during shearing. In these instances constant normal stiffness (CNS) testing is more appropriate (Muralha et al., 2014). In order to investigate the differences between the CNL and CNS boundary conditions, a number of simulated rock specimens (sawtoothed hydrostone) and concrete specimens were tested at varying normal loads and stiffness values.

This research resulted in the following conclusions:

- Machine controls established by Reclamation perform as intended.
- The rollover (initial slope break) of the CNS stress paths in sliding friction tests are in good agreement with the linear failure envelope defined by CNL testing for both the sawtoothed hydrostone and concrete specimens.
- The stress paths of the CNS tests on the sawtoothed hydrostone specimens tended to be below the CNL linear envelope, potentially showing post-peak type behavior.
- The stress paths of the CNS tests on concrete during sliding tend to follow the CNL linear failure envelope.
- The difference in stress path behavior of the sawtoothed hydrostone and concrete specimens could indicate that for materials that show a post-peak strength (strain-soften), the stress path may follow a post-peak envelope. While for the concrete specimens (which typically strain harden or show minimal decrease in strength past peak) the stress path appears to follow the CNL failure envelope.
- Further research is needed to determine if the CNS stress path can be used to approximate the CNL failure envelope.
- The CNS concrete break bond testing and interpretation is complex and needs further research. The direct shear machine may require modification to reduce any rotation of the top box.
- The amount of dilation appeared to be relatively consistent for a range of normal stiffness values for both break bond and sliding shear tests. The dilation rate under higher stiffness values appears to be non-linear. This may be affected by top cap rotation.

- The normal load at which concrete is broken appears to affect the sliding friction CNL failure envelope, with higher normal loads at breaking leading to lower sliding shear strengths.
- Incorporation of CNS strength parameters into both finite element models and limit equilibrium problems is relatively simple and should be used where it represents the correct boundary condition. The use of CNL parameters in some cases may be unconservative.

Keywords

Rock, Concrete, Direct Shear, Constant Normal Load, Constant Normal Stiffness, Stress Path

Team Members, Partners, Reviewers

Table 1. Internal members, partners, reviewers.

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Background

In order to keep with the state-of-practice and provide the most realistic boundary conditions for rock mechanics and concrete testing, this research developed the control software for a CNS boundary condition for the TSC's rock/concrete direct shear machine. In addition, this research provides information on how the CNS data can be used within Reclamation's current rock mechanics and rock/concrete interface design methods, and for characterizing existing mass concrete structures. The author knows of no research that has been performed to characterize the strength of concrete lift lines using a CNS boundary. This is likely a result of Reclamation now having the unique capability that tests concrete specimens under these varying boundary conditions.

Introduction

Rock strength characteristics are typically determined using a suite of tests, including: uniaxial compressive strength, indirect tensile strength, ultrasonic pulse velocity, and rock direct shear tests on both existing discontinuities and sawcut specimens. Two other forms of the discontinuity-type testing are the rock to concrete interface encountered with some types of dams, and the shear strength of individual lift lines within a mass concrete structure. Discontinuities play a significant role in the behavior of a rock or concrete mass and can often be the critical strength used for design. Assessing the shear strengths of these discontinuities is performed by means of a rock/concrete direct shear test, in which both normal and shear loads are recorded and used to develop a shear strength envelope, later used in design.

The typical direct shear test involves holding a constant normal load (CNL) and shearing the specimen at a constant rate. While this is appropriate in situations where the normal load is relatively constant as sliding occurs along a discontinuity, there are instances where the shear strength is dilatancy controlled (i.e. underground excavations or rock-socketed piles) and the normal load is not constant during shearing. In these instances constant normal stiffness (CNS) testing is more appropriate (Muralha et al., 2014).

Previous CNS testing has used springs instead of a normal force actuator to provide a constant stiffness (Indraratna and Haque, 2000) with an emphasis on concrete-rock interfaces to mimic a rock-socketed pile (Johnson and Lam, 1989). New servo-hydraulic direct shear equipment allows the operator to easily control the system to a degree which allows CNS testing to be performed with fine control (Blümel and Bezat, 2000, Jiang, 2017). New testing equipment, similar to that detailed in this paper, now has the ability to vary the stiffness during a test, or even vary the stiffness as a function of horizontal displacement to better mimic realistic boundary conditions (Button and Blümel, 2002).

Previous work by Indraratna and Haque (2000) made the following conclusion regarding the differences between CNL and CNS test results:

- CNS provides a higher peak shear strength than CNL for a given initial normal load
- Dilation under the CNS condition is always less than that found under the CNL condition for a given initial normal load
- The peak friction angle under the CNL condition is greater than under a CNS condition
- Shear displacements at peak shear strength are always higher for the CNS condition than the CNL condition

The above conclusions indicate that CNL test results may over estimate frictional strengths and not fully model the actual response of a rock joint where normal stress is not constant along the joint.

Jiang (2017) confirmed the first two conclusions given above, but found that the rollover in the CNS stress paths typically fell along the CNL linear failure envelope. No conclusions were given regarding shear displacements at peak shear strength. Jiang (2017) also noted that a clear peak shear stress can be observed in all CNL tests but may not occur in some CNS tests as the shear stress can continue to increase with increasing displacement (strain hardening behavior).

Selecting an appropriate normal stiffness is of critical importance as the peak strength is a function of both the initial normal stress and the assigned stiffness (Indraratna and Haque, 1999). Research into rock socketed piles found that the normal stiffness of the rock mass can be found by expanding infinite cylinder theory to obtain (Johnson and Lam, 1989):

$$k = E_m/(1+v_m)r \quad (1)$$

Where,

k is the stiffness (psi/in)

E_m is the rock mass modulus (psi)

v_m is rock mass Poisson's ratio (unitless)

r is the influenced radius (inches)

Since E_m and v_m are generally constant for a rock mass, and r is a geometric term, k is generally considered to be constant for a rock mass (Jiang, 2017). It should be noted that Eq. 1 was initially developed for rock socketed piles and there are no current guidelines for determining stiffness for a given CNS testing program (Button and Blümel, 2002).

In order to investigate the differences between the CNL and CNS boundary conditions, a number of simulated rock specimens (sawtoothed hydrostone) and concrete specimens were tested at varying normal loads and stiffness values.

Use in Design

Indaratna and Haque (2000) present two design cases which are summarized in this section. The reader is directed to their work for further detail. Fundamental to this section is their finding that the CNL testing procedure always overpredicts the joint friction angle and shear strength relative to CNS testing (Indaratna and Haque, 2000).

Case 1 – Tunneling

In an underground excavation, stability of the rock strata and removable blocks will be controlled by the stiffness of the surrounding material, with the normal stress varying along the joints during and after excavation. In this situation, using the CNL strength parameters would overestimate stability.

Indaratna and Haque (2000) present a Universal Distinct Element Code (UDEC) model of this excavation. The corresponding ground reaction curve (GRC) demonstrating that as the rock mass dilates and achieves equilibrium with the excavation, the rock mass deforms with a constant normal stiffness. The support confinement curve (SCC) should then be developed with the CNS strength parameters, as the design would be appropriate for the boundary condition. The CNL condition would likely be reached for the excavation, but not for a significant period of time.

Case 2 – Block on Slope

Stability of a free block on a slope is typically predicted with CNL strength parameters as the normal stress along the block/slope interface is constant during sliding (i.e. governed by the weight of the block). The installation of anchors (i.e. rock bolts) restrains the block, with the tension developed in the anchor (increase in normal force) dependent on the amount of dilation of the block/slope joint. The anchor restraint increases with increasing normal displacement, thereby increasing the normal stress along the block/slope interface as the block slides.

Once the dilation characteristics of the joint are known, the appropriate anchor forces can be added to the limit equilibrium problem and combined with the CNS strength parameters to find the resisting forces. The resisting forces can then be compared to the driving forces to determine the factor of safety against sliding. The use of CNL strength parameters in this condition would produce an unconservative factor of safety against sliding as they overestimate the shear strength of the joint.

Equipment Upgrades

Reclamation has built a number of direct shear testing frames dating back to the early 1970's. The current iteration is the fourth such machine and is the first to be servo-hydraulic controlled. Initial control of the system was performed by a LabView code developed in-house by Reclamation. While the system performed well for CNL testing, the software interface was not easily manipulated to change testing commands and it was determined that an upgrade was needed for CNS testing.

MTS Systems Corporation (MTS) and Reclamation engineers collaborated on a design which connected the direct shear machine to an existing MTS 815 Rock Mechanics Test System (control system for an existing triaxial test system), which would then be controlled with MTS software. As the Reclamation direct shear system hardware was modeled after the MTS Direct Shear Package, connecting the direct shear machine to the existing MTS system required relatively little work (cabling, calibration etc.).

The system upgrade included the following work items:

- Connect the existing direct shear machine to the existing MTS 815 Rock Mechanics Test System via MTS provided cabling
- Install MTS software to control direct shear system

- Calibrate existing load cells and displacement gages
- Add two contact displacement gages to the direct shear control system. The gages were selected to ensure normal and shear displacement measurements are made as close to the specimen as possible to reduce machine compliance issues.
- Install a second computer to operate the direct shear system. This computer is a "dependent" on the computer that runs the triaxial system.

As part of the system upgrade, Reclamation acquired the newest test control software from MTS. The software, TestSuite, controls the system during testing with a straight-forward interface that is simpler to use than LabView or any previous MTS software. MTS provided two days of on-site software training to two Reclamation engineers after the hardware upgrades were completed. The training familiarized the Reclamation engineers with the system, and resulted in the development of both the constant normal load and constant normal stiffness testing protocols.

Figures 1 and 2 show examples of the TestSuite software control screens.

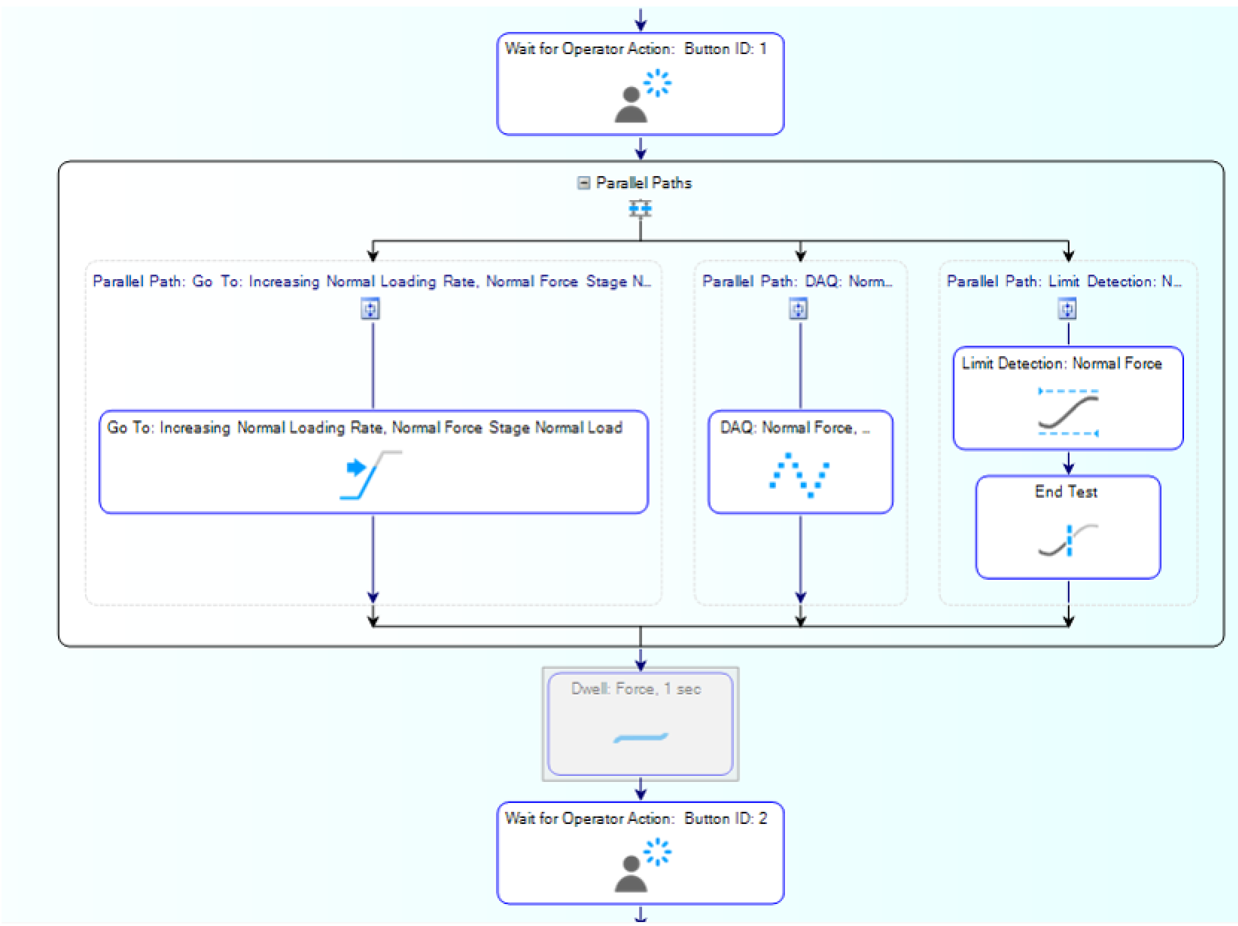


Figure 1 - TestSuite interface showing a portion of the CNS testing program.

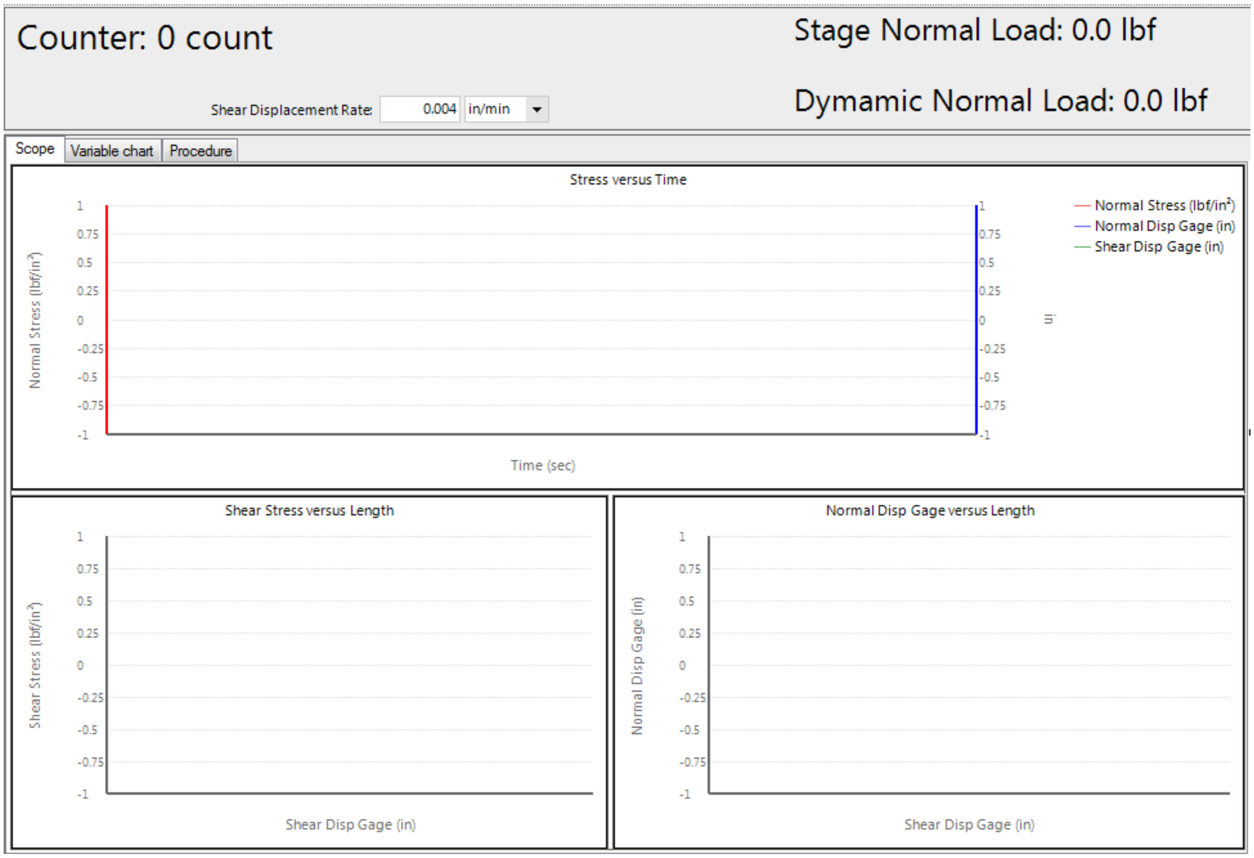


Figure 2 - TestSuite interface showing operator monitor during CNS testing.

As is common with servo-hydraulic testing equipment, tuning the PID (proportional-inverse-derivative) parameters for machine control presented the biggest challenge, particularly when switching the HPU pressures (discussed in the following section), and transitioning between joint and intact specimen testing. Tuning using the MTS system is relatively simple as the user can vary the PID parameters in real-time while commanding the machine functions. The user is able to visually monitor the machine command versus actual behavior and vary the PID parameters until acceptable control is achieved.

The normal actuator system is typically controlling load (either holding constant or varying) so this was tuned in load-control. The shear actuator system is typically controlling in displacement so this was tuned in displacement-control.

Reclamation engineers noted the following during the system tuning:

- The system must be thoroughly warmed up to have good control for shear displacement
- The ability to match control with actual behavior during either load or displacement cycling is strongly dependent on the “P” parameter
- The ability to hold a constant shear displacement value is strongly dependent on the “I” parameter (the displacement will oscillate about a set-point if the “I” value is too large)
- The “D” parameter was not used and was set to 0

- Two different sets of PID parameters were developed depending on the HPU pressure setting

Additionally, Reclamation engineers wrote new MatLab routines to post-process the data and present the final results.

Appendix A presents the MTS scope of work to upgrade the direct shear system along with the associated costs.

Testing Equipment

The direct shear system can apply a maximum normal load of 100,000 lbf and a maximum shear load of + 50,000 lbf and -33,300 lbf. The minimum normal load based on the top cap weight is 133 lbf. Normal load is applied by means of a spherical platen to the center of the specimen top, with normal displacement measured by laser displacement devices at each corner of the top cap, and at the spherical platen by means of a MTS Model 632.06H-30 contact displacement gage with a range of +/- 0.5 in. Shear displacement is measured with two laser displacement devices and another a MTS Model 632.06H-30 contact displacement gage. Figures 3 through 6 show the test machine constructed by Reclamation.

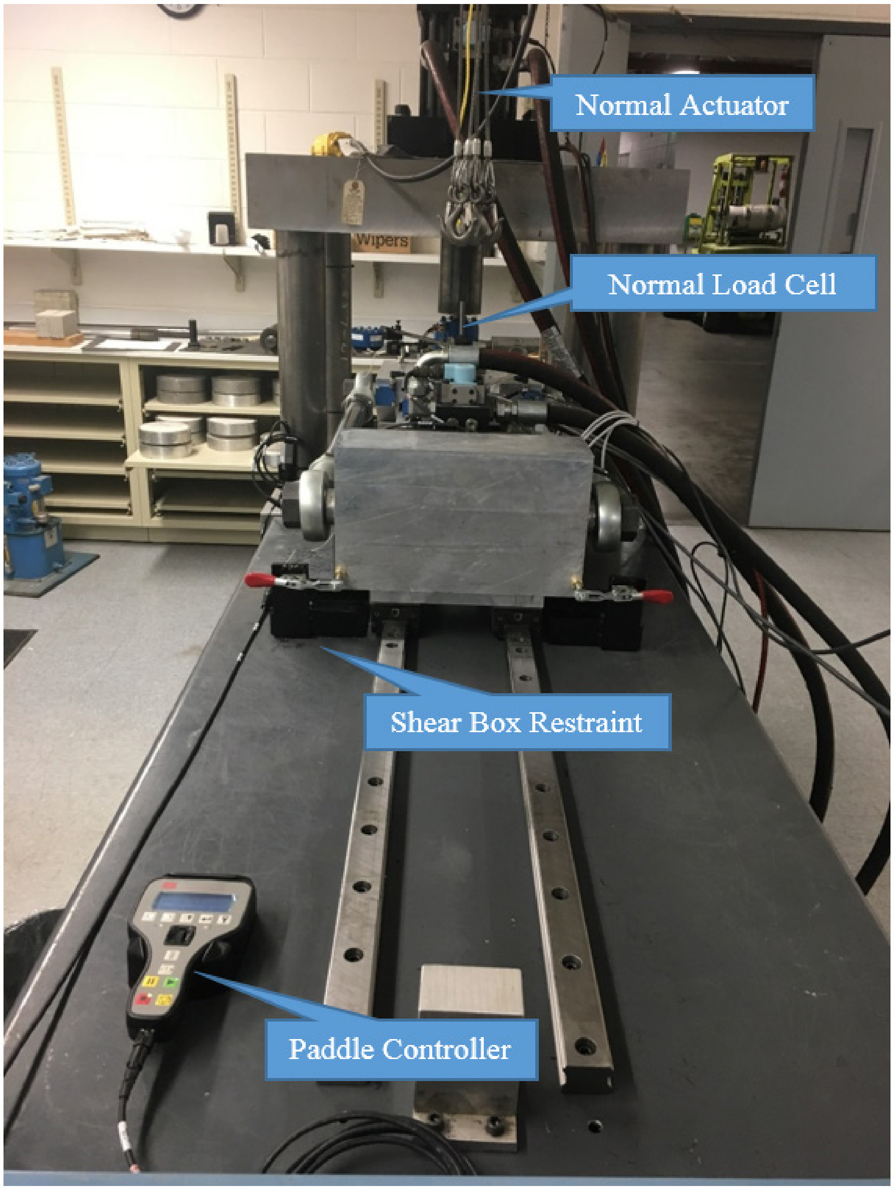


Figure 3– Small direct shear machine viewed from the HPU. Note hand paddle controller in foreground.

