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MEMORANDUM

To: Technology Development Program Manager, Dam Safety Office
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From: Evan Lindenbach, Civil Engineer
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Subject: Dam Safety Technology Development Report DSO-2017-09 – Concrete Shear Strength Parameters Compared to Other Laboratory Determined Properties

A report on Concrete Shear Strength Parameters Compared to Other Laboratory Determined Properties, DSO-2017-09 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.

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DSDaMS
Archives
86-68530 (Bartojay, Rinehart)

Concrete Shear Strength Parameters Compared to Other Laboratory Determined Properties

DSO-2017-09

8530-2017-42

Dam Safety Technology Development Program

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

September 2017

Mission Statement

Protecting America's Great Outdoors and Powering Our Future.

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REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE: SEPTEMBER 2017		**T2. REPORT TYPE:** RESEARCH				**T3. DATES COVERED** FY17
T4. TITLE AND SUBTITLE Concrete Shear Strength Parameters Compared to Other Laboratory Determined Properties						**5a. CONTRACT NUMBER**
						5b. GRANT NUMBER
						5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Evan J. Lindenbach, 303.445.2336, elindenbach@usbr.gov						**5d. PROJECT NUMBER** DSO-2017-09
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER CDSSC
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of the Interior, Bureau of Reclamation Technical Service Center, Denver Federal Center PO Box 25007 (86-68530) Denver, CO 80225-0007						**8. PERFORMING ORGANIZATION REPORT NUMBER** 8530-2017-42
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Department of the Interior, Bureau of Reclamation Dam Safety Office, Denver Federal Center PO Box 25007 (84-44000) Denver, CO 80225-0007						**10. SPONSOR/MONITOR'S ACRONYM(S)** **BOR/USBR:** Bureau of Reclamation **DOI:** Department of the Interior **DSO:** Dam Safety Office
						11. SPONSOR/MONITOR'S REPORT NUMBER(S) **DSO-2017-09**
12. DISTRIBUTION / AVAILABILITY STATEMENT						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT ***(Maximum 200 words)*** *Examination of a large sample of direct shear test results on concrete specimens offers a unique insight into material properties for use in appraisal level design or a screening level evaluation of an existing structure. Several factors, such as cost, lack of suitable cores for testing, or historical data sets that do not contain direct shear test results, often make inference of direct shear strength, in both breaking and sliding friction, via correlation from other properties desirable. In order to investigate a possible correlation between the results of unconfined compressive strength, direct tensile and splitting tensile tests, and shear strength, the results of numerous tests conducted on core samples from various projects were analyzed.* *Results of the study confirmed commonly used relationships between compressive and tensile strength parameters. No direct correlation between compressive/tensile strength parameters was noted. The study did note that the cohesion intercept for break-bond testing can be roughly approximated using splitting tensile or uniaxial compressive testing results, and that the Mohr-Coulomb friction angle for break-bond testing is similar to that found during sliding shear testing.*						
15. SUBJECT TERMS Concrete, Direct Shear, RCC, AAR, Lift Line, Shear Strength						
16. SECURITY CLASSIFICATION OF: U			**17. LIMITATION OF ABSTRACT:** UU	**18. NUMBER OF PAGES**		**19a. NAME OF RESPONSIBLE PERSON:** Evan J. Lindenbach
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U				**19b. TELEPHONE NUMBER** 303.445.2336

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

Bureau of Reclamation

Dam Safety Technology Development Program

Concrete, Geotechnical & Structural Laboratory, 86-68530

DSO-2017-09

8530-2017-42

Concrete Shear Strength Parameters Compared to Other Laboratory Determined Properties

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Acronyms and Abbreviations

AAR – Alkali-Aggregate Reaction

DT – Direct Tensile Strength

psi – Pounds per Square Inch

RCC – Roller Compacted Concrete

ST – Splitting Tensile Strength

UCS – Uniaxial Compressive Strength

Symbols

φ – Friction Angle

° – Degree(s)

σ – Normal Stress

τ – Shear Stress

c – Apparent Cohesion

f_{st} – Splitting Tensile Strength

f_{dt} – Direct Tensile Strength

f'_c – Uniaxial Compressive Strength

Executive Summary

Examination of a large sample of direct shear test results on concrete cores offers unique insights into material properties for use in appraisal level design or a screening level evaluation of an existing structure. Several factors, such as cost, lack of suitable cores for testing, or historical data sets that do not contain direct shear test results, often make inference of direct shear strength, in both breaking and sliding friction, via correlation from other properties desirable. In order to investigate a possible correlation between the results of unconfined compressive strength, direct tensile and splitting tensile tests, and direct shear strength, the results of numerous tests conducted on core samples from various projects were analyzed.