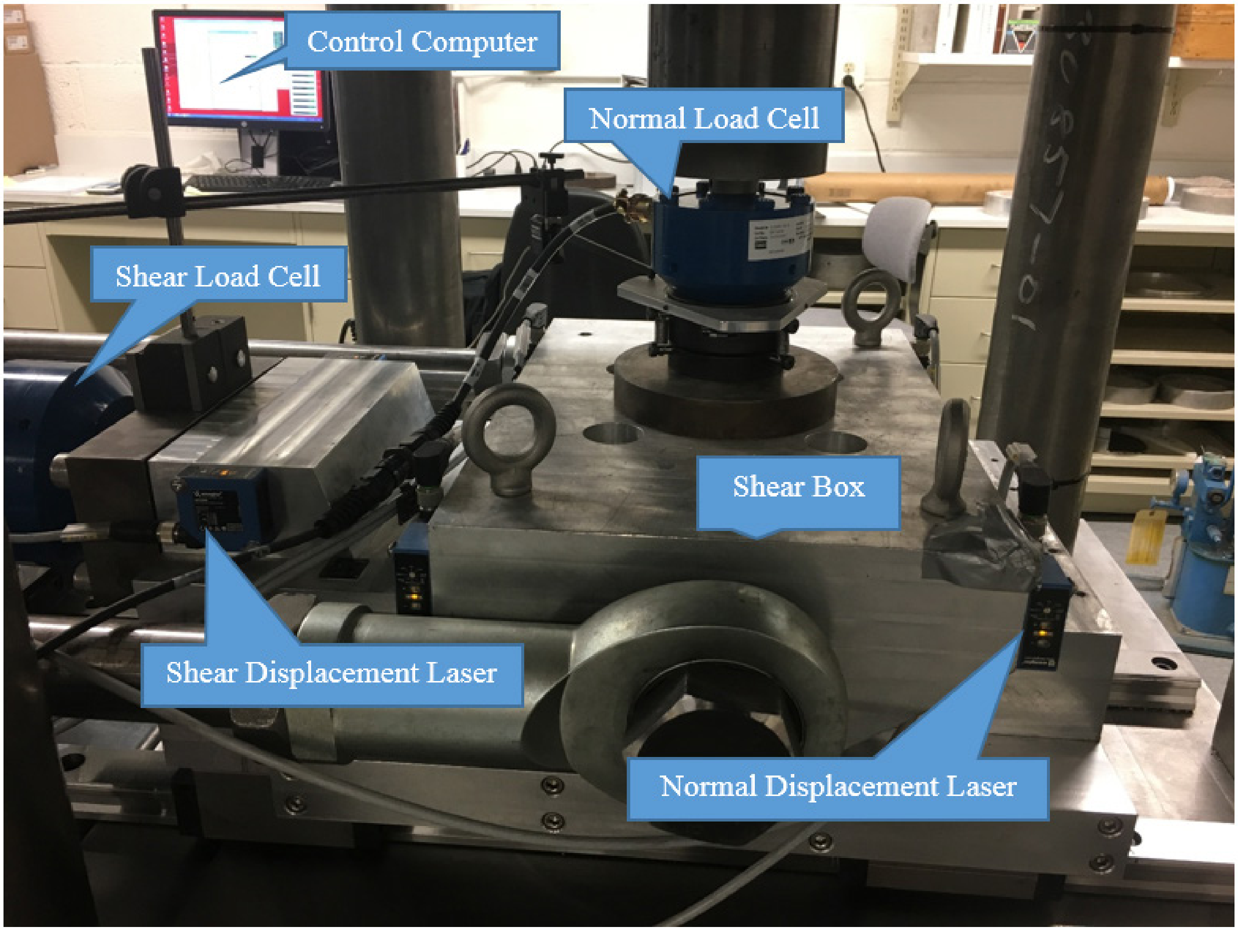


Figure 4 - Side view of shear box with parts labeled.

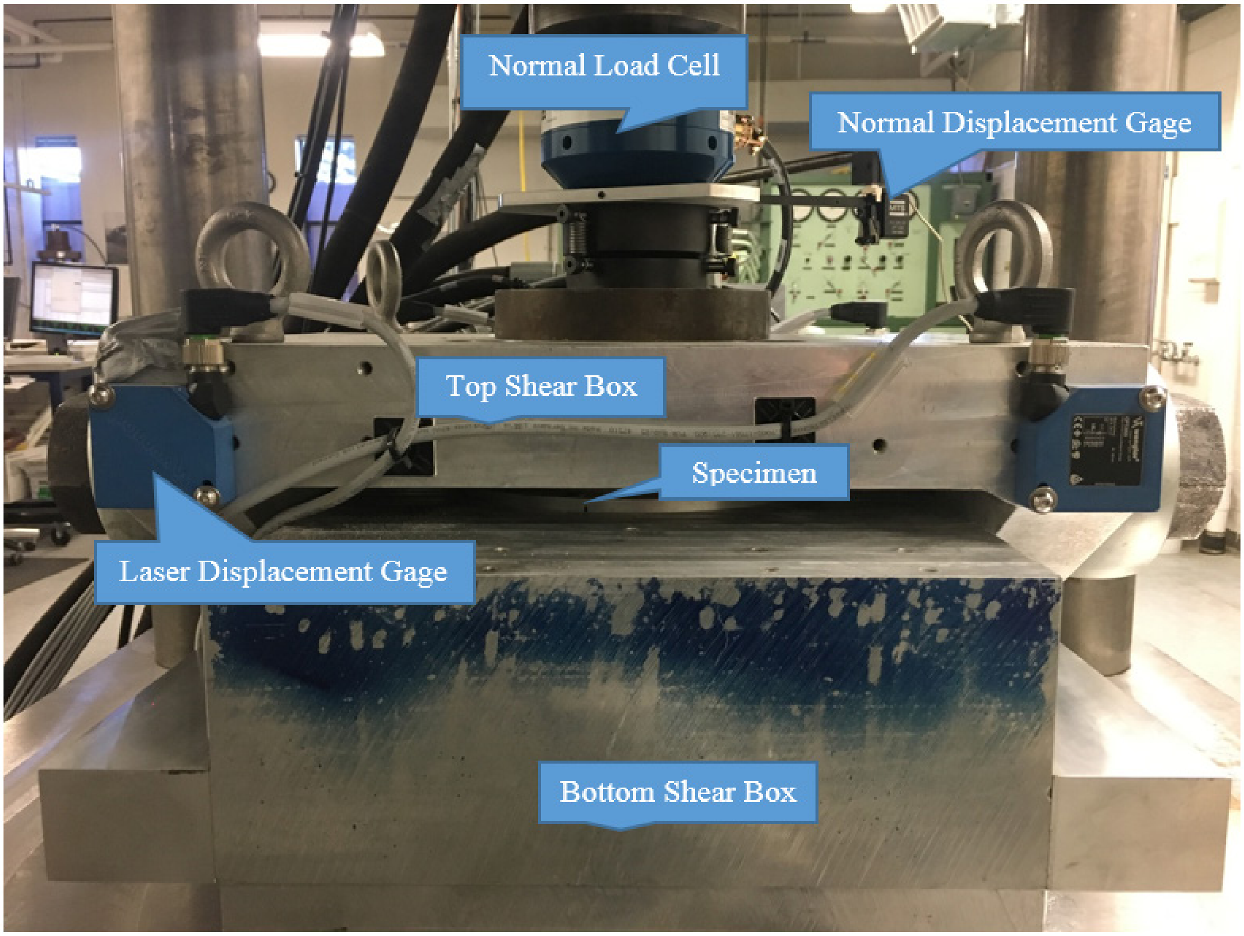


Figure 5 - Direct shear specimen in testing machine. Normal actuator used to apply constant normal load with displacement measured by gage. Top shear box remains stationary while bottom shear box moves towards camera at a constant rate. Note 0.2 inch isolated section between shear boxes.

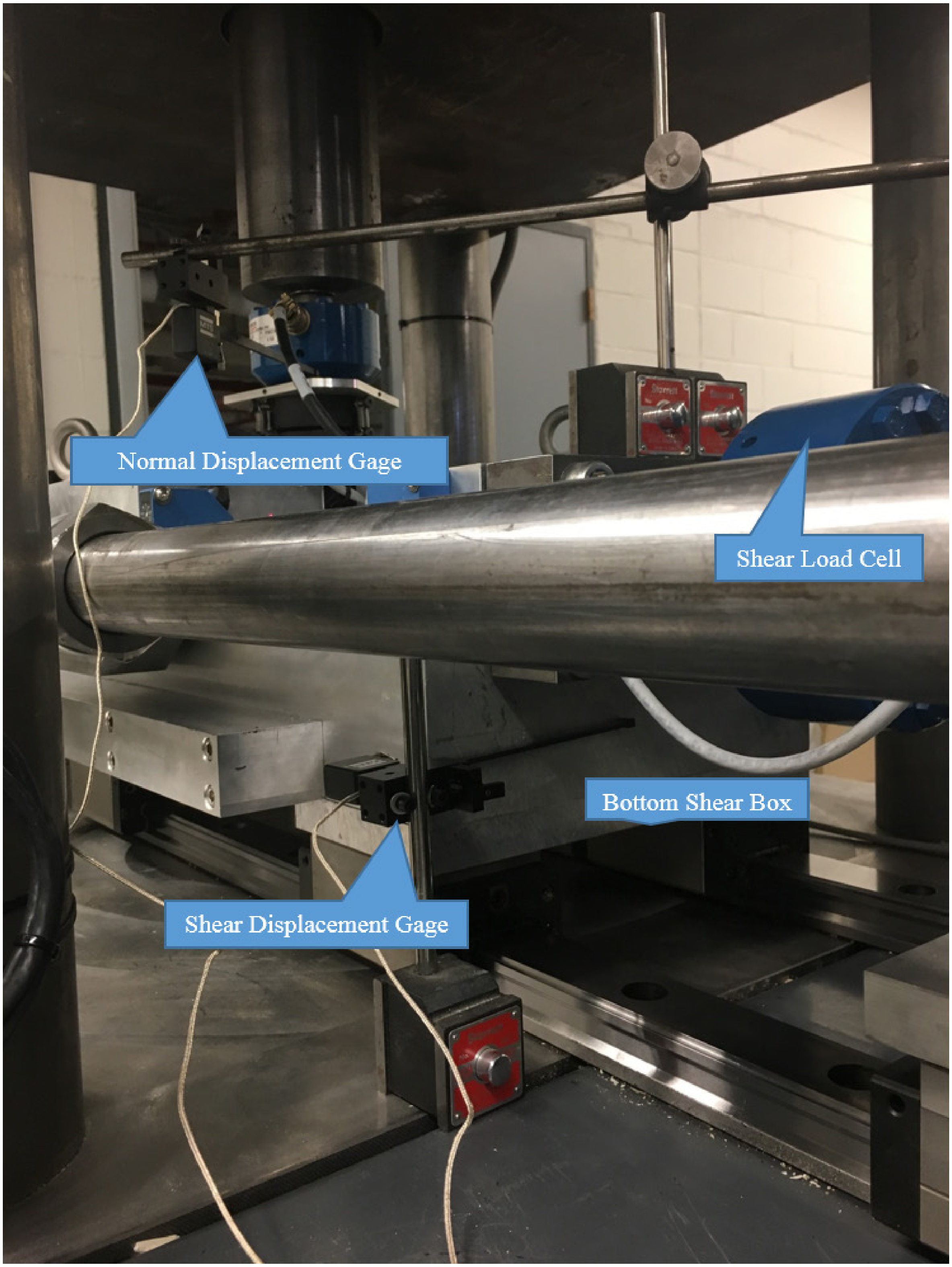


Figure 6 - View of normal and shear displacement gages.

In order to more accurately measure and control normal and shear loads, the load cells used with the machine are modular and are selected/installed by the laboratory engineer depending on the specimen type. The high-pressure unit (HPU) driving the normal and shear actuators can be turned up or down accordingly to limit the chance of overloading the system.

For typical rock discontinuity testing, the load cells are 10,000 lbf and 5,000 lbf in normal and shear capacity, respectively. Typical concrete testing is performed with 10,000 lbf and 50,000 lbf normal and shear load cells, respectively.

Testing Procedures

The testing procedures were developed by Reclamation engineers and MTS representatives using MTS TestSuite software. The CNL test used for this research was performed by the following procedure:

- Input test parameters, specimen ID, etc.
- Apply normal load (σ_n) at a rate to reach the target load in about 1 minute
- Hold σ_n until specimen displacements have stopped (typically about 1 -5 minutes)
- Shear specimen at 0.008 in/min (based on ISRM, 2014 guidance)
- Stop shear after peak shear strength has been reached
- Apply subsequent σ_n without resetting specimen. Repeat until testing is completed

The CNS test uses the following relationship:

$$\sigma_{dyn} = \sigma_0 + kx \quad (2)$$

Where,

σ_{dyn} is the (real time) dynamic normal stress to be targeted during shearing. This parameter is defined as the dynamic normal load (f_{dyn}) divided by the initial area of the specimen.

σ_0 is the initial normal stress defined as the initial normal load (f_0) divided by the initial area of the specimen.

k is the stiffness, in this equation the units are in stress/length; in our machine controls units are in force/length (for simplicity in control software)

x is the (real time) normal displacement with dilation considered to be positive (i.e. dilation increases the normal force)

Note that no correction for changing area during shearing was used during this testing.

The CNS test was performed by the following procedure:

- Input test parameters, specimen ID, etc.
- Apply f_0 at a rate to reach the target load in 1 minute
- Hold f_0 until specimen displacements have stopped
- Shear specimen at 0.008 in/min (based on ISRM, 2014 guidance)
- Vary normal load during testing based on Eq. (2) with the f_{dyn} recalculated on a 5 Hz cycle

- Stop shear after reaching either a user determined shear displacement (in the case of sliding tests) or peak shear stress (in the case of break bond tests)

CNL testing was performed over a specified range of normal stresses prior to CNS testing. CNS testing targeted an f_0 and k value such that the stress path would likely fall within the envelope developed during CNL testing. The following procedure was used to determine f_0 and k.

- Perform CNL test, observe dilation of specimen during entire test (x_{CNL})
- Assume σ_0 (corresponding to f_0) equal to or slighlty less than lowest CNL normal stress
- Determine k values for CNS tests such that the increase in normal stress due to anticipated dilation (assumed to be similar to x_{CNL}) will result in a final normal stress within the CNL normal stress range

The intent of this procedure was to allow a comparison of the shear behavior of the specimens under different boundary conditions but at similar stresses.

All values for load and displacement given herein consider compression/contraction to be positive and tension/dilation to be negative.

Test Specimens

Tests were performed on both sawtoothed hydrostone and concrete specimens. The hydrostone was prepared by combining USG Hydro-Stone Super X at a ratio of 22 parts water to 100 parts product and mixing for 3 minutes in a Globe SP20 industrial mixer at a speed setting of “1”, corresponding to about 60 rpm. The hydrostone was then cast against steel specimens to develop the sawtoothed specimens as shown in Figure 7.

Figure 7 - Sawtoothed aluminum specimen ready for hydrostone pour. Note 0.2 in plexi-glass spacer between upper and lower rings.

Two different ridge pattern aluminum specimens were used to cast two distinct geometries of hydrostone specimens. Figure 8 illustrates the two types of specimens.

Figure 8 - Sawtoothed hydrostone specimens after casting. Specimens in the foreground were labeled LR (large ridge), while specimens in the background were labeled SR (small ridge).

The specimens designated SR-X (where X is the specimen number) had a total of nine complete ridges with half-ridges at each end along an about 7.0 inch shear surface length. The ridges were angled at about 12 degrees from horizontal.

The specimens designated LR-X had a total of two complete ridges with half-ridges at each end along an about 7.0 inch shear surface length. The ridges were also angled at about 12 degrees from horizontal.

Concrete specimens were cast using Quikrete Concrete Mix No. 1101 purchased from a nearby hardware store and mixed per the manufacturer's specifications. Direct shear specimens were cast as 6 in by 12 in cylinders and cut into thirds along the long axis (approximitly 4-inch tall specimens) after a brief set-up period. The specimens were cast such that a 0.2 in section was left exposed between the encapsulating rings as the shear surface. Specimens were labeled CC-1 through CC-6.

The concrete was mixed and molded as cylinders on November 3, 2017 and cast into direct shear specimens on November 22, 2017. Concrete cylinders were stored in a fog room from mixing until casting.

Results

Sawtoothed Hydrostone

The sawtoothed hydrostone specimens were used primarily to verify the machine controls for CNS testing were functioning correctly, and to provide an initial data set for optimizing the analysis code. Figure 9 presents a plot showing machine response during CNS testing.

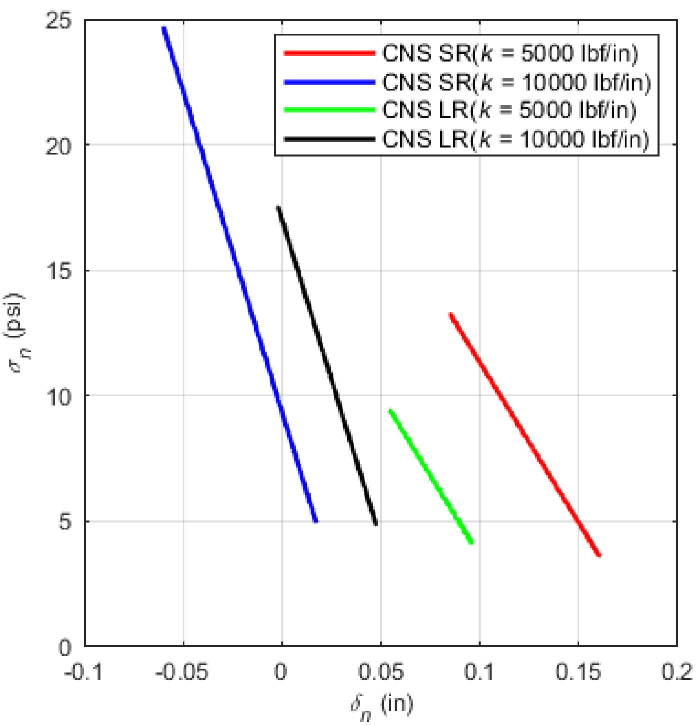


Figure 9 - CNS test results showing normal load versus vertical displacement (tests start at the right and move to the left).

In Figure 9, the normal load varies linearly with the normal displacement, with a slope based on the assigned *k*. Note that normal movement (dilation) is negative based on the sign conventions used. This machine response indicates that the system is being controlled as intended for the CNS tests.

CNL tests were performed on one SR and one LR type specimen with each test encompassing four values of σ_n (5, 10, 20, and 40 psi). The specimens were not reset between each normal load. CNS testing was performed on both SR and LR specimens by using a σ_0 of 5 psi, with k values of 5,000 lbf/in and 10,000 lbf/in. The tests with different k values used different specimens to limit wear on the shear surface; therefore, there were two SR and two LR specimens tested under CNS. The results of this testing are plotted below in Figures 10 and 11.

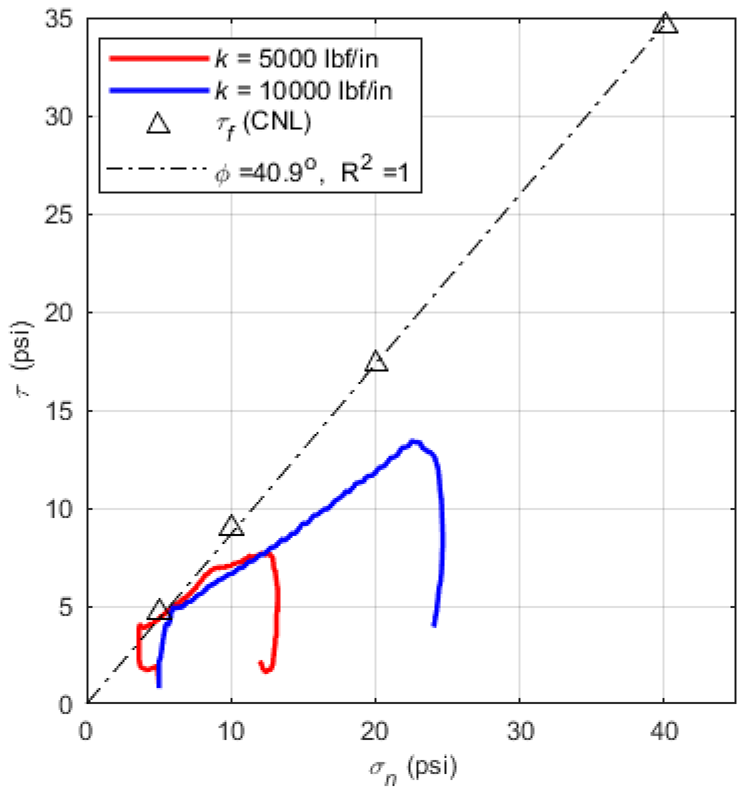


Figure 10 - CNL and CNS test results for the SR specimens.

Figure 10 illustrates the CNL failure envelope is defined by the three τ_f points and fit with the given linear Mohr-Coulomb parameters. Stress paths are also shown for the two CNS specimens under the given k values.