Reclamation's direct shear data contained in reports dating from 1977 through the present were obtained in both paper and electronic formats to develop a robust data set. A total of 59 reports from 32 projects or features, including research studies and non-Reclamation projects, were included in the data set. Projects included: Altus Dam, Arrowrock Dam, Black Canyon Dam, Cold Springs Dam, Deadwood Dam, Dworshak Dam, East Canyon Dam, Elephant Butte Dam, Folsom Dam, Galesville Dam, Gerber Dam, Glen Canyon Dam, Guayabal Dam, Horse Mesa Dam, Milltown Dam, Minidoka Dam, Monticello Dam, Ochoco Dam, Olympus Dam, Owyhee Dam, Pajarito Dam, Parker Dam, Port Mann Tunnel, Pueblo Dam, Research Study No. DR-457, Seminoe Dam, Stewart Mountain Dam, Stoney Gorge Dam, Strawberry Canal, Theodore Roosevelt Dam, Upper Stillwater Dam, and Warm Springs Dam. Unique to this particular project is the fact that direct shear strength data for each test was tabulated, such that each row of data provides unique shear and normal stresses for break-bond and/or sliding shear strengths, allowing for detailed data analysis. Additionally, compressive/tensile strength data (splitting tensile strength (ST), direct tensile (DT) and uniaxial compressive strength (UCS)) was obtained and paired with the direct shear test data.

The direct shear test results were categorized by: type of test (break-bond or sliding), reliability of compressive/tensile strength data (ST, DT and UCS), type of concrete (conventional concrete lift lines versus roller compacted concrete (RCC) lift lines versus concrete lift lines from projects with known alkali-aggregate reaction (AAR) issues). The result is a broad data set that covers a breadth of direct shear tests, but allows for targeted estimations of shear strength based on particular parameters. Additionally, relationships between strength parameters (UCS, ST and DT) were investigated for the entire data set, and for each type of concrete lift line.

While no clear correlation was found between any of the compressive/tensile and/or direct shear strength parameters, a number of trends could be noted. The ratios of splitting tensile: uniaxial compressive strength, direct tensile: uniaxial compressive strength, and splitting tensile: direct tensile were generally similar between all types of concrete (all data, conventional concrete lift lines, RCC lift lines and AAR lift lines) with only a few exceptions. The RCC lift lines tended to have higher splitting and direct tensile strengths relative to the compressive strength, and the AAR lift lines tended to have lower direct tensile strength relative to splitting tensile or uniaxial compressive strength.

For appraisal level design, the apparent cohesion intercept for break-bond can be approximated as either as 10% of the uniaxial compressive strength ($0.1f'_c$) or as the splitting tensile strength. The failure envelope for the break-bond strength can be approximated using the Angle-Envelope Method (Reclamation, 1976) with data from sliding friction tests. It should be noted that a great deal of uncertainty must be incorporated into a design using these relationships. It is the author's recommendation that for anything but a appraisal level design, actual laboratory testing be performed at the anticipated normal stresses to develop a mix-specific understanding of direct shear strength. This same recommendation holds true for evaluations of existing structures.

Keywords

Concrete, Direct Shear, Roller Compacted Concrete (RCC), Alkali-Aggregate Reaction (AAR), Lift Line, Shear Strength, Unconfined Compressive Strength (UCS), Splitting Tensile, Direct Tensile

Team Members, Partners, Reviewers

Table 1. Internal members, partners, reviewers.

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Background

There are currently no models that accurately correlate the results of the most commonly performed concrete strength tests, compressive strength and splitting/direct tensile strength, with estimates of the shear strength. The ability to predict the shear strength of concrete based on the compressive strength, and splitting/direct tensile strength could provide valuable insight into material properties for: appraisal level design, development of more economic testing plans and evaluations of existing structures.