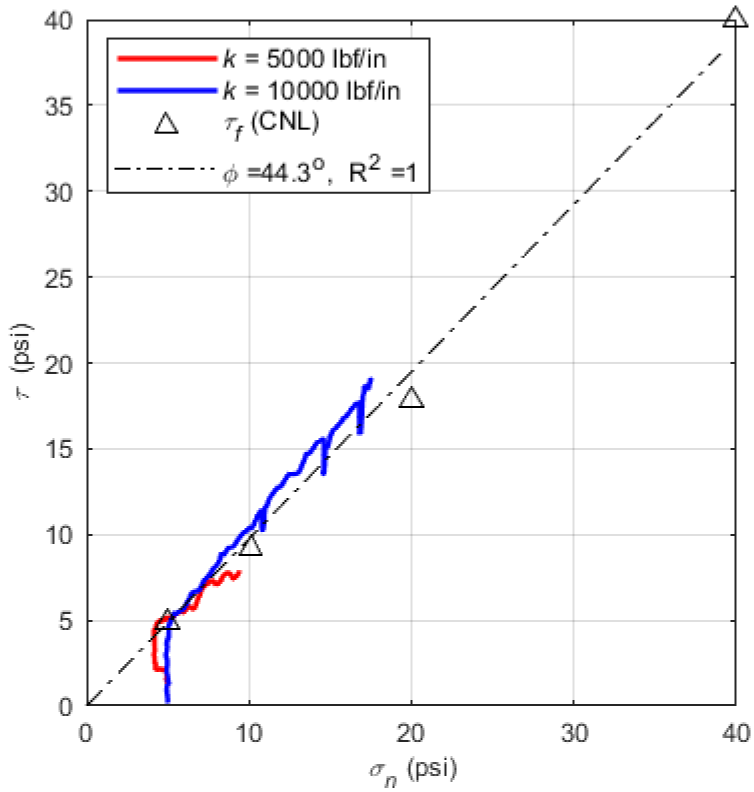


Figure 11 - CNL and CNS test results for the LR specimens.

Figures 10 and 11 indicate that the rollover (initial slope break) of the CNS stress paths is in close proximity to the CNL linear failure envelope for both the SR and LR specimens. The CNS stress path follows the trend of the CNL failure envelope up to the end of the test in the case of the higher stiffness LR test, but the CNS SR and lower stiffness LR tests define a lower strength envelope than that of the CNL tests. The CNL failure points were selected as peak strengths, with the stress paths of the CNS tests after the rollover point potentially reflecting a post-peak strength. The CNS tests may be reflective of both peak (rollover point) and post-peak (stress paths) behavior.

The friction angle between the CNL SR and LR specimens varies from 40.9° to 44.3°, respectively. As the specimens are of identical material with the same ridge angle, it would be anticipated that the friction angle would be the same. It appears that the highest stress LR CNL point is "pulling" the failure envelope "up" resulting in a greater friction angle. A 40.9° friction angle is likely a reasonable value for these specimens.

Figures 12 and 13 present the changes in τ and σ_n versus shear displacement (δ_s) during testing.

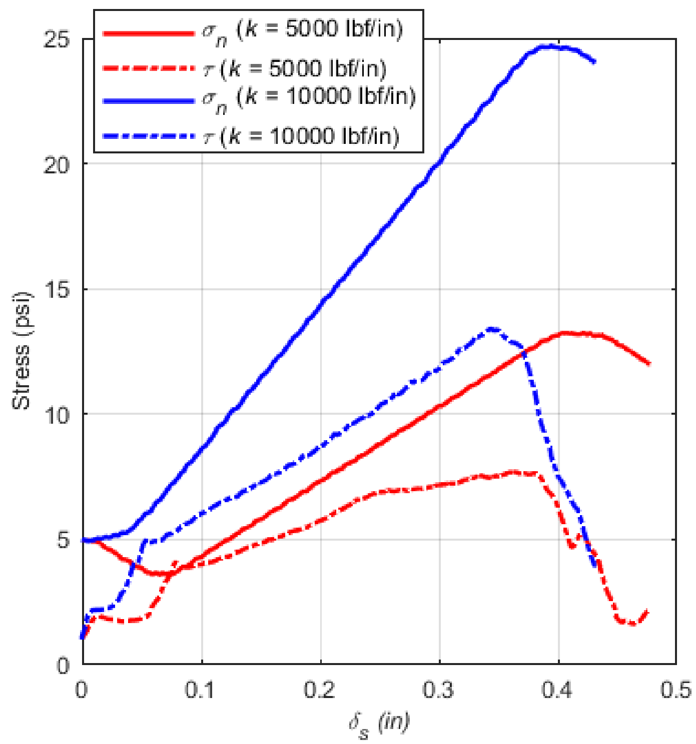


Figure 12 - Stress versus shear displacement during testing for the SR specimens.

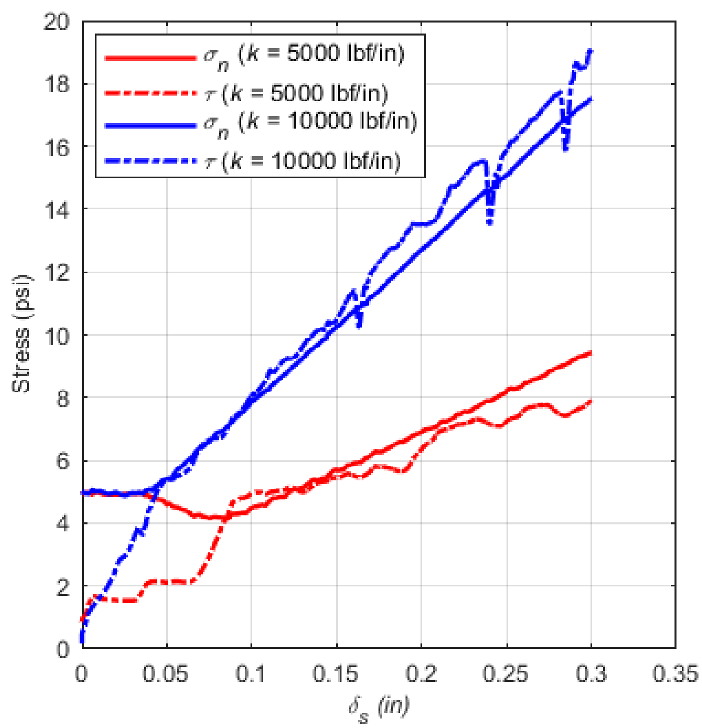


Figure 13 - Stress versus shear displacement during testing for the LR specimens.

Figure 12 indicates that for the SR specimens peak shear strength was reached prior to the peak normal stress, while this was not the case for the LR specimens shown in Figure 13. The initial contraction of specimens SR k = 5,000 lbf/in and LR k = 5,000 lbf/in is thought to be a result of the specimens not being perfectly interlocked at the start of shearing.

The CNS tests were ended for the SR specimens when specimen dilation stopped, indicating that the sawtoothed ridge had been overcome and the specimen was sliding down the back-side of the ridge. CNS testing on the LR specimens was stopped after about 0.3 inches of shear displacement. Figure 14 shows specimen LR-3 (CNS with k = 10,000 lbf/in) after testing.

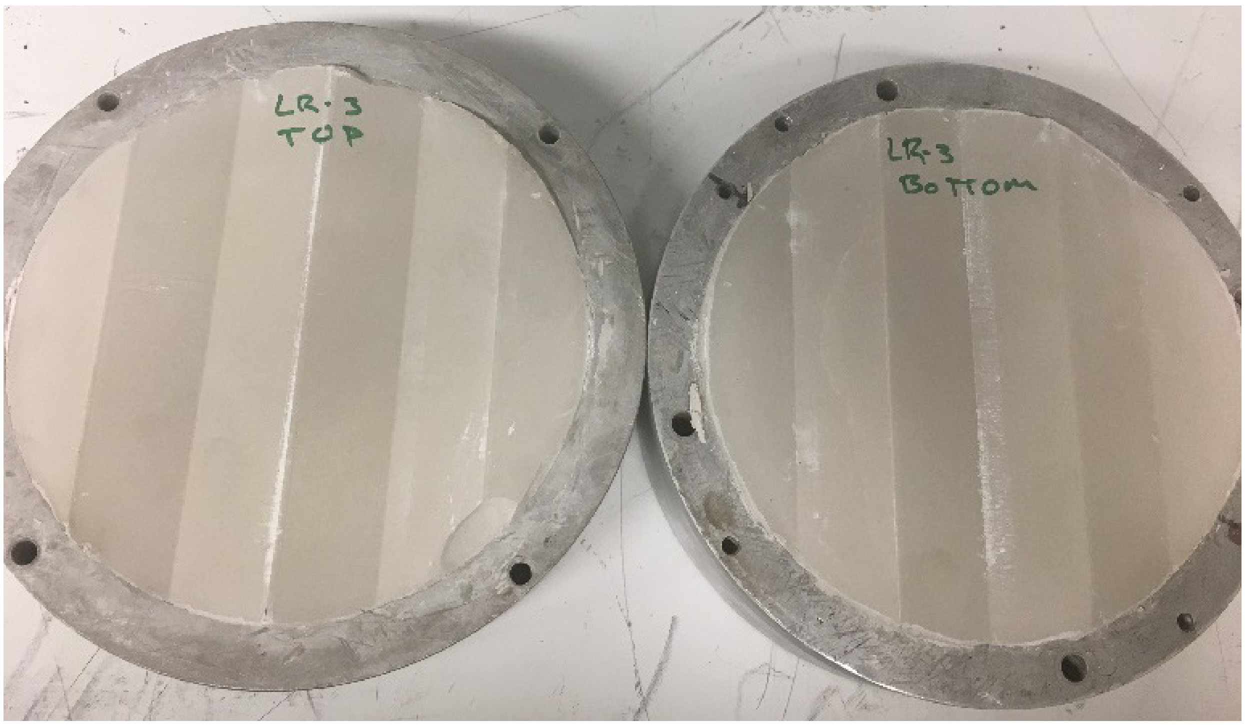


Figure 14 - Specimen LR-3 after CNS testing. Note minimal damage to the sliding surface with apparent force concentrations at the ridges. This amount and type of damage was typical for the sawtoothed specimen testing.

Appendix B presents the results from the individual CNL direct shear tests, while Appendix C provides post-test photographs of the specimens.

Concrete Specimens

Concrete specimens were tested under both CNL and CNS boundary conditions for break bond and sliding friction strength. The CNL tests were performed on three specimens (CC-1 through CC-3) and proceeded such that each specimen was broken at a different σ_n with the sliding tests performed immediately afterwards. The σ_n values during sliding went from low to high in order to limit specimen degradation. The CNL specimens were broken and slid at each test encompassing three values of σ_n: 15, 20 and 40 psi. In this way, each specimen was broken at a distinct σ_n, then slid at three additional normal stresses. Data from all of the slides was then combined to generate failure envelopes for both the break bond and sliding friction strengths.

A σ_0 of 10 psi with k values of 1,500, 4,000 and 7,000 lbf/in were used for the CNS tests (specimens CC-4 through CC-6). Each specimen was broken and slid at the same k (i.e. CC-4 was broken and slid under a σ_0 of 10 psi with a k of 1,500 lbf/in). Figure 15 shows a typical concrete specimen after testing.

Figure 15 - Specimen CC-3 after CNL testing (break bond at 40 psi). Inclined breaks are typical with this type of test, with the sliding occurring in the "down-hill" direction. Specimen top on the left side of photo.

No trends in the specimen break characteristics by boundary condition were noted after testing.

Break Bond Testing

The results of the break bond testing were unclear and appear to indicate some previously unknown machine irregularities. The data presented in this section may not be reflective of actual material behavior. Figure 16 presents the results of CNL and CNS break bond testing.

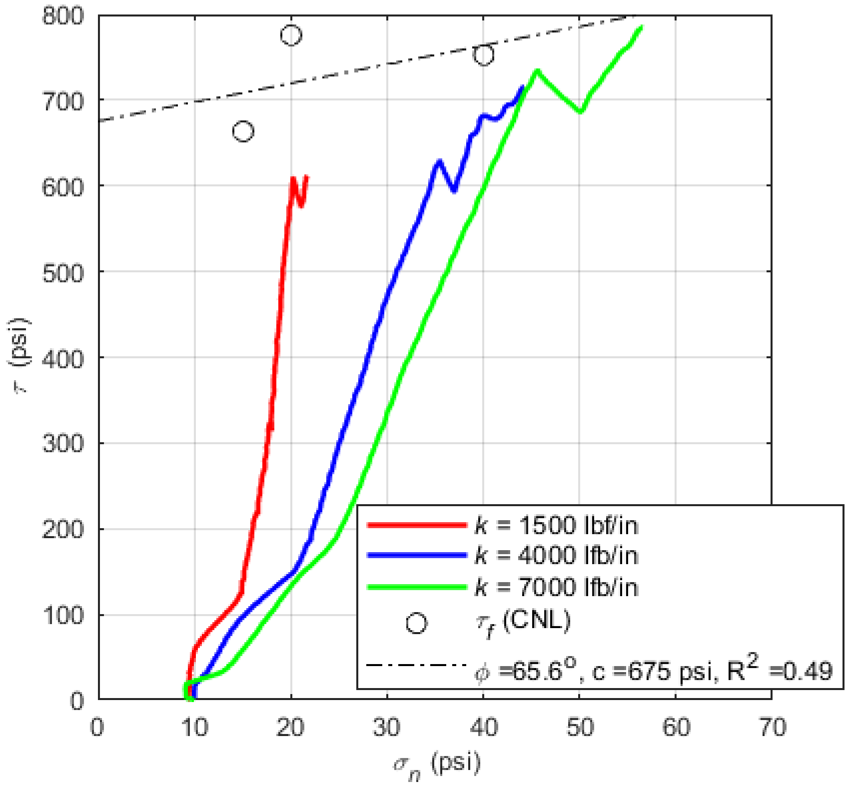


Figure 16 - Break bond CNL and CNS test results.

Note that little correlation was found between the break bond testing results under CNL and CNS boundary conditions. Figure 17 shows the stresses versus shear displacement and Figure 18 shows the dilatancy during testing.

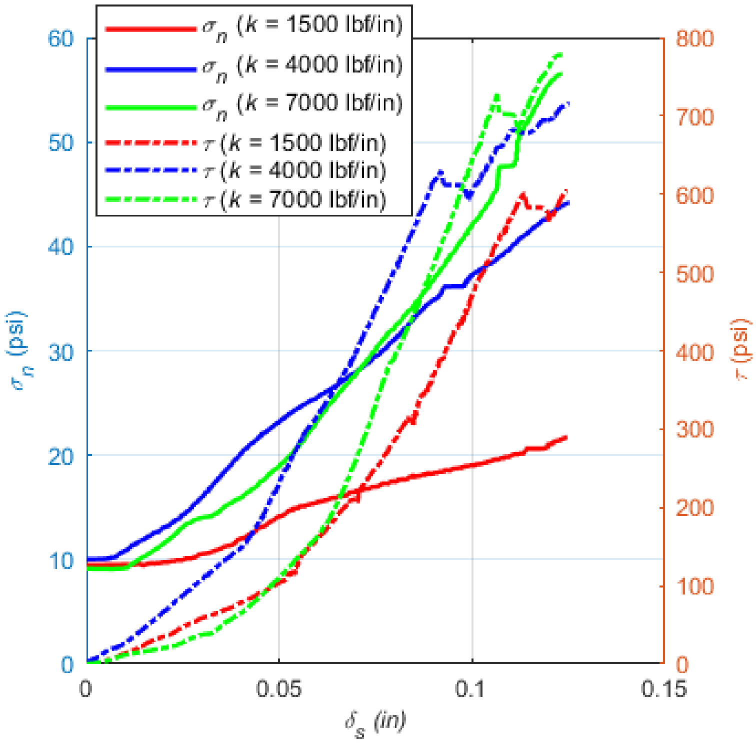


Figure 17 - Stress versus displacement for CNS break bond testing.

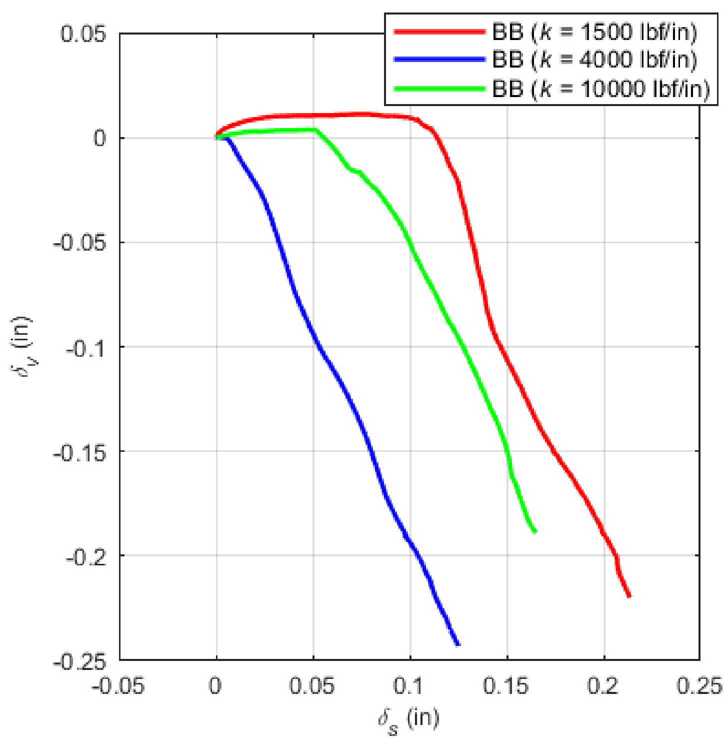


Figure 18 - Break bond dilatancy during CNS testing.

Figures 17 and 18 indicate that the specimens moved more than 0.1 inches in shear and dilated 0.2 inches or more at failure. It is not clear if this behavior is a function of the specimen or if it is caused by some rotation of the shear box top during testing creating artificially large displacements. This is being further investigated and may result in additional mechanical upgrades for break bond testing.

Sliding Shear Testing

The sliding shear test data for both CNL and CNS testing is presented in Figure 19.

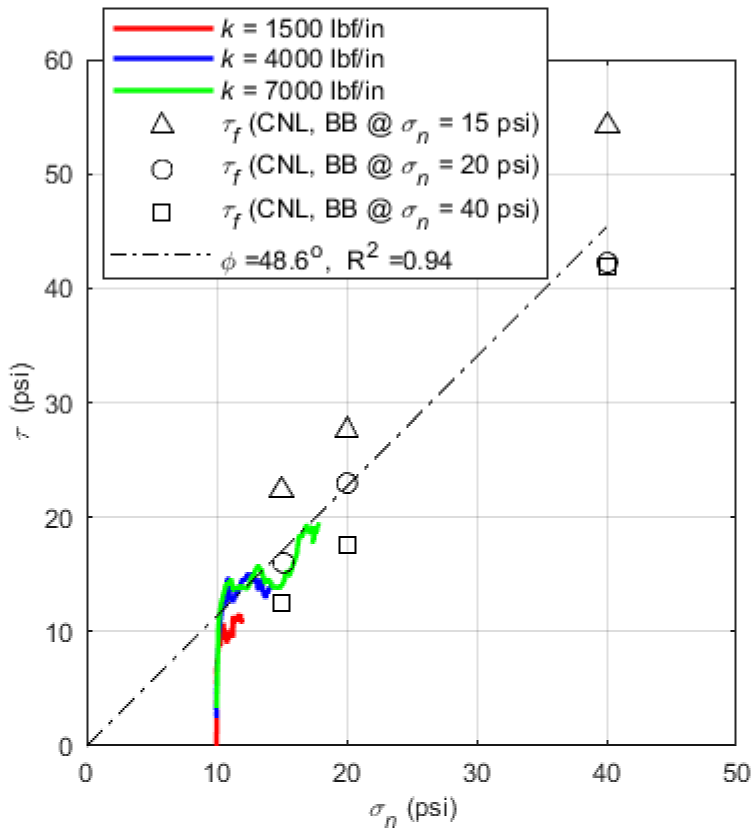


Figure 19 - CNL and CNS test results for the concrete sliding shear tests.

The CNS stress path rollovers are in close proximity with the CNL failure envelope in Figure 19, and appear to generally follow the CNL failure envelope as shearing continued. Of note is that the CNL specimens showed a decrease in sliding shear strength with an increase of break bond normal stress. This could be a result of increased damage to the specimen when broken under higher normal stresses. Further study of this phenomenon may be of interest.

Figure 20, below, found that increasing the normal stiffness during CNS testing resulted in the specimen achieving both higher peak shear and normal stresses. There is no apparent trend between the shear displacement at which peak stress is achieved, and normal stiffness.

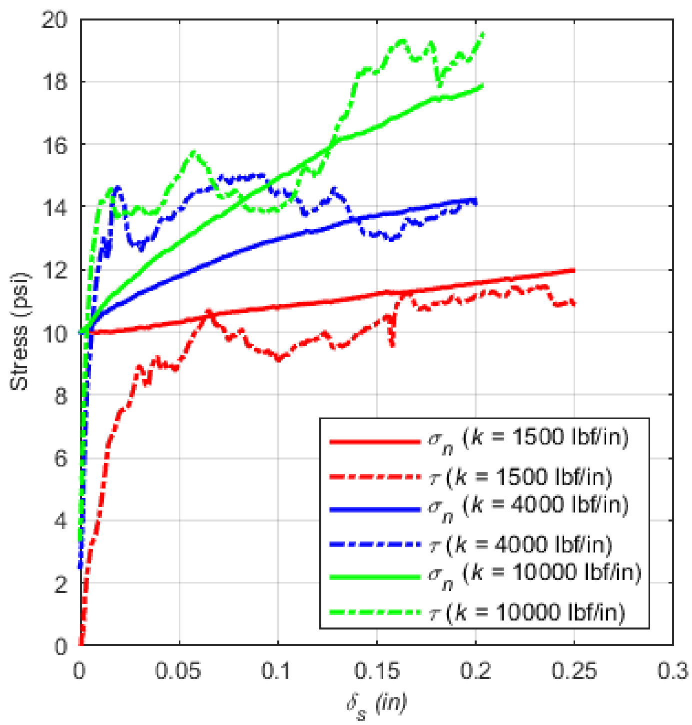


Figure 20 - CNS test results for the concrete break bond shear tests showing the change in both shear and normal stress as a function of shear displacement.