Introduction

Examination of a large sample of concrete direct shear test results offers a unique insight into material properties for use in appraisal level design or a screening level evaluation of an existing structure. Several factors, such as cost, lack of suitable cores for testing, or historical data sets that do not contain direct shear test results, often make inference of direct shear strength, in both breaking and sliding friction, via correlation from other properties desirable. In order to investigate a possible predictive relationship between the results of unconfined compressive strength, direct tensile and splitting tensile tests, with shear strength, the results of numerous tests conducted on core samples from various projects were analyzed.

Reclamation's direct shear data contained in reports dating from 1977 through the present were obtained in both paper and electronic formats to develop a robust data set. A total of 59 reports from 32 projects or features, including research studies and non-Reclamation projects, were included in the data set. Projects included: Altus Dam, Arrowrock Dam, Black Canyon Dam, Cold Springs Dam, Deadwood Dam, Dworshak Dam, East Canyon Dam, Elephant Butte Dam, Folsom Dam, Galesville Dam, Gerber Dam, Glen Canyon Dam, Guayabal Dam, Horse Mesa Dam, Milltown Dam, Minidoka Dam, Monticello Dam, Ochoco Dam, Olympus Dam, Owyhee Dam, Pajarito Dam, Parker Dam, Port Mann Tunnel, Pueblo Dam, Research Study No. DR-457, Seminoe Dam, Stewart Mountain Dam, Stoney Gorge Dam, Strawberry Canal, Theodore Roosevelt Dam, Upper Stillwater Dam, and Warm Springs Dam. Unique to this particular project is the fact that direct shear strength data for each test was tabulated, such that each row of data provides unique shear and normal stresses for break-bond and/or sliding shear strengths, allowing for detailed data analysis. Additionally, compressive/tensile strength data (splitting tensile strength (ST), direct tensile (DT) and uniaxial compressive strength (UCS)) was obtained and assigned to the direct shear test data.

The direct shear test results were categorized by: type of test (break-bond or sliding), reliability of compressive/tensile strength data (ST, DT and UCS), type of concrete (conventional concrete lift lines versus roller compacted concrete (RCC) lift lines versus concrete lift lines from projects with known alkali-aggregate reaction (AAR) issues). The result is a broad data set that covers a breadth of direct shear tests, but allows for targeted estimations of shear strength based on particular parameters. Additionally, relationships between strength parameters (UCS, ST and DT) were investigated for the entire data set, and for each type of concrete lift line.

Concrete Direct Shear Testing

Reclamation's direct shear testing was generally performed in accordance with the applicable standards proposed by ASTM, the International Society of Rock Mechanics Suggested Methods, and/or Reclamation's Earth and/or Concrete Manuals. As standards evolve through time, not all testing was performed in precisely the same manner. The direct shear testing method has not changed substantially over time, therefore combining the data is thought to be appropriate. The current Reclamation method generally follows ASTM D5607 (ASTM, 2016).

In a direct shear test, a portion of concrete is isolated between two encapsulating rings (size of isolated section is either about 0.2 inches for the small direct shear machine, or about 1 inch for the large direct shear machine), a normal load is applied to the concrete and the specimen is sheared (rings moving in opposite directions) at a constant rate. Figure 1 shows an encapsulated specimen, while Figure 2 shows the specimen within the direct shear testing device.

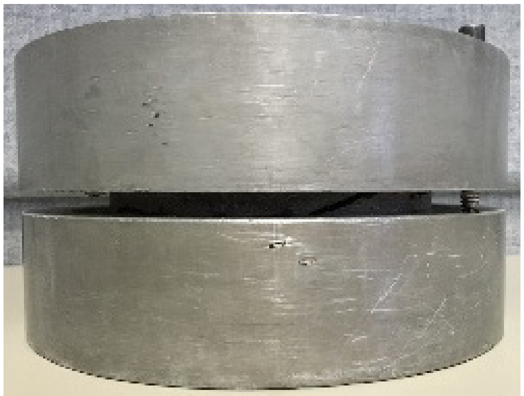

Figure 1 - Concrete direct shear specimen encapsulated within rings. Note 0.2 inch isolated section visible between rings.

Figure 2 - Direct shear specimen in testing machine. Normal actuator used to apply constant normal stress. 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.

The strength for each test is then recorded as a peak shear stress at a corresponding normal stress. Bonded specimens (intact concrete cores) are broken to develop a break-bond strength, with subsequent sliding friction tests performed on the newly created fracture. Where the bond was previously broken or was not present, sliding friction tests are performed. Sliding friction tests are usually performed across a range of normal stresses on the same specimen.

The strength data is then plotted as shear stress versus normal stress to develop a failure envelope. Typical failure envelopes are assumed to be linear, with strength data provided in Mohr-Coulomb space as the slope of the failure envelope (the friction angle, φ) and the y-intercept of the envelope (apparent cohesion, c). Each specimen tested for sliding friction then has its own unique failure envelope. Since the break-bond can only be performed once per specimen, data is typically combined between a number of break-bond tests on similar specimens broken at different normal stresses to determine a break-bond failure envelope.

Shear strength tests can be performed on lift lines (the bond between sections of concrete poured or cast at different times) or on the parent concrete (sections of concrete within each pour or cast). Typically, the lift lines are assumed to be weaker than the parent material, therefore this research focuses primarily on characterizing the lift lines.

All Data and Well-Constrained Data

Break-bond and sliding shear strength data were collected and tabulated into a large, undifferentiated data set to look at broad trends in compressive/tensile strength parameters and shear strength. Each specimen included in the data set had a number of unique shear and normal stresses as determined during direct shear testing. While most specimens had break-bond and sliding friction data, some had only one or the other.

In addition to direct shear data, concrete compressive/tensile strength data (ST, DT and UCS) were obtained and paired with each direct shear data point. If the strength data could be directly correlated to an individual direct shear test by being from within 5-feet of the direct shear test in the boring, the data was included in the "Well-Constrained" data set. In many cases the strength data was obtained through Reclamation's Aging Concrete Information System (ACIS) (Reclamation, 2005) and was therefore an average by boring or project. The average data from ACIS is only included in the "All Data" data set. In order to be included in either data set, the UCS, ST and DT tests had to occur in close temporal proximity to the direct shear tests. It should be noted that the "All Data" data set includes all strength data (averages from ACIS and those correlated to an individual direct shear test, i.e. the "Well-Constrained Data" data set).

Compressive/Tensile Strength Property Correlations

Strength properties (UCS, ST and DT) from the "All Data" data set were plotted against each other to investigate predictive relationships. Cutis et al. (2017) found the following relationships in data obtained from Tennessee Valley Authority (TVA) Dams:

Splitting Tensile Strength: $f_{st} = 0.1f'_c$ (1)

Direct Tensile Strength: $f_{dt} = 0.04f'_c$ (2)

Where, f_{st} and f_{dt} are the splitting and direct tensile strengths, respectively, and f'_c is the uniaxial compressive strength. The strength relationships are in general agreement to those found by Reclamation (2005). Data obtained from the current study is presented in the following figures and histograms.