Figure 20 indicates that two of the three CNS sliding friction specimens continued to dilate during shearing and did not reach a peak normal stress when shearing was stopped at about 0.20 – 0.24 inches of displacement. Based on Figure 20, it is likely that only one specimen (k = 4,000 lbf/in) reached peak shear strength.

Figure 21 shows the change in normal displacement as a function of shear displacement during shearing for the CNS tests.

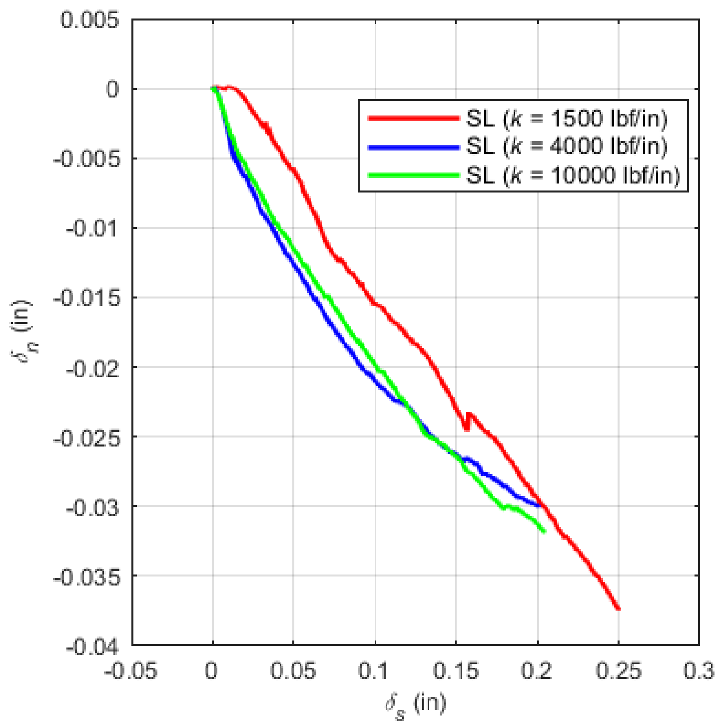


Figure 21 - Normal displacement versus shear displacement during sliding shear testing.

Figure 21 does not indicate any trend in the amount of dilation as a function of the normal stiffness during sliding shear testing. The lowest stiffness value CNS specimen does appear to have a relatively constant dilation rate, while the two higher stiffness value tests show a non-linear trend, with the dilation rate decreasing with increasing shear displacement. This is probably due to the increase in *k* resulting in higher normal stresses, and thereby suppressing dilation.

Appendix B presents the test results for each of the CNL tests, while photographs of the specimens are presented in Appendix C.

Conclusions

Based on the laboratory testing presented, the following conclusion were made:

- Machine controls established by Reclamation perform as intended.
- The rollover (initial slope break) of the CNS stress paths in sliding friction tests are in good agreement with the linear failure envelope defined by CNL testing for both the sawtoothed hydrostone and concrete specimens.
- The stress paths of the CNS tests on the sawtoothed hydrostone specimens tended to be below the CNL linear envelope, potentially showing post-peak type behavior.
- The stress paths of the CNS tests on concrete during sliding tend to follow the CNL linear failure envelope.
- The difference in stress path behavior of the sawtoothed hydrostone and concrete specimens could indicate that for materials that show a post-peak strength (strain-soften), the stress path may follow a post-peak envelope. While for the concrete specimens (which typically strain harden or show minimal decrease in strength past peak) the stress path appears to follow the CNL failure envelope.
- Further research is needed to determine if the CNS stress path can be used to approximate the CNL failure envelope.
- The CNS concrete break bond testing and interpretation is complex and needs further research. The direct shear machine may require modification to reduce any rotation of the top box.
- The amount of dilation appeared to be relatively consistent for a range of normal stiffness values for both break bond and sliding shear tests. The dilation rate under higher stiffness values appears to be non-linear. This may be affected by top cap rotation.
- The normal load at which concrete is broken appears to affect the sliding friction CNL failure envelope, with higher normal loads at breaking leading to lower sliding shear strengths.
- Incorporation of CNS strength parameters into both finite element models and limit equilibrium problems is relatively simple and should be used where it represents the correct boundary condition. The use of CNL parameters in some cases may be unconservative.

Recommendations

CNS testing provides a unique boundary condition which should be considered where the normal stress is not constant along a discontinuity during shearing. Furthermore, CNS testing provides insight into material behavior as shearing progresses. Of future interest is the use of the CNS stress paths to define reasonable upper and lower bound failure envelopes to provide a range of strength parameters, or to define peak and post-peak envelopes. Further research is needed to understand the mechanics of break bond testing under the CNS boundary condition. Machine upgrades may be required to eliminate the rotation of the top shear box during break bond testing.

References

Blümel, M., and F.A. Bezat. 1999. Advanced control techniques for direct shear testing of jointed rock specimens. In Nondestructive and Automated Testing for Soil and Rock Properties, ASTM STP 1350, eds. W.A. Marr and C.E. Fairhurst, 276-299.

Button, E.A., and M. Blümel. 2002. Servo-controlled direct shear tests on phyllites. In Proceedings of the 5th North American Rock Mechanics Symposium, Toronto.

Indraratna, B. and A Haque. 2000. Shear Behavior of Rock Joints. 1st ed. Vermont: A.A. Balkema Publishers.

Jiang, Y. 2017. Rock joints shearing testing system. In Rock Mechanics and Rock Engineering: Volume 2: Laboratory and Field Testing, ed. X. Feng, 217-249.

Johnston, I.W., and T.S.K. Lam. 1989. Shear behavior of regular triangular concrete/rock joints-analysis. J. Geotech. Eng. Vol. 115, No. 5: 711-727.

Muralha, J., G. Grasselli, B. Tatone, M. Blümel, P. Chryssanthakis, and J. Yujing. 2014. ISRM suggested method for laboratory determination of the shear strength of rock joints: revised version. In The ISRM Suggested Methods for Rock Characterization, ed. R. Ulusay, 131–142.

Appendix A – MYS Quote for Controller Upgrade for Direct Shear System

Quotation

Prepared For:

Evan J. Lindenbach
US Bureau of Reclamation

Denver, Colorado 80225
Phone: (303) 445-2336
Email: elindenbach@usbr.gov

Quotation Number:	2016-30021rev6 USBR FlexTest controller upgrade for direct shear system
Quotation Date:	June 2, 2017
Quotation is valid for:	60 Days
Currency:	US Dollar
Estimated Shipment Schedule:	120 Days (ARO)
Estimated Delivery to Customer Site:	135 Days (ARO)
Billing Plan:	100% on Shipment
Payment Terms:	Net 30
Shipment Terms:	FOB Destination -
Freight:	Prepaid
Equipment Packed For:	Ground/Air Freight
Mode of Transport:	Ground Transport

Prepared By :

Merrill Bishop

Phone: 303 881 7065

Address Order To :

Merrill Bishop
MTS Systems Corporation

Fax: 970 613 0908
Email: merrill.bishop@mts.com

Quotation

Quotation Number: 2016-30021rev2 USBR FlexTest controller upgrade for direct shear system
Estimated Shipment Schedule: 120 Days (ARO)
Billing Plan: 100% on Shipment
Payment Terms: Net 30
Shipment Terms: FOB Destination

Summary:

Description		Net Price
1.0 - Quantity 1 x Controller Components		$53,491.00
2.0 - Quantity 2 x MTS Extensometers		$12,440.00
	Bottom Line Discount	$3,296.55
	Total Price	USD $62,634.45

Quotation

Description	Net Price
1.0 - Quantity 1 x Controller Components	$53,491.00

------ Component Summary ------

- 494.16 Valve Driver / DUC's : 2
- 494.26 Dual DUC's : 2
- 494.45 Analog Input (A/D) : 1
- 494.40 I/O Carrier Modules : 2
- 494.75 Analog Input (A/D) Transition Modules : 1

------ Controller Software Summary ------

- FLEXTEST 494:
- Customer Existing 793 Software Version 5.9 Current - Released June 2015.
- Customer does not have Elastomer, Damper, RPC, 793 F&F or other software that depends on 793.

------ Application Software Summary ------

- TESTSUITE:
- Customer Existing Version is Current.

Line	Description	Unit Price	Quantity	Net Price
1.1	494.40B Module Assembly; IEEE +/- 15, ROHS	$1,590.00	2	$3,180.00

- PN: 100206704

Line	Description	Unit Price	Quantity	Net Price
1.2	494.16 DUC/Valve Driver	$1,610.00	2	$3,220.00

- PN: 100212061

Line	Description	Unit Price	Quantity	Net Price
1.3	494.26 Dual DUC	$3,230.00	2	$6,460.00

- PN: 100208033

Line	Description	Unit Price	Quantity	Net Price
1.4	494.45 Eight Channel A/D Board with Breakout Cables or 494.75 Transition Board	$3,100.00	1	$3,100.00

Quotation

- Provides 8 high-level (+/-10 V DC) input signals

• Details:
• A/D Channels 1-8 with 494.75 and 2 transition cables

Line	Description	Unit Price	Quantity	Net Price
1.5	MTS Model 494.05 Handset	$1,080.00	1	$1,080.00

The Model 494.05 Handset provides an easy, convenient and compact means to install and replace specimens, and to setup and initiate tests at the load frame or test rig. It is available for use with the FlexTest® 40, 60, 100 and 200 controllers.

It also provides the ability to adjust actuators, auto-offset signals, start and stop tests, and turn hydraulics on or off.

Photos are for reference only, not to scale.

- Visible test status display
- Precision controls for fine actuator positioning
- Ergonomic design for both right- and left-handed operators
- PN: 100292300

• Cable Length
• Handset Cable #1 7.6 m (25 ft)

Line	Description	Unit Price	Quantity	Net Price
1.6	Handset Retainer with Mounting Screws	$70.00	1	$70.00

- PN: 100188282

Line	Description	Unit Price	Quantity	Net Price

Line	Description	Unit Price	Quantity	Net Price
1.7	MTS Computer-WIN7, 64 bit, 8GB RAM, 2x500GB hard drive, Desktop	$2,330.00	1	$2,330.00

- Computer specifications subject to change
- Includes Microsoft Excel
- MTS-Supplied computers comply with the following certifications:
- Argentina IRAM & UL, Australia C-tick, Canada UL
- China CCC, EU CE & WEEE, Japan VCCI
- Korea KCC, Singapore Safety, Taiwan BSMI Safety, United States FCC & UL
- PN: 100325044
- Computer Power Cord North America 100 - 120 V (AC) (NEMA 5-15)

Line	Description	Unit Price	Quantity	Net Price
1.8	MTS Supplied Monitor - 23" LCD	$590.00	1	$590.00

- PN: 100330544

Line	Description	Unit Price	Quantity	Net Price
1.9	Cable Assembly; 252 and 256 valves to 494.16, 7.5 m (25 ft)	$190.00	2	$380.00

- PN: 57193704

Line	Description	Unit Price	Quantity	Net Price
1.10	Cable Assembly; LVDT with RJ50 to PT connector, 7.5 m (25 ft)	$190.00	2	$380.00

- PN: 57099104

Line	Description	Unit Price	Quantity	Net Price
1.11	290/293/294 HSM cable; Off/Low/High, 7.5 m (25 ft)	$240.00	1	$240.00

- PN: 39701404

Line	Description	Unit Price	Quantity	Net Price
1.12	Model 793.04 PC Per Station Option for FT60/100/200/GT/IIM	$2,420.00	1	$2,420.00

Capability to use a separate PC for each test station, up to maximum of 4 stations, enabling up to four PCs on one FlexTest 200 controller. This allows different users to simultaneously operate their respective tests without requiring them to share a PC. Multiple stations can still be operated through single PC. Four PC maximum. PCs not included.

- Each kit includes the required network hardware and cables.
- For 2 PCs: 2 hubs, 2 network adapters, 4 network cables
- For 3 PCs: 2 hubs, 3 network adapters, 6 network cables
- For 4 PCs: 2 hubs, 4 network adapters, 8 network cables
- PN: 100055698

Line	Description	Unit Price	Quantity	Net Price
1.13	PC per Station Hardware Kit, FT40/60, 2 Station	$1,340.00	1	$1,340.00

- Controller hardware and patchcords required for PC-per-Station.
- PN: 52531501

Line	Description	Unit Price	Quantity	Net Price
1.14	MTS TestSuite™ Reporter Add-In	$2,230.00	1	$2,230.00

For easy report design and generation, the Reporter Add-In for use with Microsoft® Excel® allows you to organize your raw data and create impressive reports with little time investment or manual intervention.

- Generates reports from existing MTS TestSuite test data
- Creates test reports that require no post-processing
- Supports text, charts and calculations
- Required Software (not included in this line item): MTS TestSuite MP Elite, MP Express, TW Elite, TW Essential or TW Express for test execution and automated report generation, Microsoft Excel 2003 or newer to view reports
- In the event that the customer needs to re-install MS Excel or MS Office, the customer must supply their own version
- PN: 100205364

------ --------------------- Commercial Software --------------------- ------

• Item MS Excel Included with MTS Supplied Computer

MTS

Quotation

Line	Description	Unit Price	Quantity	Net Price
1.15	Onsite Calibration	$5,307.00	1	$5,307.00

-----Configuration Details-----

- Axial Force Calibration, 0-500 kN (0-110 kip) (5)
- Onsite Calibration, LVDT/TEMPO Displacement Transducer (2)
- Calibration Standards Fee

Line	Description	Unit Price	Quantity	Net Price
1.16	Onsite Install & Commissioning	$7,616.00	1	$7,616.00

-----Configuration Details-----

- Standard Service Hour (32)

------ NOTES ------

• Installation Notes On site installation and commissioning

Line	Description	Unit Price	Quantity	Net Price
1.17	Onsite Basic Operator Training	$3,808.00	1	$3,808.00

-----Configuration Details-----

- Standard Service Training Hour (16)

------ NOTES ------

• Training Notes On site training

Engineered Content:

Line	Description	Unit Price	Quantity	Net Price
1.18	Engineered Cable Set • Engineered cable set. - Shore Western HSM - Qty. 2 - servovalves - Qty. 2 - load cells - Qty. 2 - MTS Temposonics	$2,000.00	1	$2,000.00
1.19	TestSuite MP Elite software • TestSuite MPE Elite license	$7,240.00	1	$7,240.00
1.20	Cables for Laser Sensors • Cables for Laser Sensors Qty. 6 100-208-771 Qty. 1 57-221-701	$150.00	1	$150.00
1.21	HPU Cable • HPU Cable 25' For Shore Western HPU	$350.00	1	$350.00

Line 1.0 Package Total	USD $53,491.00

Quotation

Description	Net Price
2.0 - Quantity 2 x MTS Extensometers	$12,440.00

Line	Description	Unit Price	Quantity	Net Price
2.1	Model 632.06H-30 Displacement Gage	$4,420.00	1	$4,420.00

This is an extremely versatile displacement gage that can be used to measure fixture, shaft, or any other component movement during the test cycle. Designed for use where small deformations must be measured, in bend tests, or where unusual geometries are involved; it's protected from overtravel in all directions.

Photos are for reference only, not to scale.

- Gage Length: N/A
- Travel: +/- 12.5 mm (+/- 0.5 in)
- Temperature Range: -100°C to 150°C (-150°F to 300°F)
- 632.06 is a displacement gage, no gage length, therefore no strain available
- PN: 47400516

Line	Description	Unit Price	Quantity	Net Price
2.2	Cable, TEDS Adapter to Extensometer, PT Connector	$280.00	1	$280.00

- Compatible with 494 controller (FT40/60/100/200) and extensometer
- Length: 1.5 m (5 ft)
- PN: 57272605

Line	Description	Unit Price	Quantity	Net Price
2.3	Cable Assembly; RJ50 to JT connector, 7.5 m (25 ft)	$290.00	1	$290.00

Quotation

- PN: 57241404

Line	Description	Unit Price	Quantity	Net Price
2.4	Onsite Calibration	$992.00	1	$992.00

-----Configuration Details-----
- Onsite Cal for 632.06 Extensometer
- Calibration Standards Fee

Line	Description	Unit Price	Quantity	Net Price
2.5	Onsite Install & Commissioning	$238.00	1	$238.00

-----Configuration Details-----
- Onsite Installation of Servohydraulic Accessory

Line 2.0 Package Total	USD $12,440.00

Total Price

Bottom Line Discount	$3,296.55
Final Price	**USD $62,634.45**

Supplemental Information

MTS General Terms And Conditions

The parties expressly agree that the purchase and use of material and/or services from MTS are subject to MTS' General Terms and Conditions, in effect as of the date of this document, which are located at http://www.mts.com/en/about/terms/ and are incorporated by reference into this proposal and any ensuing contract. Printed terms and conditions can be provided upon request by emailing info@mts.com.

Qualifications for Order Fulfillment

After MTS and customer agree to final terms of a contract, MTS may submit changes to the customer due to customer actions or inaction, including changes to the scope of work, technical requirements, and/or schedule.

Information required by the customer for the project execution needs to be supplied at a timely manner. In cases where this information is not available, a change request to extend the schedule will be based on the date the information was received.

MTS Limited Warranty

MTS Product Limited Warranty

Unless otherwise expressly agreed to in writing by MTS, MTS warrants Products of its manufacture to be free from defects in materials and workmanship for a period a twelve (12) months from date of shipment by MTS; or if MTS is responsible for installation, for a period of twelve (12) months from customer acceptance, but not to exceed eighteen (18) from date of shipment by MTS. Products are warranted only to the extent used under normal conditions that are equivalent to those as tested by MTS. MTS shall, at its option, repair or replace free of charge within the warranty period any Product supplied by MTS which proves to be defective in workmanship or materials. Consumables and normal wear and tear are not covered under warranty. MTS reserves the right to reject those claims for warranty where it is reasonably determined that failure is caused by Customer- or third party made-modifications, improper maintenance, misuse, misapplication, improper or incomplete qualification, abuse of the Product, damage due to factors which are beyond the control of MTS, damage caused by connections, interfacing or use in unforeseen or unintended environment. These conditions will render warranties null and void.

Services Warranty

Services are warranted to be in a workmanlike manner for a period of ninety (90) days after performance. MTS' entire liability and Customer's exclusive remedy, whether in contract, tort or otherwise for any claim related to or arising out of the breach of warranty covering Services will be re-performance or credit, at MTS' option.

WARRANTY LIMITATION

THE MTS LIMITED WARRANTIES IN THE AGREEMENT ARE EXPRESSLY IN LIEU OF ALL OTHER WARRANTIES, EXPRESSED OR IMPLIED, AND WHETHER STATUTORY OR OTHERWISE, INCLUDING ANY IMPLIED WARRANTY OF INFRINGEMENT, MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, AND NO WARRANTIES ARE EXPRESSED OR IMPLIED WHICH EXTEND BEYOND THE DESCRIPTION OF THE FACE HEREOF.

Commissioning

Following installation by an MTS technician or authorized service representative, there will be a demonstration of the functional performance of the purchased system or products to verify proper installation. This demonstration constitutes final acceptance and prompts final payment to MTS.

Specific testing with customer supplied specimens, test fixturing, or running tests to demonstrate a specific set of performance criteria is not included within the scope of this offering unless specifically included and defined herein.

Delivery of product or products as defined by Incoterms 2010 constitutes acceptance when a MTS or an authorized service representative is not involved in installation.

Customer Responsibilities

Facility Requirements

Certain site preparations may be required to insure a successful and timely installation of your new equipment. Please review our Site Prep Guides to verify what specific preparations are required for your new equipment. Our Site Prep Guides can be found on our website at: http://www.mts.com/en/services/Manuals/index.htm. The customer should perform a detailed review of the machine specifications to assure that the facility where the machine will be installed has an appropriate sized dock to accommodate the dimensions of the MTS system being purchased. The path that the system will take to its final destination should be measured to verify that the entry into the building, any doorways, elevators, or stairways that the machine must travel through, will accommodate the dimensions of the purchased MTS system. The customer should have appropriate moving equipment available to position the machine. Please pay close attention to the fork-lift handling instructions that accompany the shipment.

Equipment & Personnel

The customer will provide suitable equipment and personnel to unload and set in place all items in this quote, prior to the arrival of the MTS installation engineer. It is the customer's responsibility to ensure the system is handled and manipulated per the packing instructions. The customer may need an overhead crane or other lifting device for use in the installation and assembly of system components, as well as the routine setup of test system fixturing.

Power

Electrical power for MTS supplied equipment will be provided by the customer. All wiring from power supply to the MTS equipment is customer supplied. This electrical supply should be free from power transients caused by other equipment on the circuit. This includes appropriate electrical power for the hydraulic power supply (HPS) as well as a fused disconnect when an HPS is purchased. The desired HPS voltage must be specified at the time of the order.

Water

If a hydraulic power supply with a water-to-oil heat exchanger or water-cooled accessories is purchased, a cooling water supply and drain of sufficient capacity is required. The cooling water lines shall be provided and connected by the customer.

Environment

Environmental requirements are indicated in the associated product literature. If purchased, the hydraulic power supply will require a room with adequate ventilation to ensure the maximum temperature for the room does not exceed 104 degree F (40 degree C). The electronic components and computer equipment should be located in a suitable environment with respect to temperature, humidity, and dust.