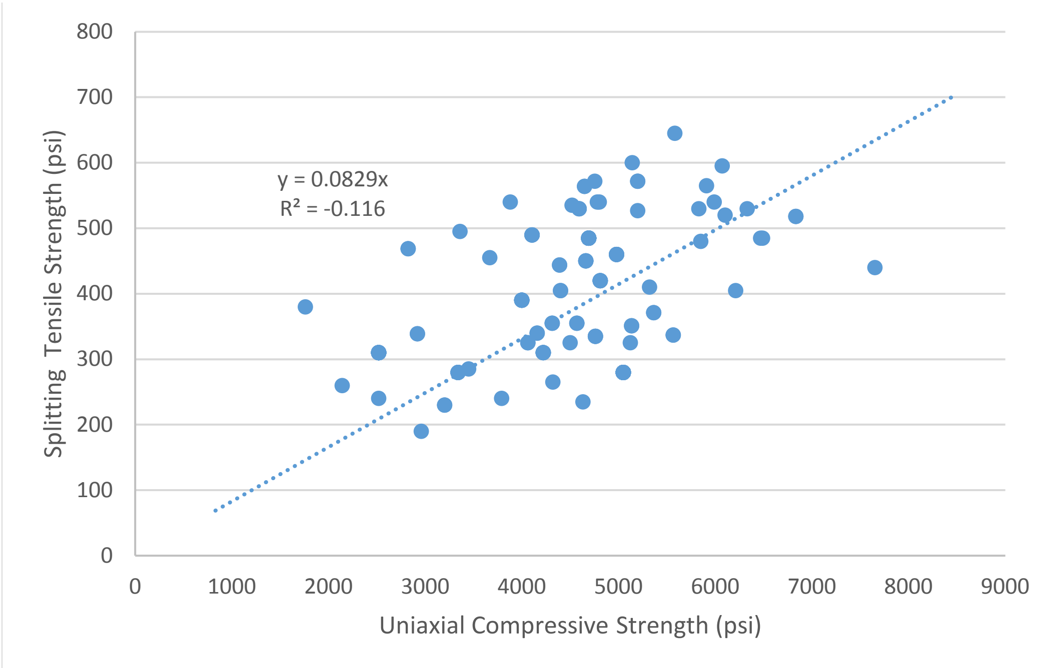

Figure 3 – All data, splitting tensile versus uniaxial compressive strength.

Note that a negative R^2 value indicates that a horizontal line fits the data better than the proposed fit, with the proposed fit need a constant term to better fit the data (Coster, 2017). The R^2 value then cannot be interpreted as the square of a correlation.

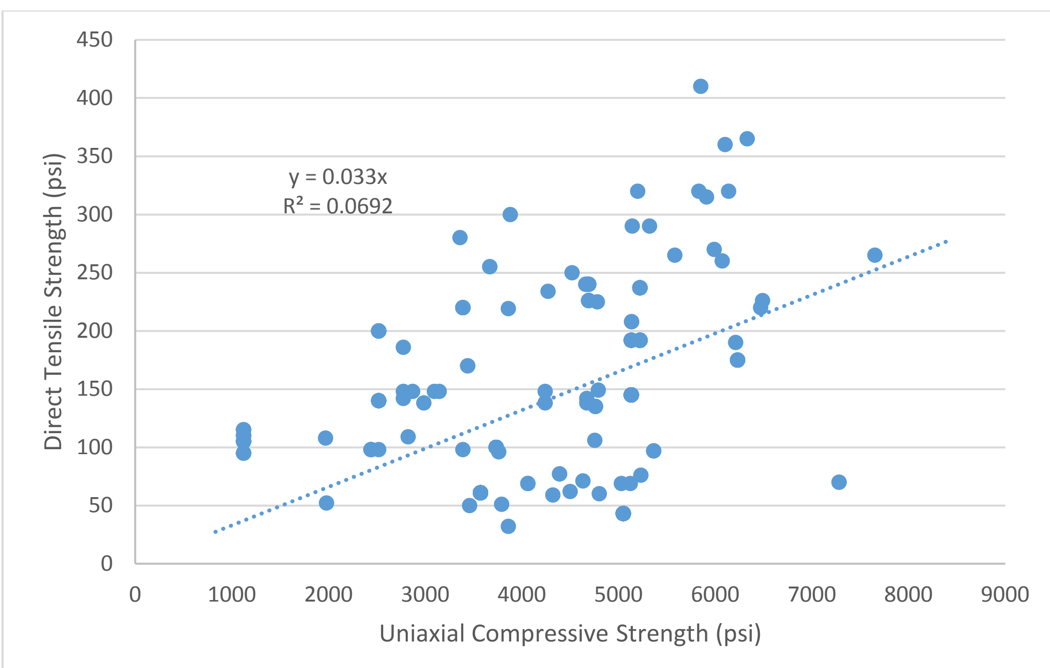

Figure 4 – All data, direct tensile versus uniaxial compressive strength.