Specimens

For installation, demonstration, and training, suitable specimens and other materials may be required. (Note: MTS supplies a specimen for this purpose with Acumen systems). For other systems, the customer is responsible to supply specimens and materials.

Taxes, Duties, & Fees

Customer is responsible for any necessary national or local sales taxes, import duties or customs fees.

Disposal of Dunnage

Customer is responsible for the disposal of all packaging items, empty containers, and other items resulting from the installation of MTS equipment.

Inspection Charges

Charges for inspection by an independent agency, if required by the customer, will be paid by the customer.

Documentation

Standard Products and Standard Systems

Manuals for standard products and standard systems are available from the MTS web site. You will also find software reference information (in English only) to support the Operators Guides provided with our standard MTS Landmark, MTS Acumen, MTS TestLine, and MTS Criterion systems. Refer to the Manuals tab at http://www.mts.com/en/services/index.htm.

Custom and Engineered to Order Systems

For engineered-to-order and custom systems, MTS provides operation and maintenance information on one CD or DVD. In some cases, the CD/DVD will include assembly level drawings and parts lists to aid our trained Field Service Engineers in installing, maintaining, and servicing the equipment.

Software

MTS controller software provides electronic documentation accessible from the application or, in some cases, from the Start menu. Software documentation includes basic user interface, operation, and test design information. Additional software reference documentation for the entire feature set of the controller software can be found on the MTS web site in English only. Refer to the Manuals tab at http://www.mts.com/en/services/index.htm.

Language

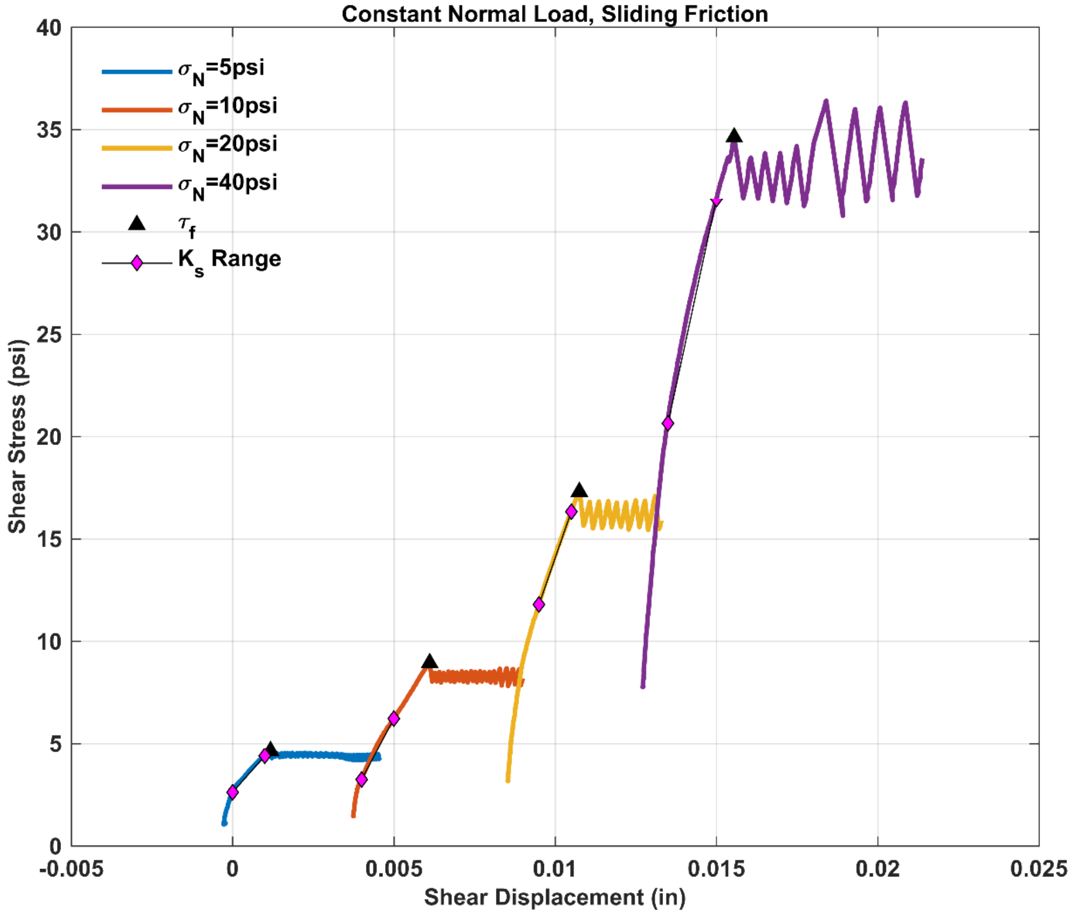
For European Community – MTS will provide language translated operation manuals. Specify the required language when placing the Purchase Order.

For all other countries – MTS provides documentation in English. Translation into major languages is available for many standard products and system level documentation. Contact MTS Systems for availability and price.

U.S. Government Note

Prior to placing an order, you must first notify MTS if this order is: (A) for ultimate end-use by the U.S. Government or (B) being paid for with U.S. Government funding.

Appendix B – CNL Test Data

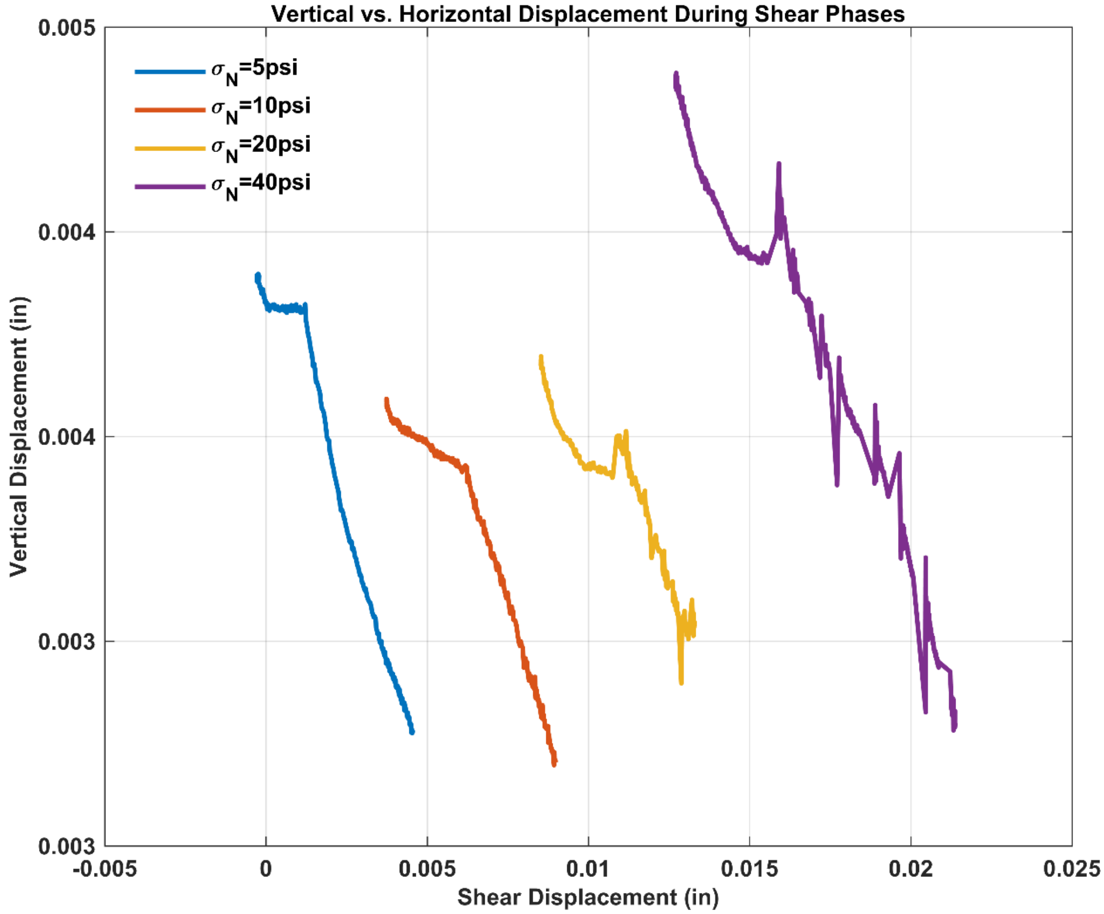


σ_N (psi)	τ_f (psi)	K_s (lb/in)
5	5	1794
10	9	2970
20	17	4534
40	35	7307

Project: Dam Safety Research
Feature: SR-1 CNL
Drill Hole: NA
Depth (ft): NA
Sample: SR-1 CNL

Core Size (in): NA
Material: Hydrostrone
Type of Test: Sliding
Shear Mode: unidirectional

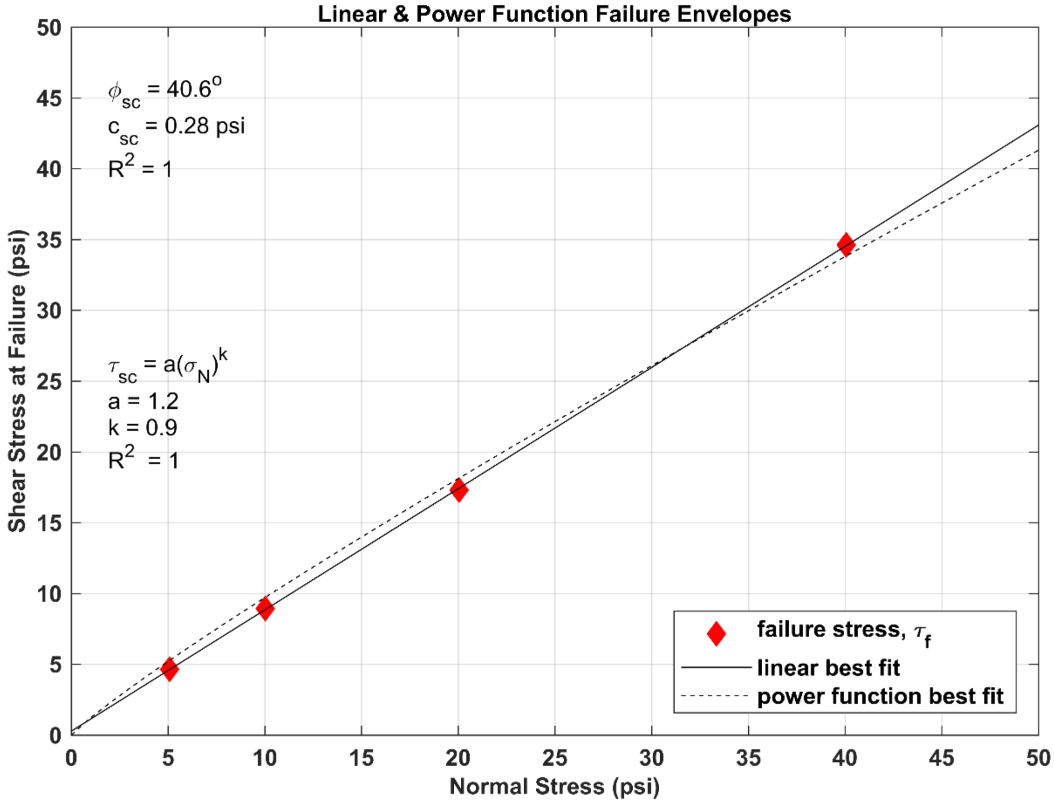
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: SR-1 CNL
Drill Hole: NA
Depth (ft): NA
Sample: SR-1 CNL

Core Size (in): NA
Material: Hydrostrone
Type of Test: Sliding
Shear Mode: unidirectional

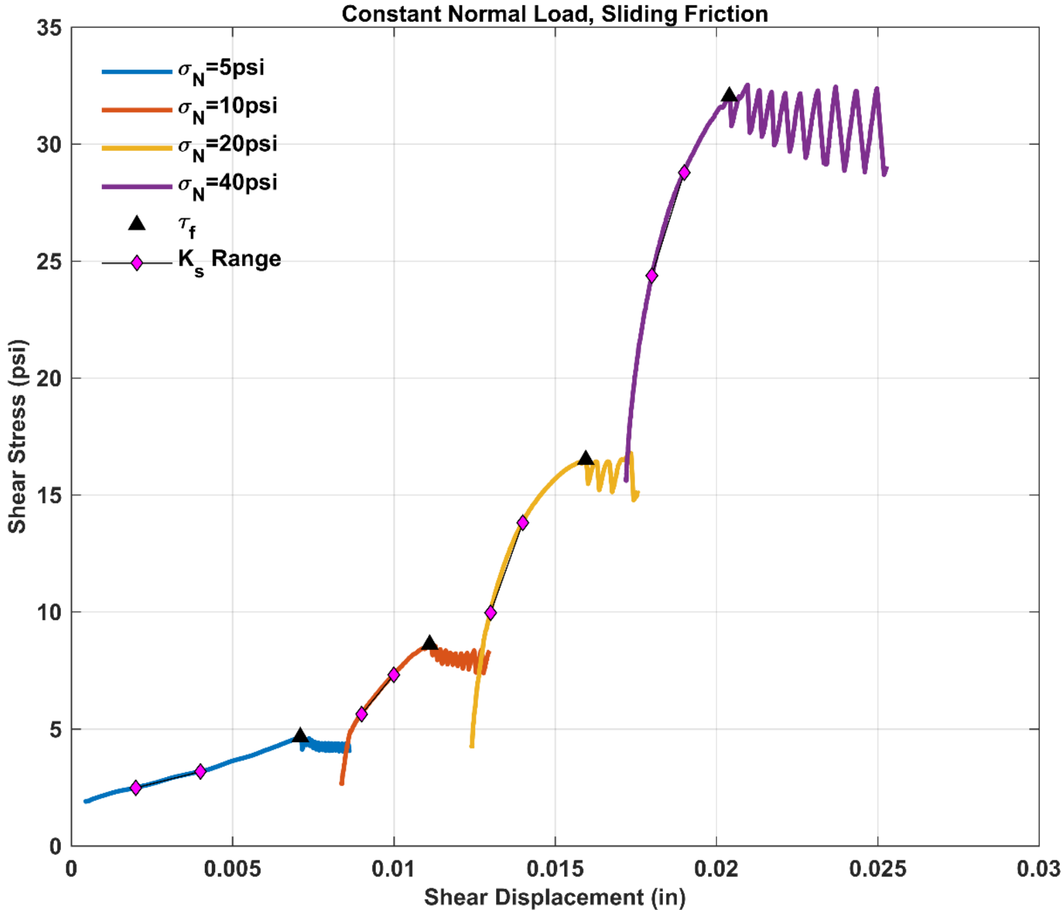
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: SR-1 CNL
Drill Hole: NA
Depth (ft): NA
Sample: SR-1 CNL

Core Size (in): NA
Material: Hydrostrone
Type of Test: Sliding
Shear Mode: unidirectional

Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA

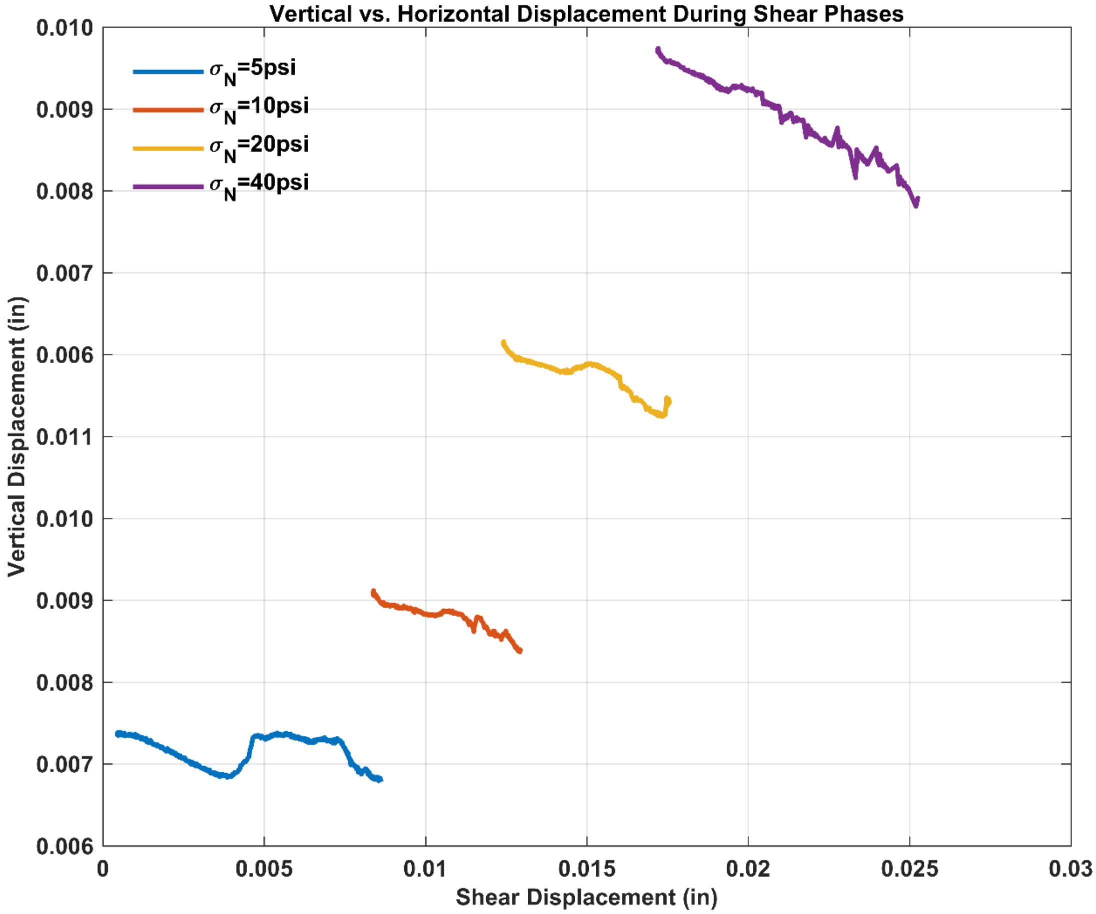


σ_N (psi)	τ_f (psi)	K_s (lb/in)
5	5	346
10	9	1682
20	17	3848
40	32	4400

Project: Dam Safety Research
Feature: LR-1 CNL
Drill Hole: NA
Depth (ft): NA
Sample: LR-1_NL

Core Size (in): NA
Material: Hydrostrone
Type of Test: Sliding
Shear Mode: unidirectional

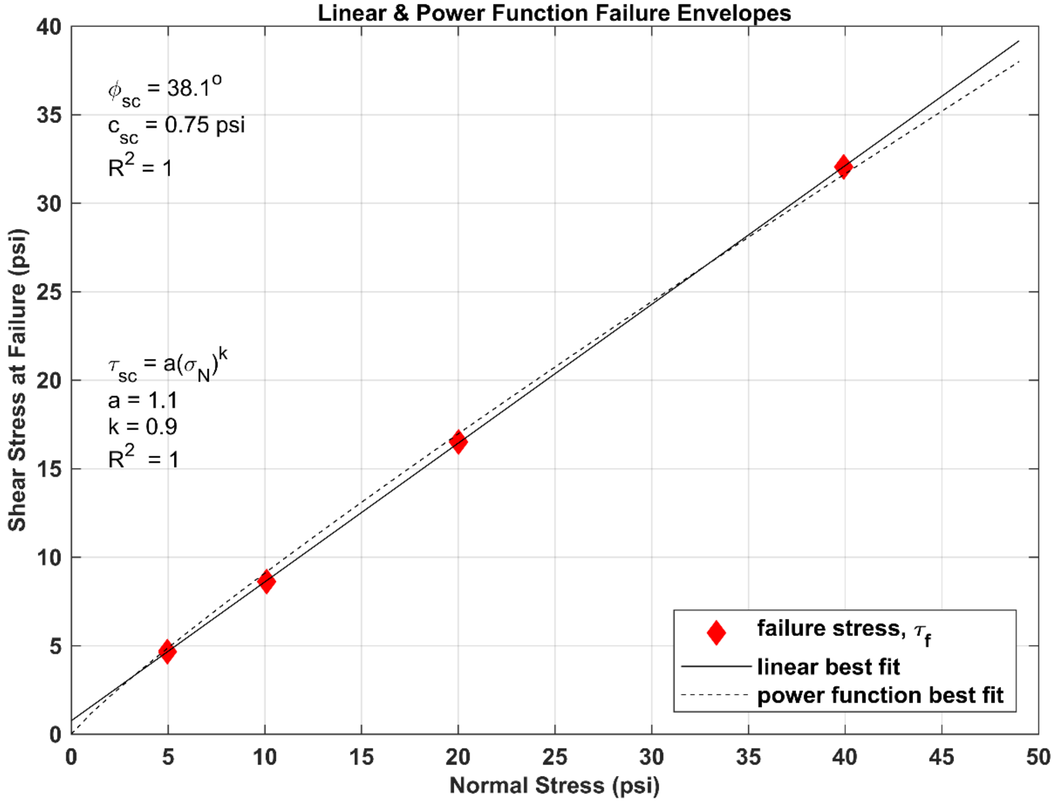
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: LR-1 CNL
Drill Hole: NA
Depth (ft): NA
Sample: LR-1 CNL

Core Size (in): NA
Material: Hydrostrone
Type of Test: Sliding
Shear Mode: unidirectional

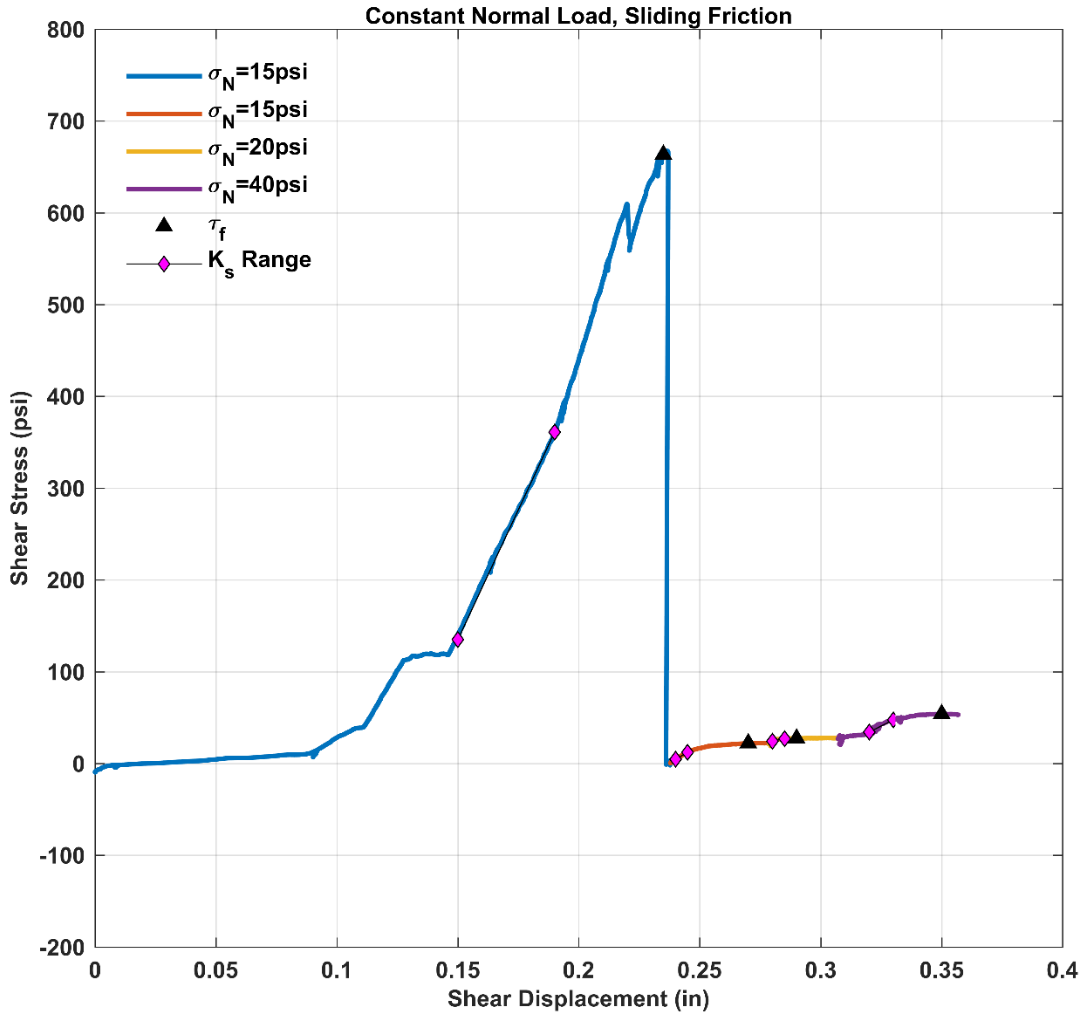
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: LR-1 CNL
Drill Hole: NA
Depth (ft): NA
Sample: LR-1 CNL

Core Size (in): NA
Material: Hydrostrone
Type of Test: Sliding
Shear Mode: unidirectional

Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA

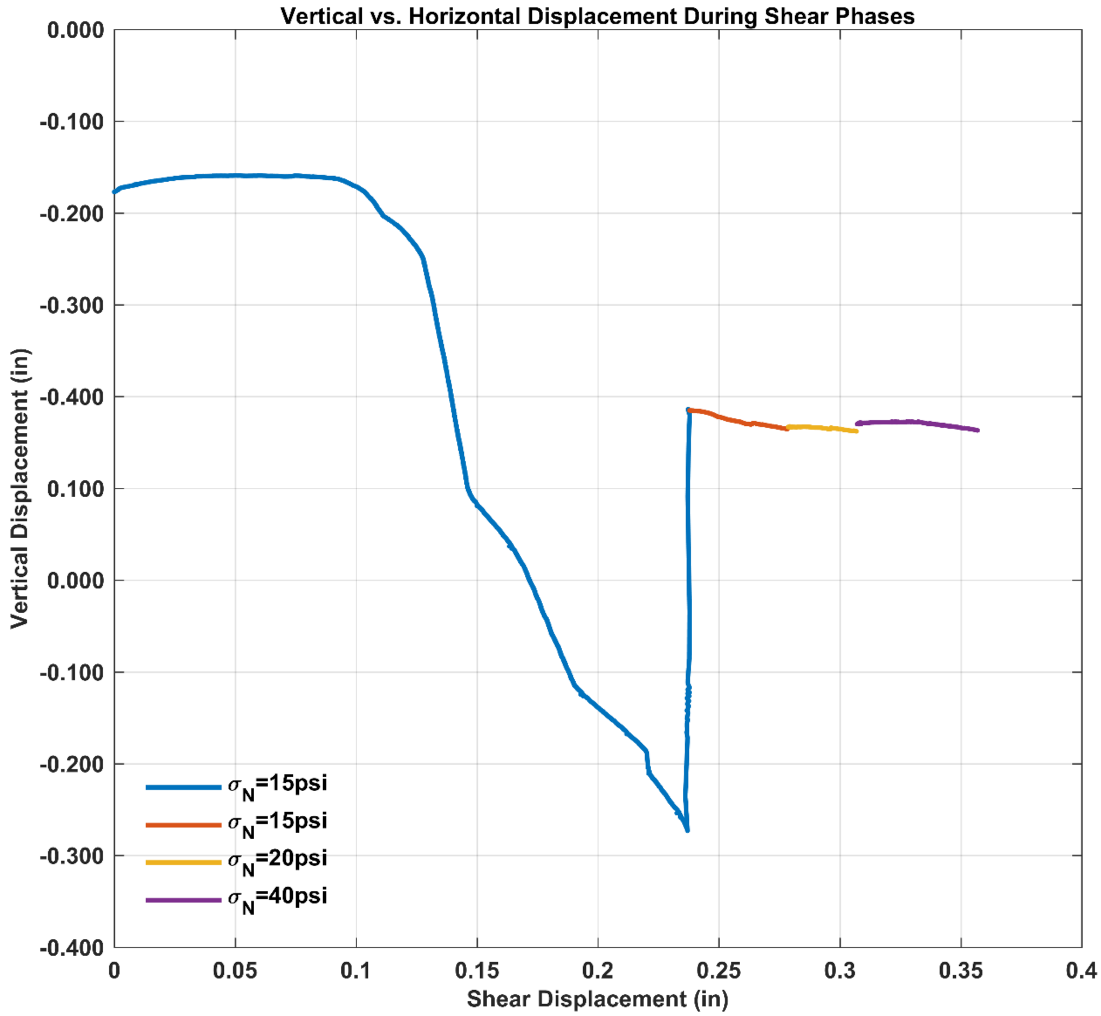


σ_N (psi)	τ_f (psi)	K_s (lb
15	664	
15	22	
20	28	

Project: Dam Safety Research
Feature: CC-1 CNL BB15
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

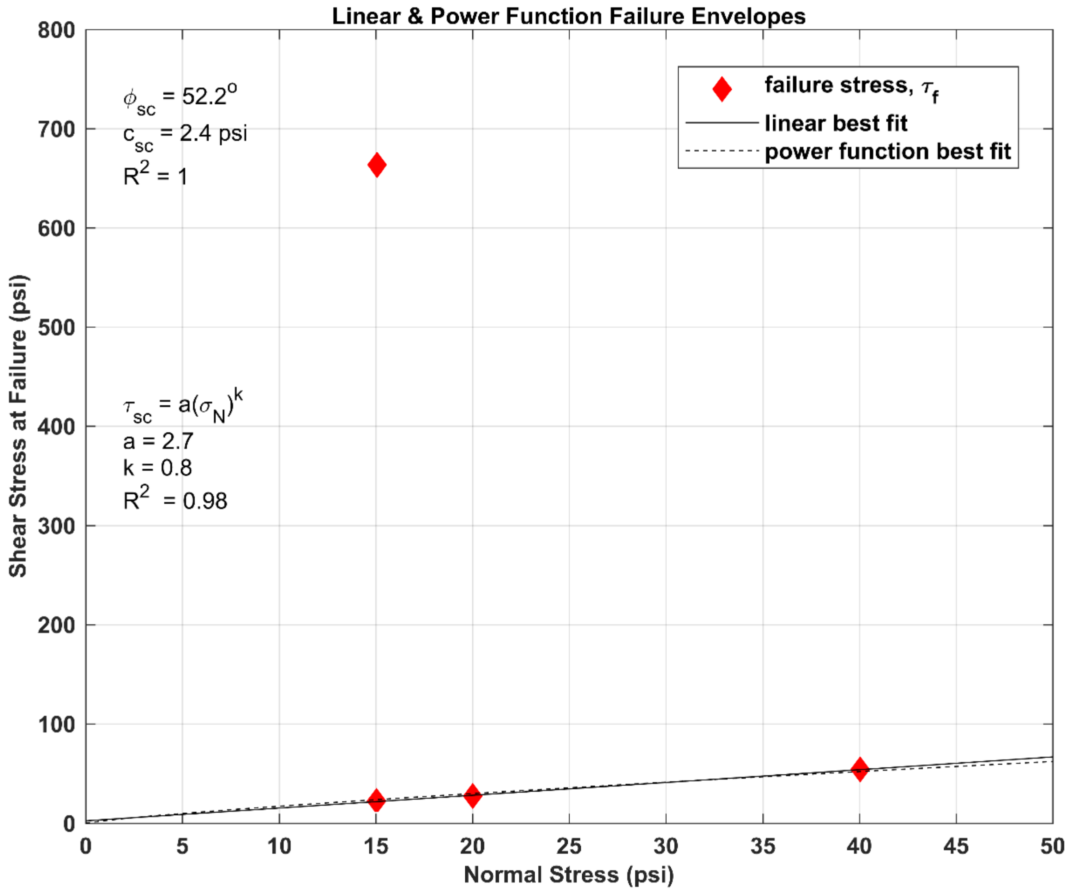
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: CC-1 CNL BB15
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

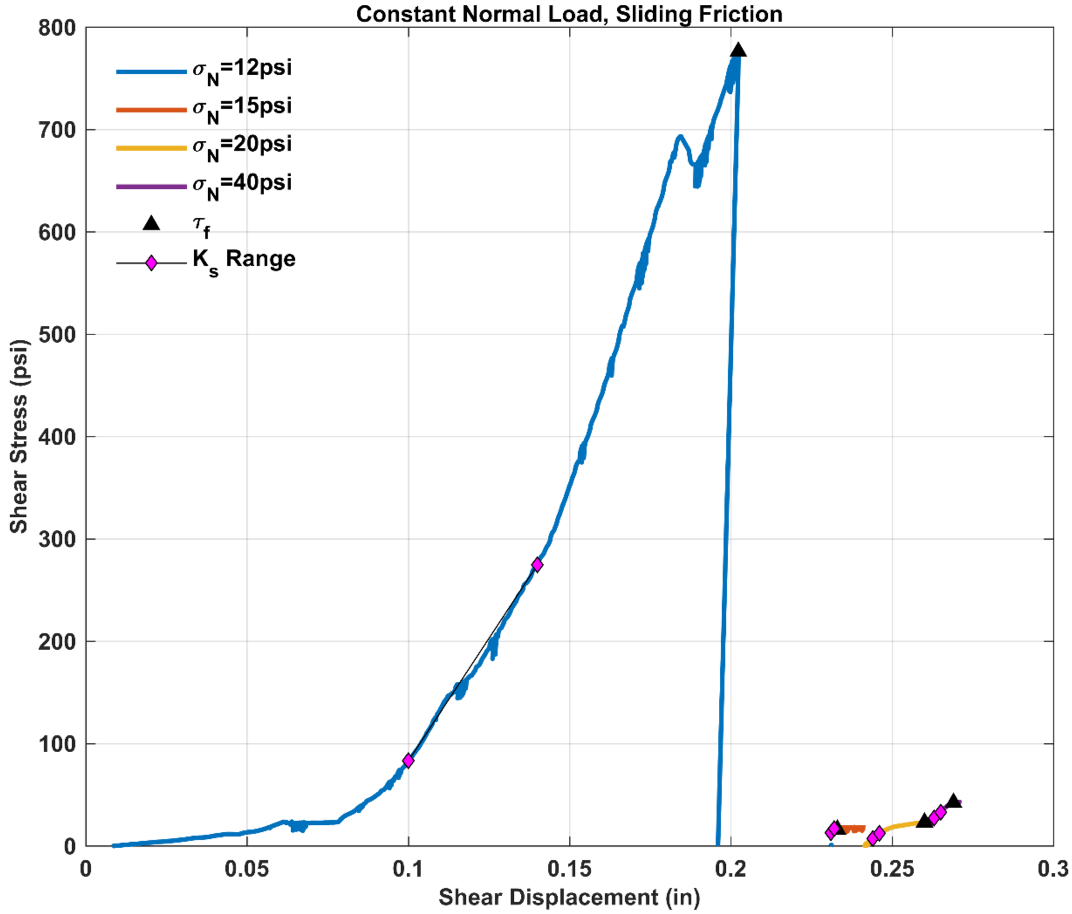
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: CC-1 CNL BB15
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA

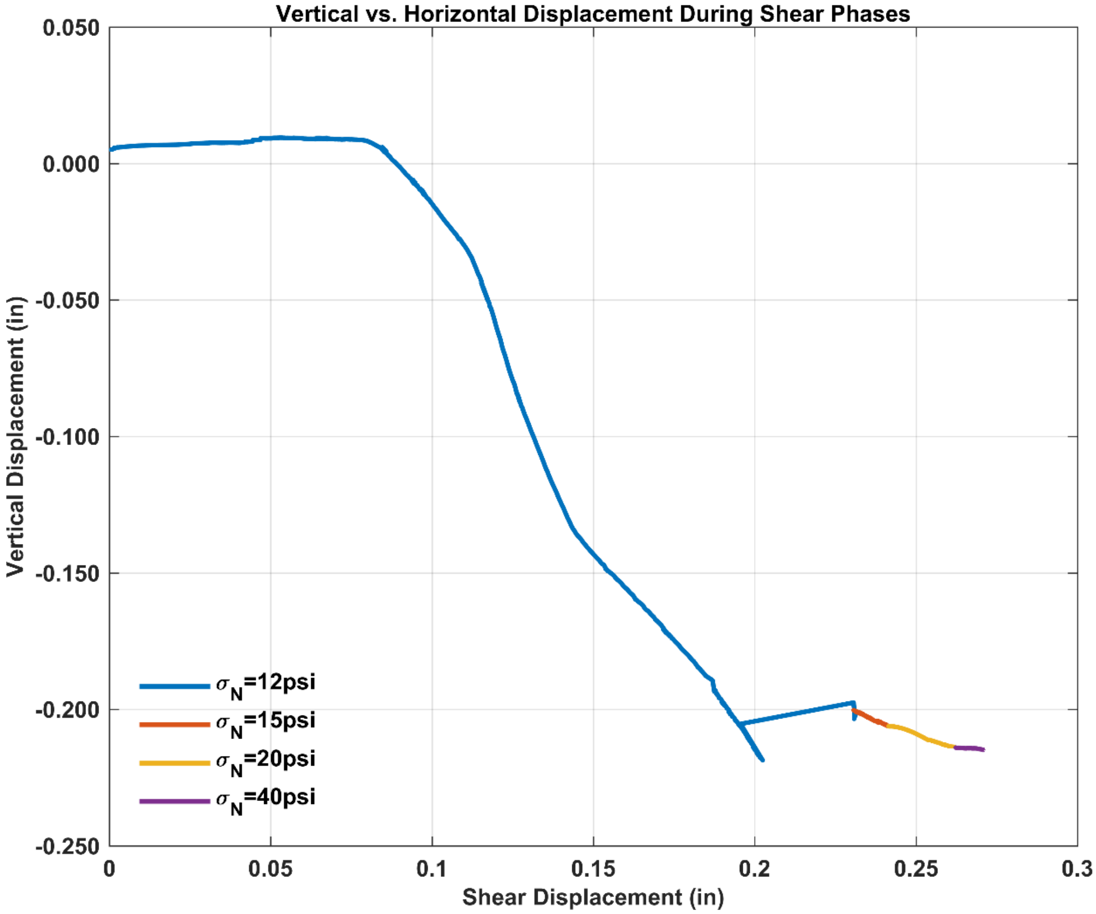


σ_N (psi)	τ_f (psi)	K_s (lb/in)
12	776	4790
15	16	4104
20	23	2504
40	42	2817

Project: Dam Safety Research
Feature: CC-2 CNL BB20
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

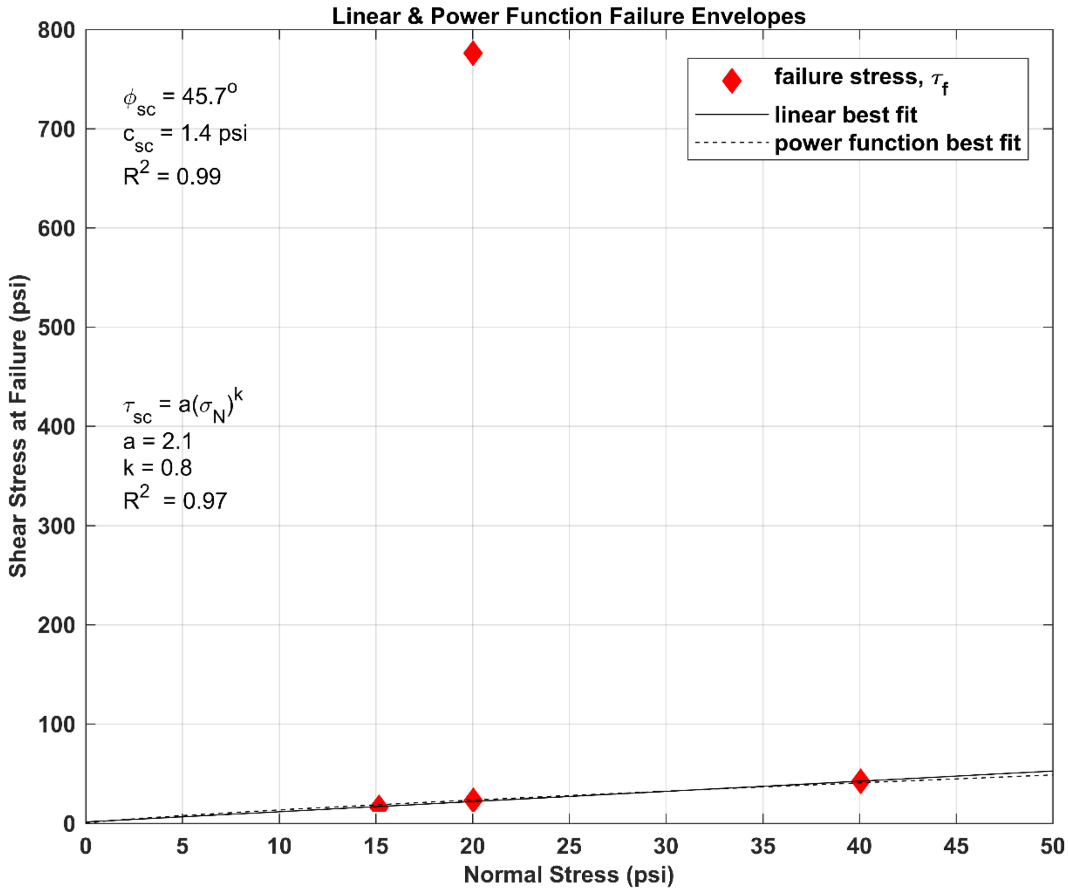
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: CC-2 CNL BB20
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

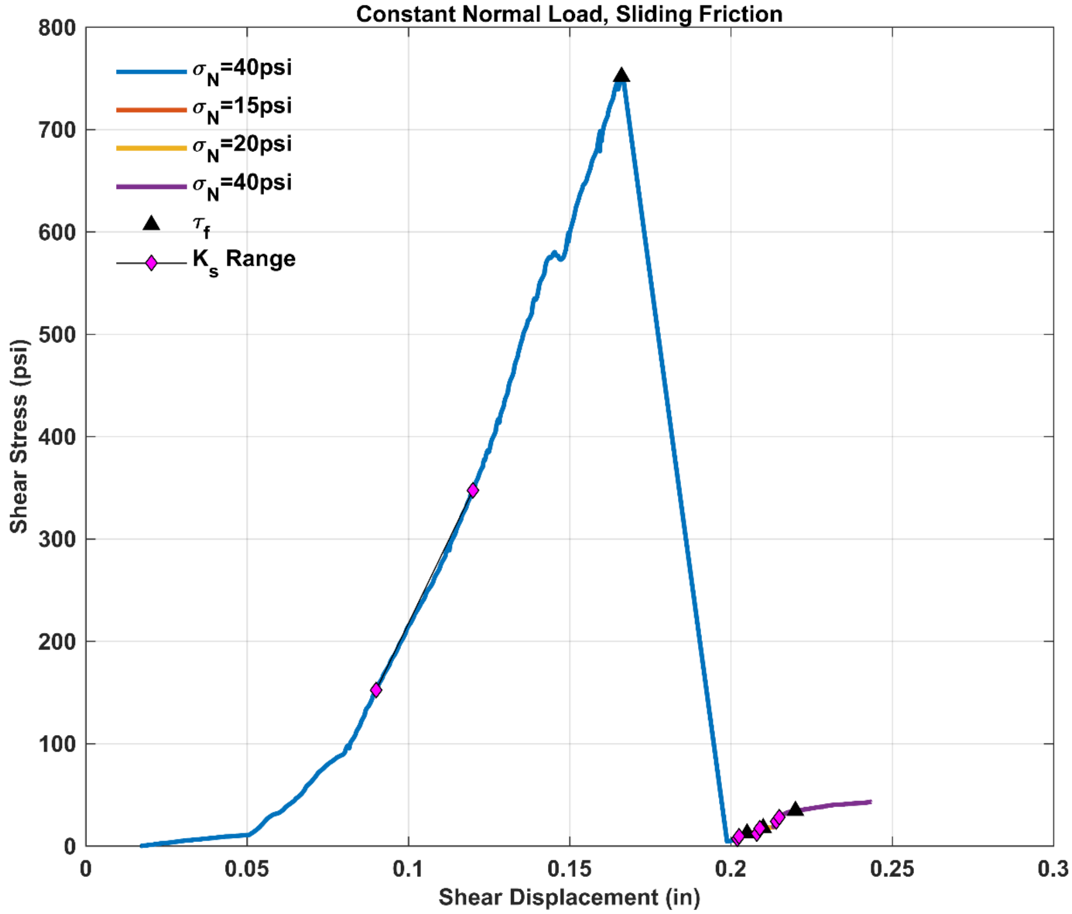
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: CC-2 CNL BB20
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA

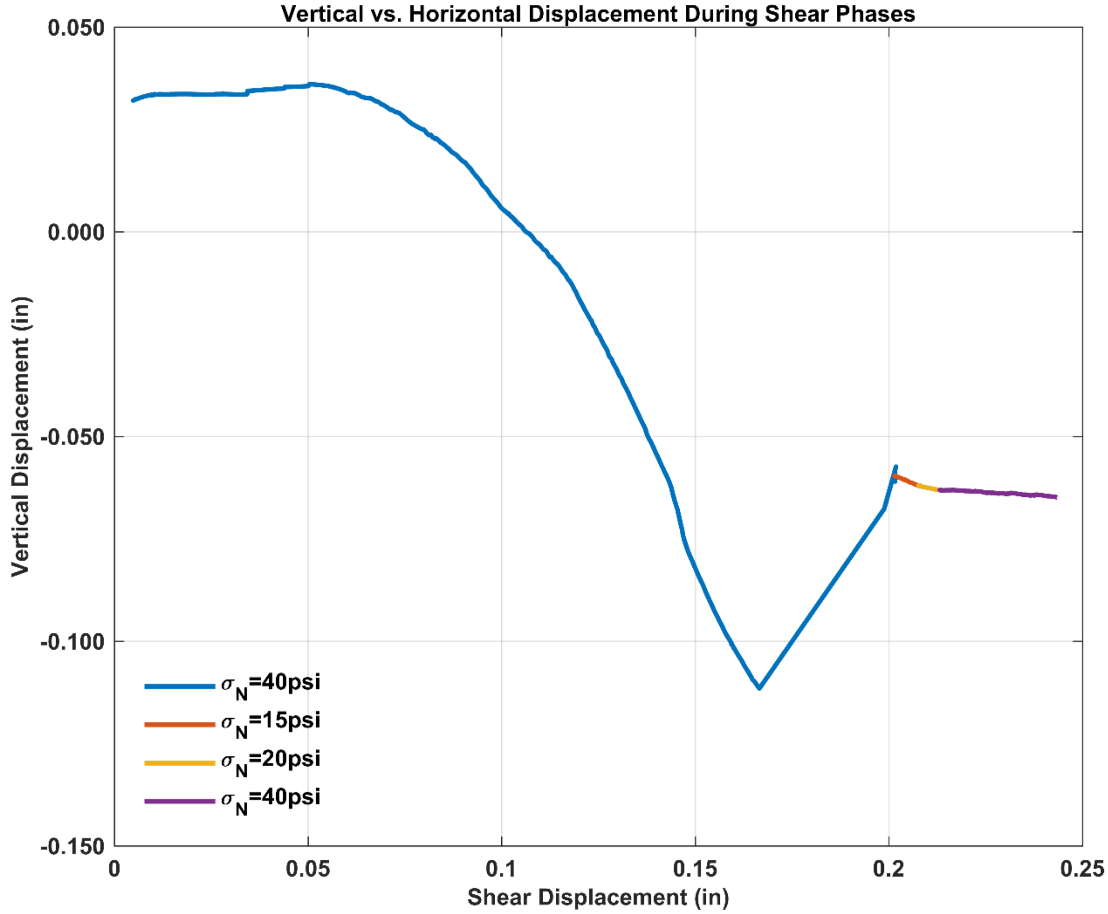


σ_N (psi)	τ_f (psi)	K_s (lb/in)
40	752	6507
15	12	4425
20	17	4949
40	34	4158

Project: Dam Safety Research
Feature: CC-3 CNL BB40
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

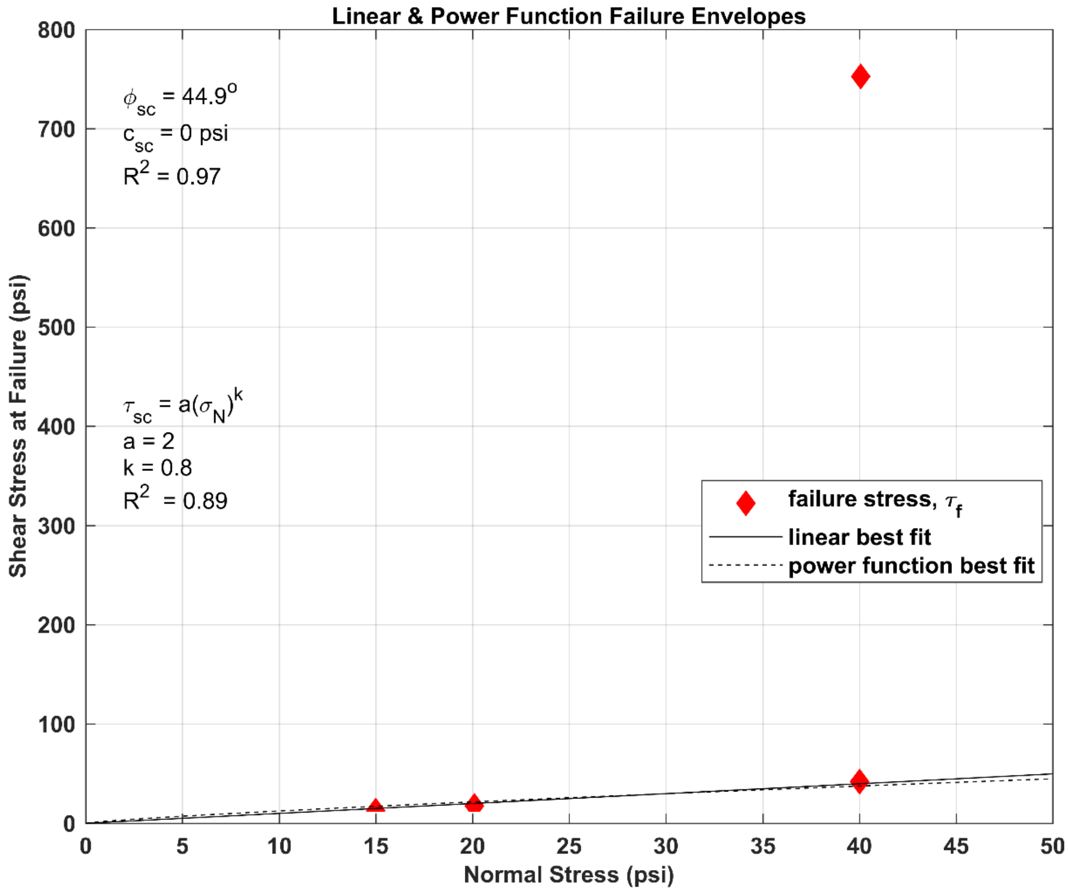
Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA



Project: Dam Safety Research
Feature: CC-3 CNL BB40
Drill Hole: NA
Depth (ft): NA
Sample: NA

Core Size (in): 6"
Material: Concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA

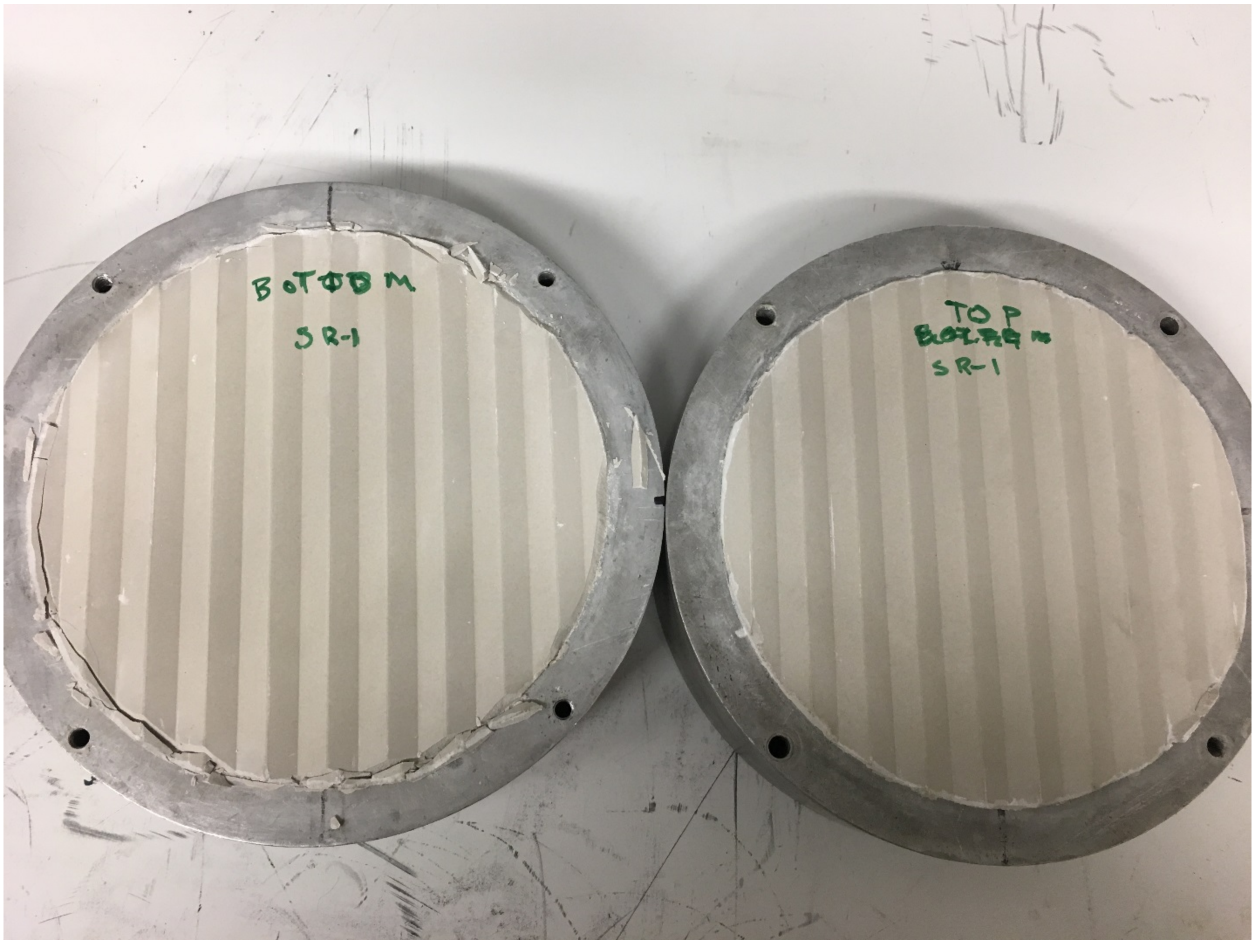


Project: Dam Safety Research
Feature: CC-3 CNL BB40
Drill Hole: NA
Depth (ft): NA
Sample: NA

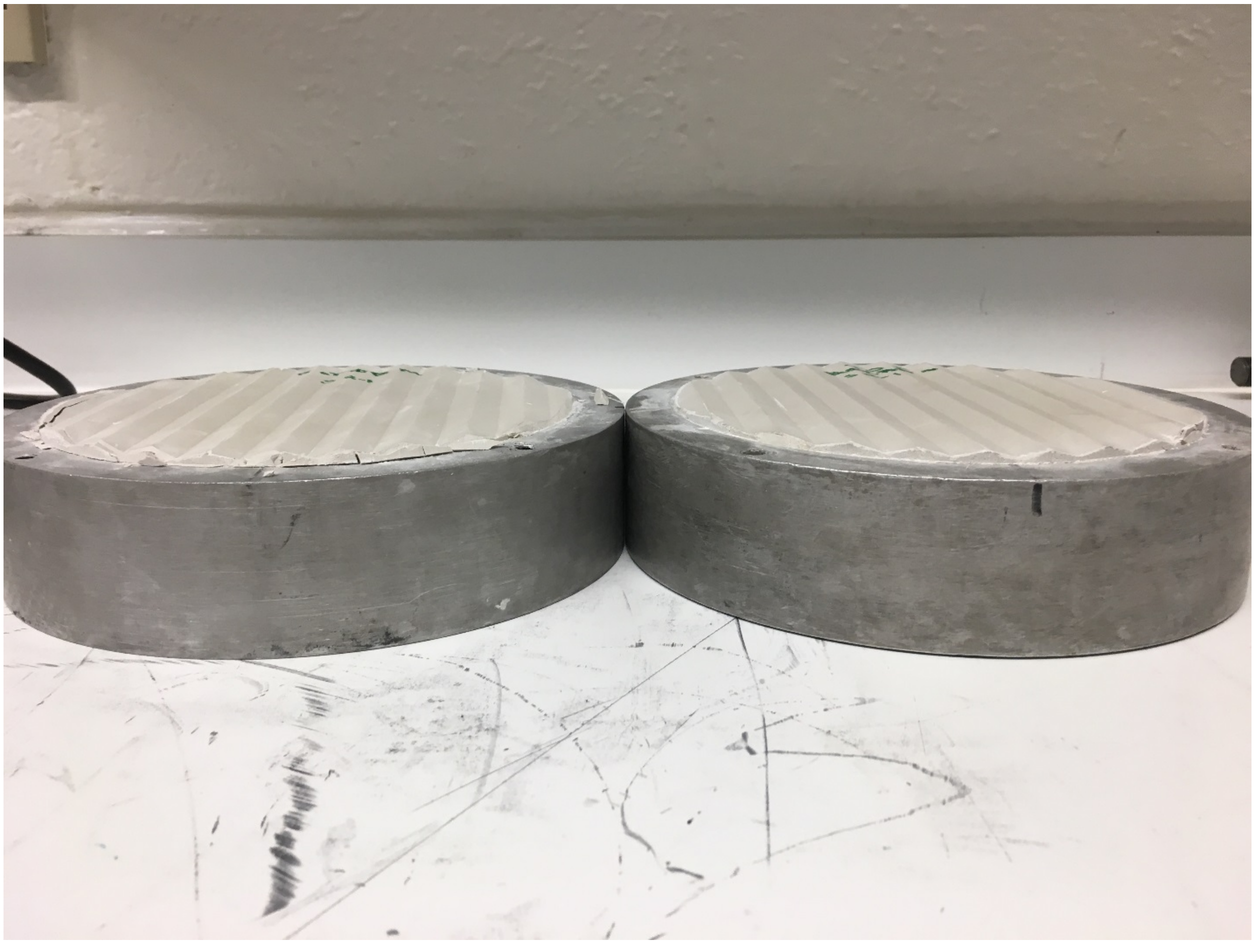
Core Size (in): 6"
Material: concrete
Type of Test: BB and Sliding
Shear Mode: unidirectional

Joint Orientation: NA
Joint Description: NA
Angle Drilled
from Horizontal (deg): NA

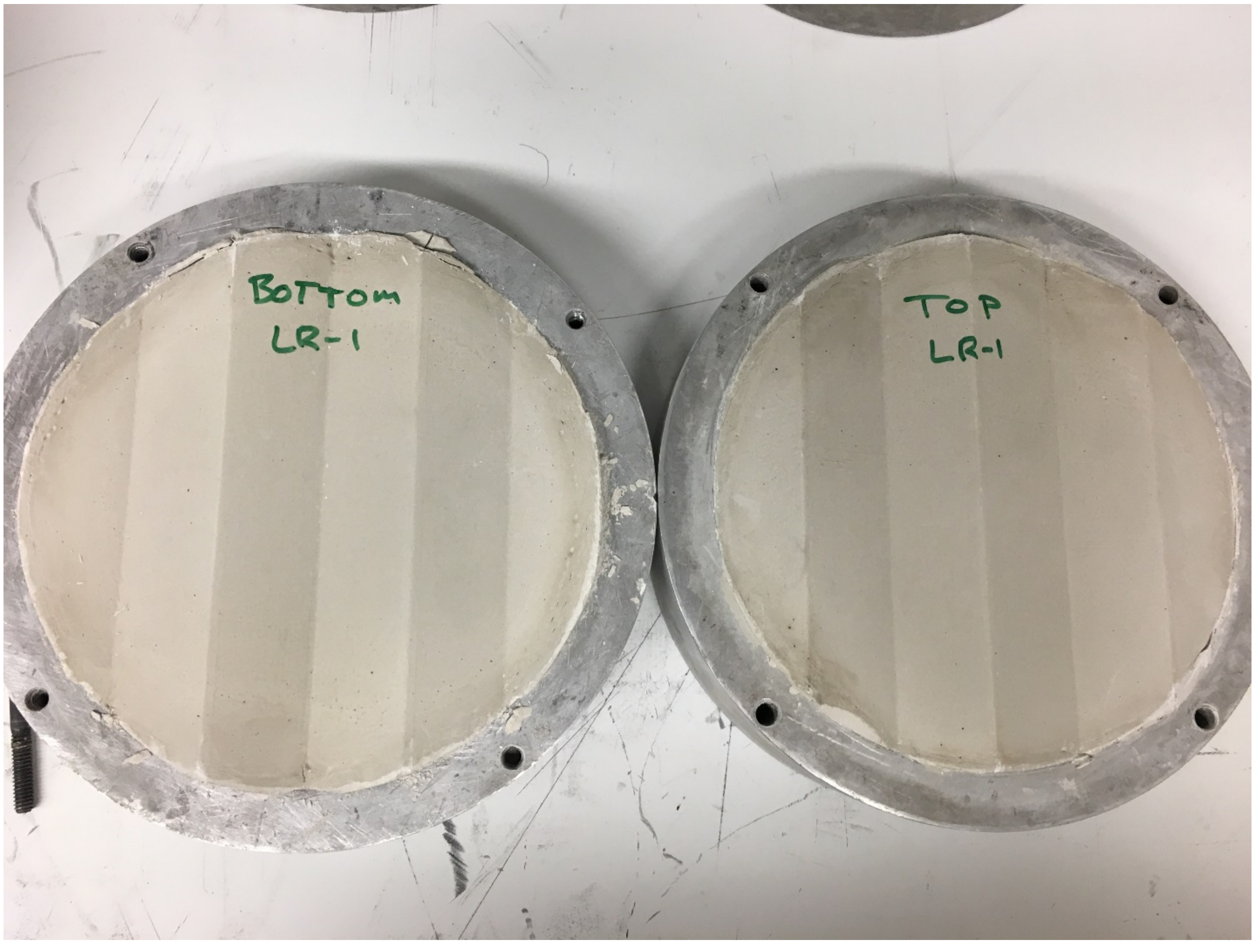
Appendix C – Photos



Appendix C Figure 1 - Post-test.

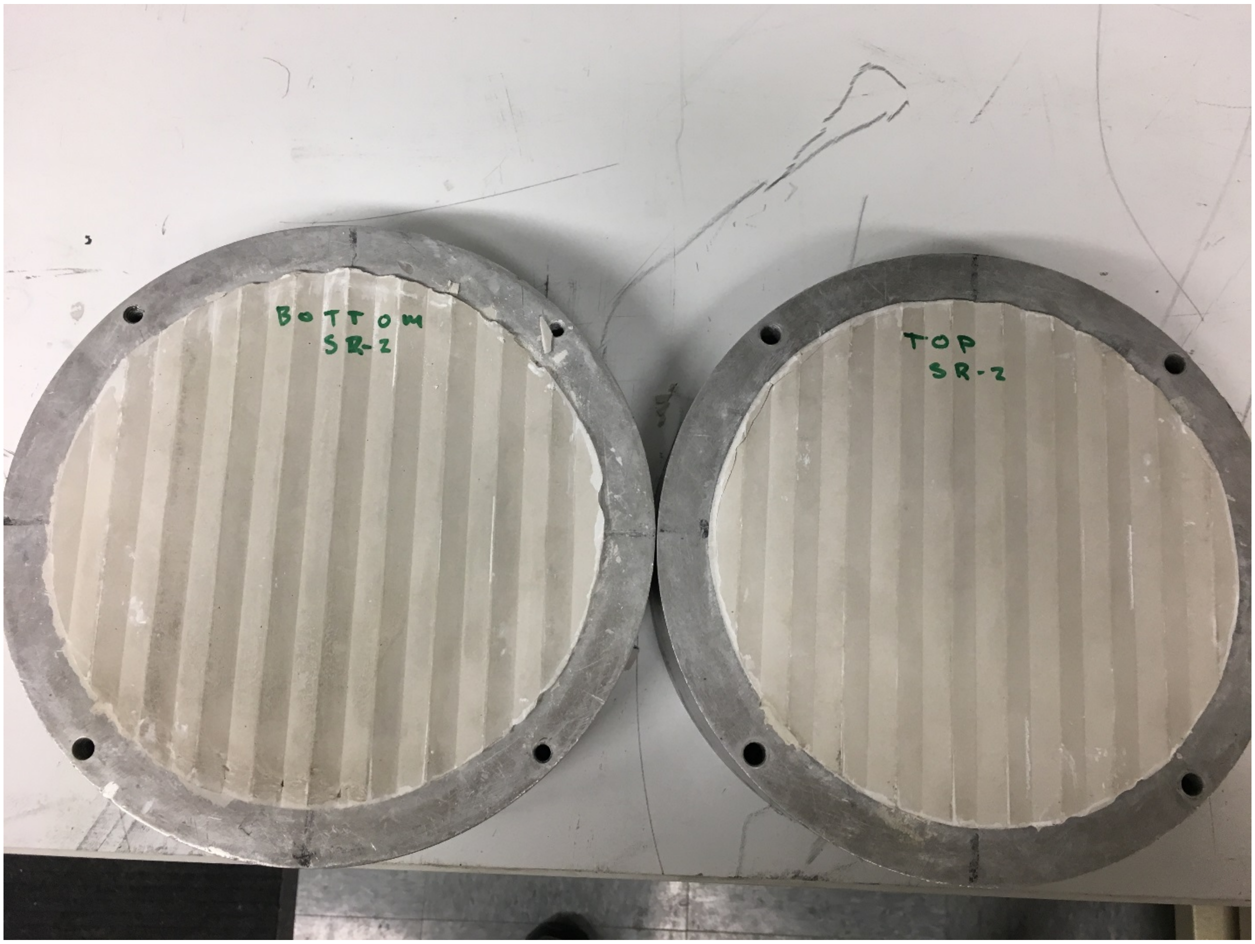


Appendix C Figure 2 - SR-1 post-test.



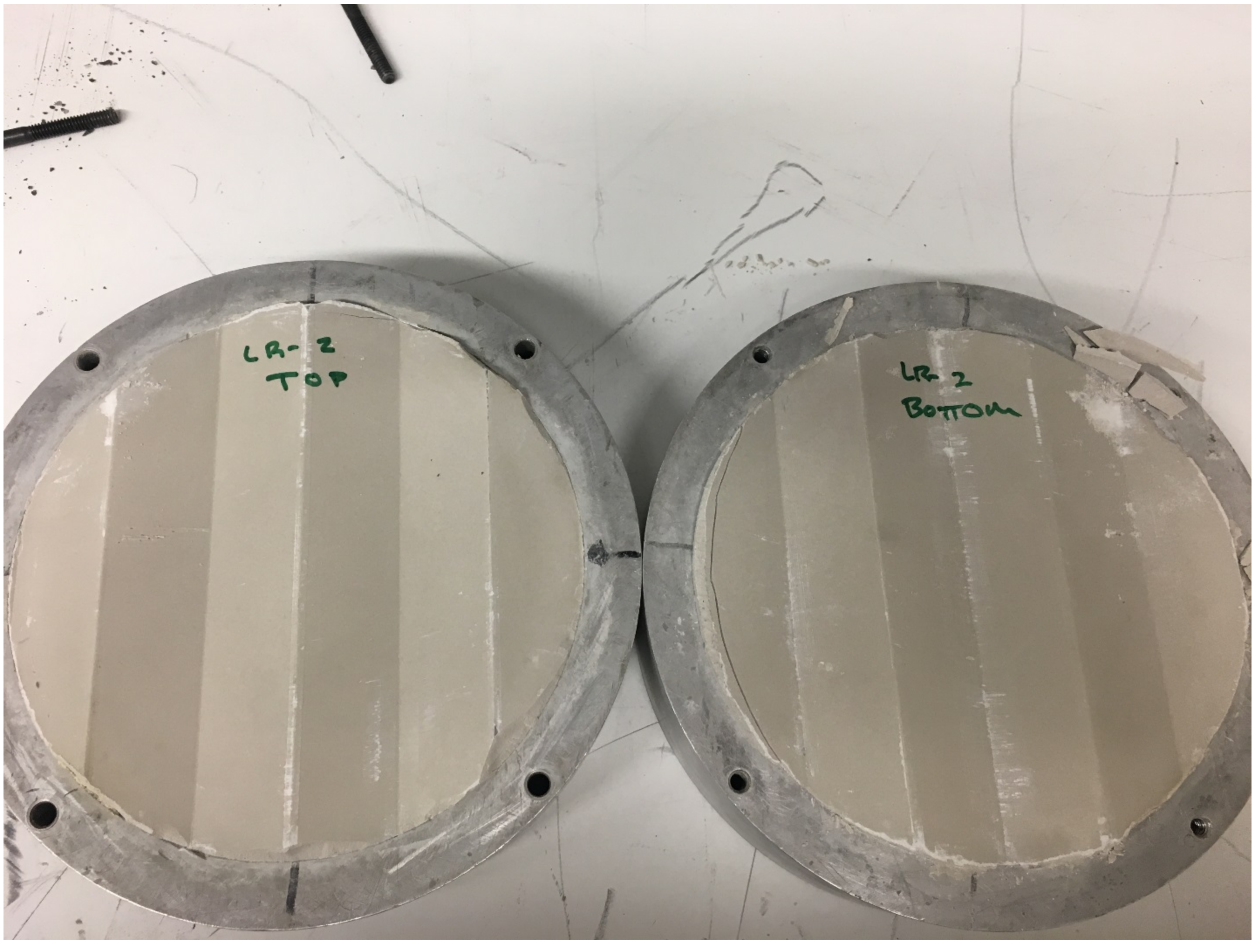
Appendix C Figure 3 - Post Test

Appendix C Figure 4 - LR-1 post-test.

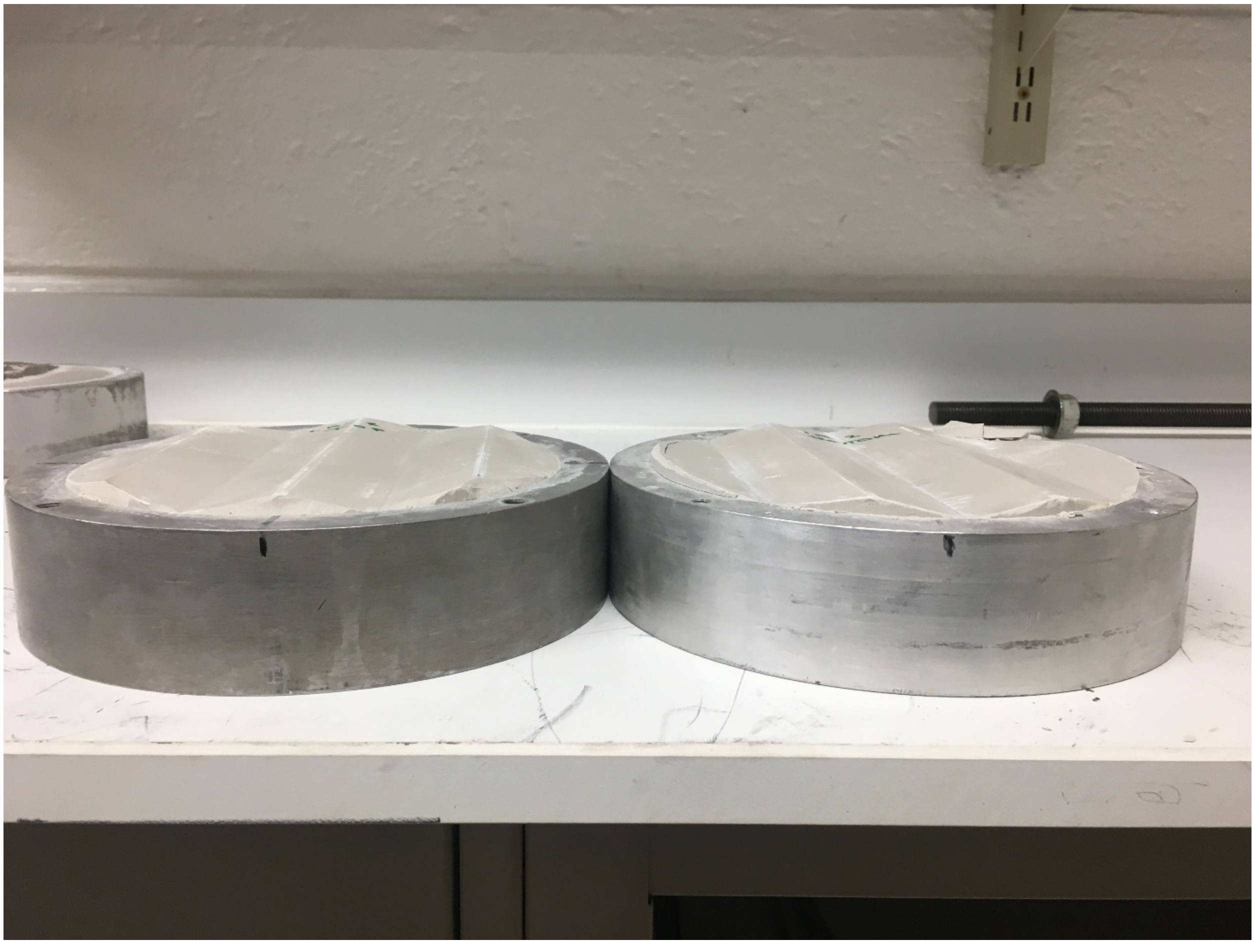


Appendix C Figure 5 - Post-test.

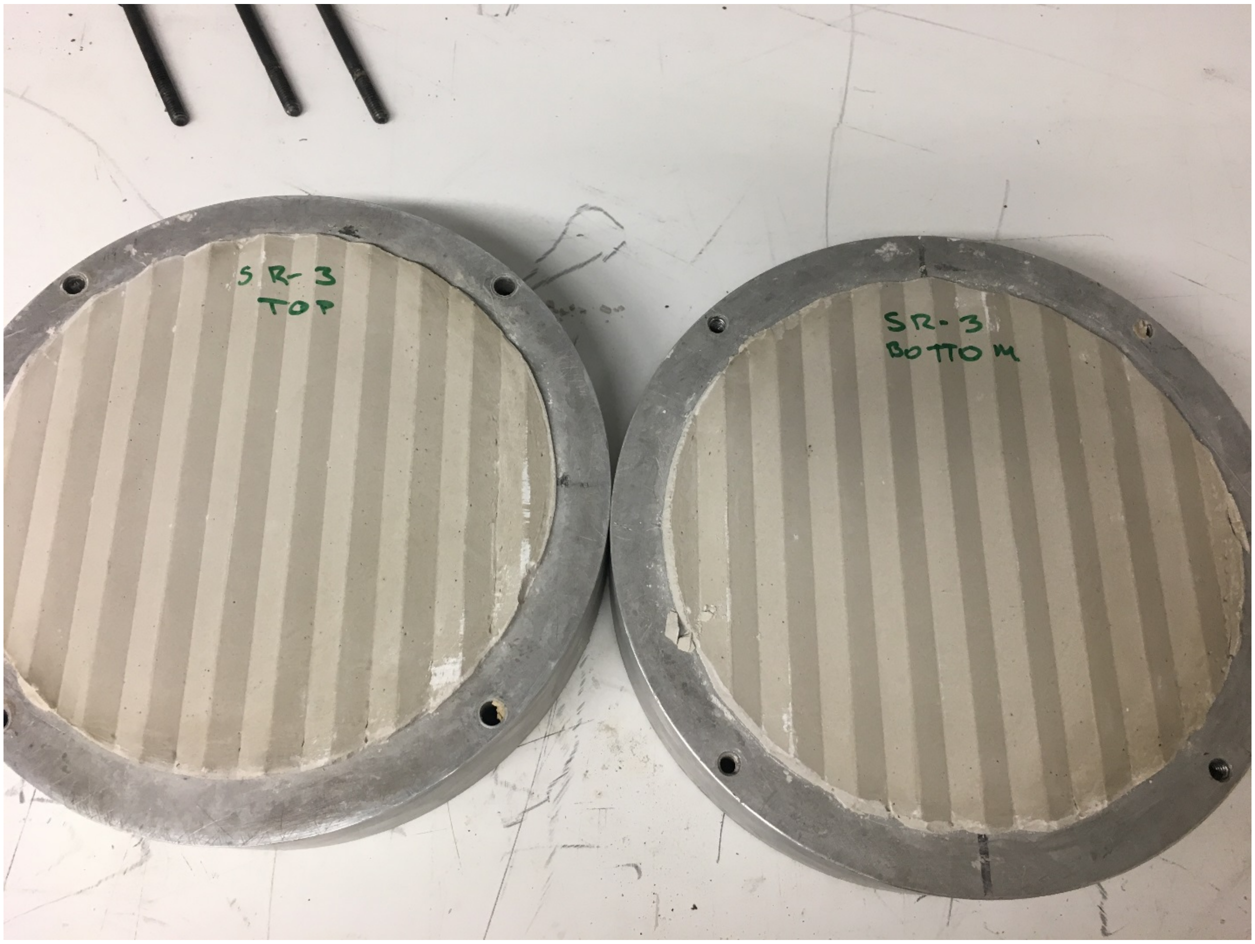
Appendix C Figure 6 - SR-2 post-test.



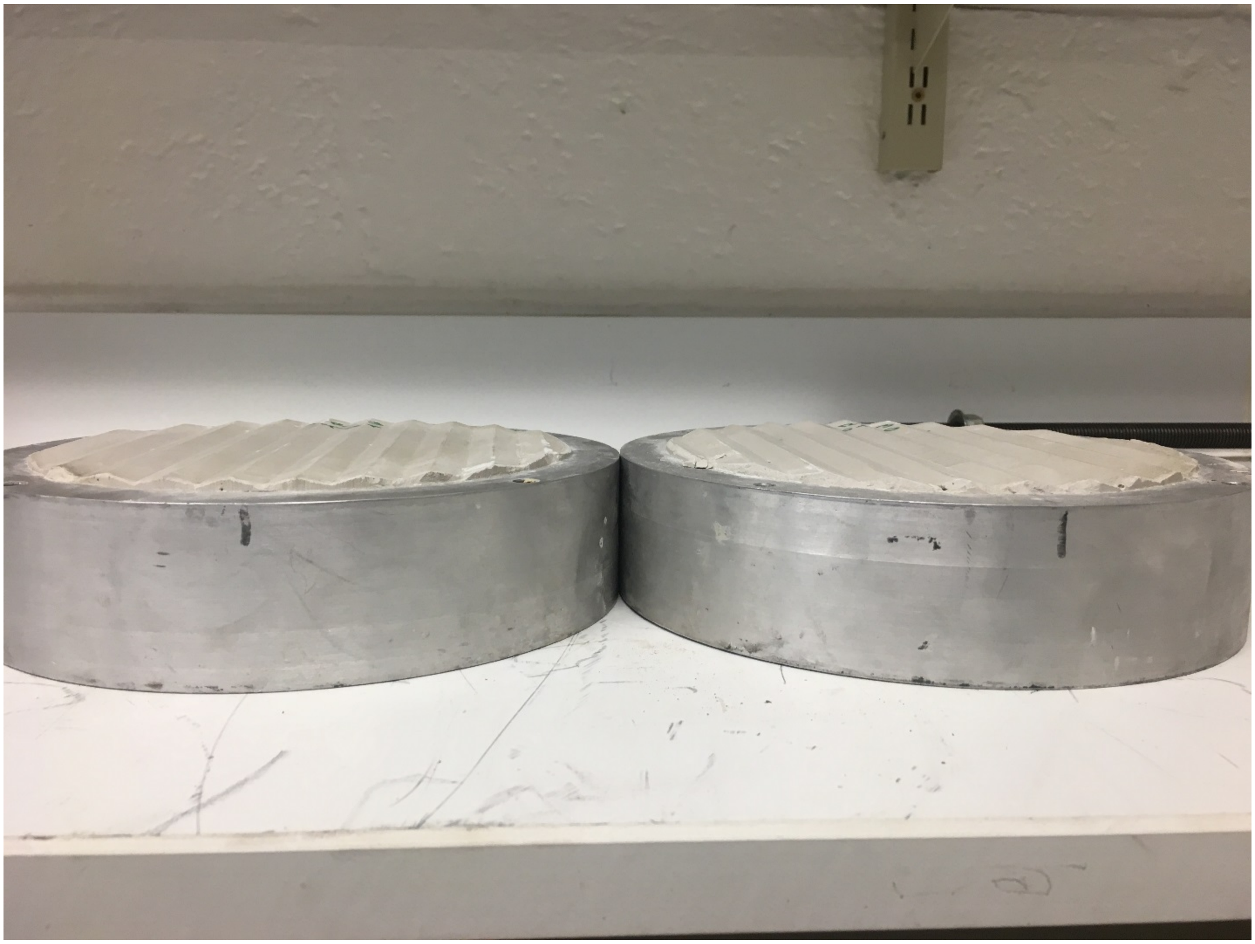
Appendix C Figure 7 - Post-test.



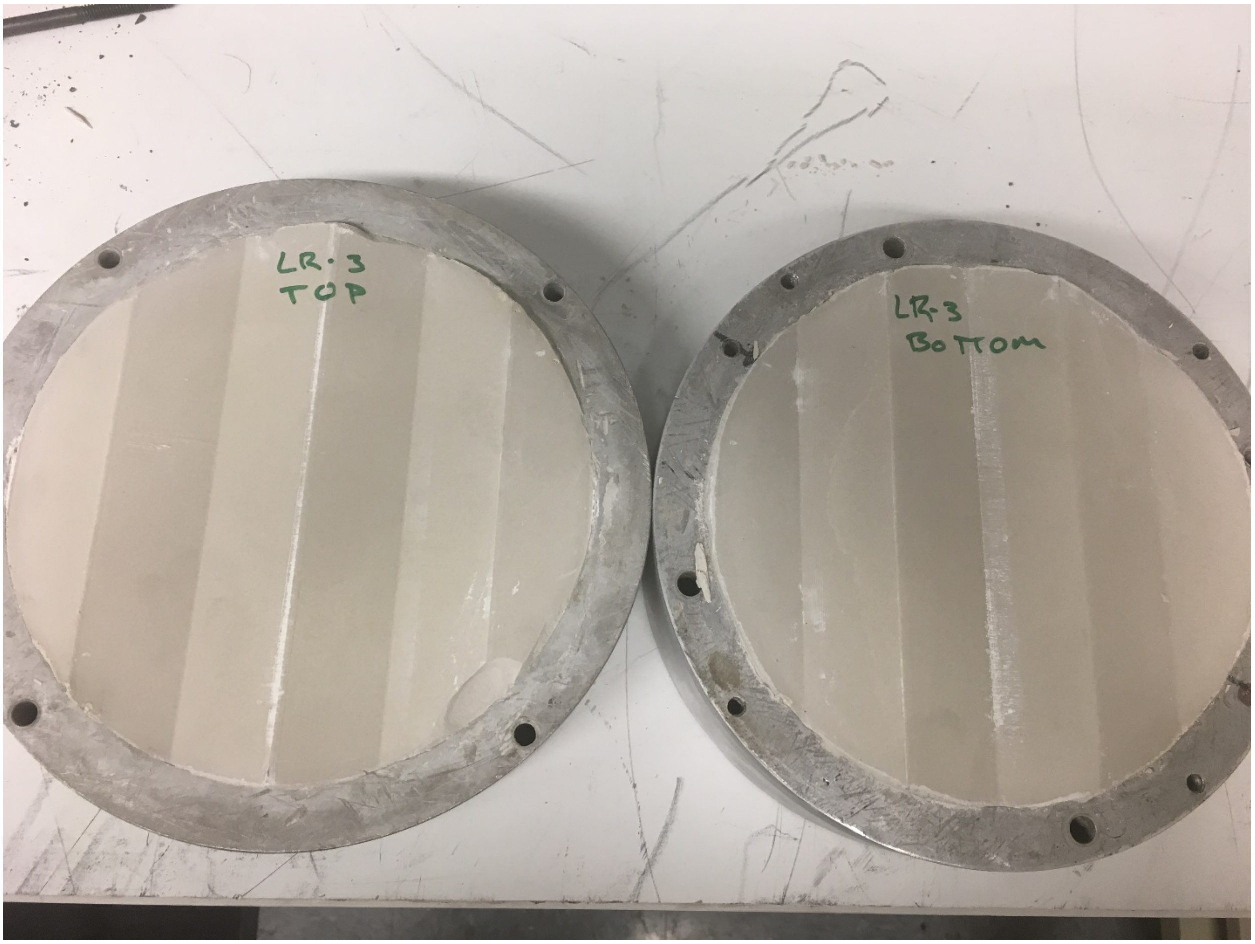
Appendix C Figure 8 - LR-2 post-test.



Appendix C Figure 9 - Post-test.



Appendix C Figure 10 - SR-3 post-test.



Appendix C Figure 11 - Post-test.

Appendix C Figure 12 - LR-3 post-test.

Appendix C Figure 13 - CC-1 post-test.

Appendix C Figure 14 - CC-1 post-test.

Appendix C Figure 15 - CC-2 post-test.

Appendix C Figure 16 - CC-2 post-test.

Appendix C Figure 17 - CC-3 post-test.

Appendix C Figure 18 - CC-3 post-test.

Appendix C Figure 19 - CC-4 post-test.

Appendix C Figure 20 - CC-4 post-test.

Appendix C Figure 21 - CC-5 post-test.

Appendix C Figure 22 - CC-5 post-test.

Appendix C Figure 23 - CC-6 post-test.

Appendix C Figure 24 - CC-6 post-test.