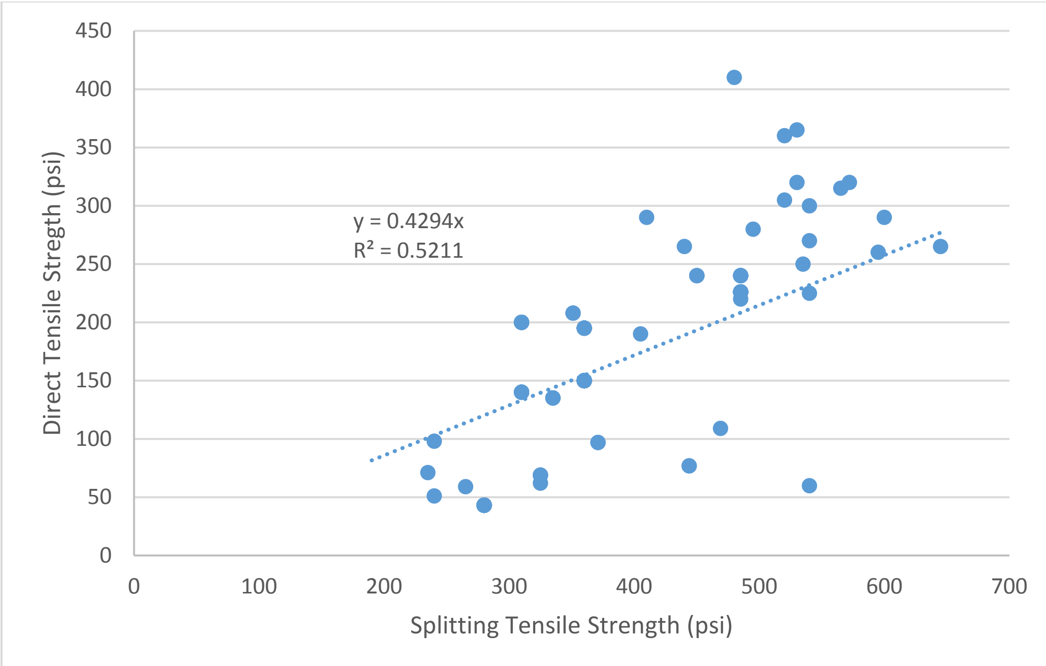

Figure 5 – All data, direct tensile versus splitting tensile strength.

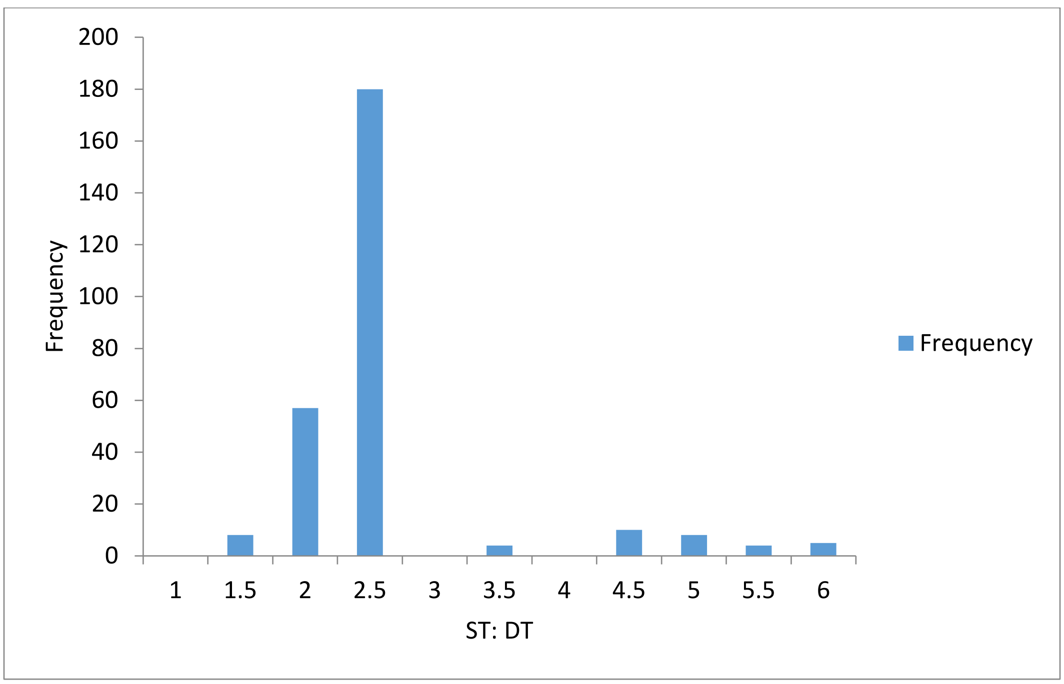

Figure 6 - Histogram of the ratio between splitting tensile and direct tensile strengths (ST/DT).

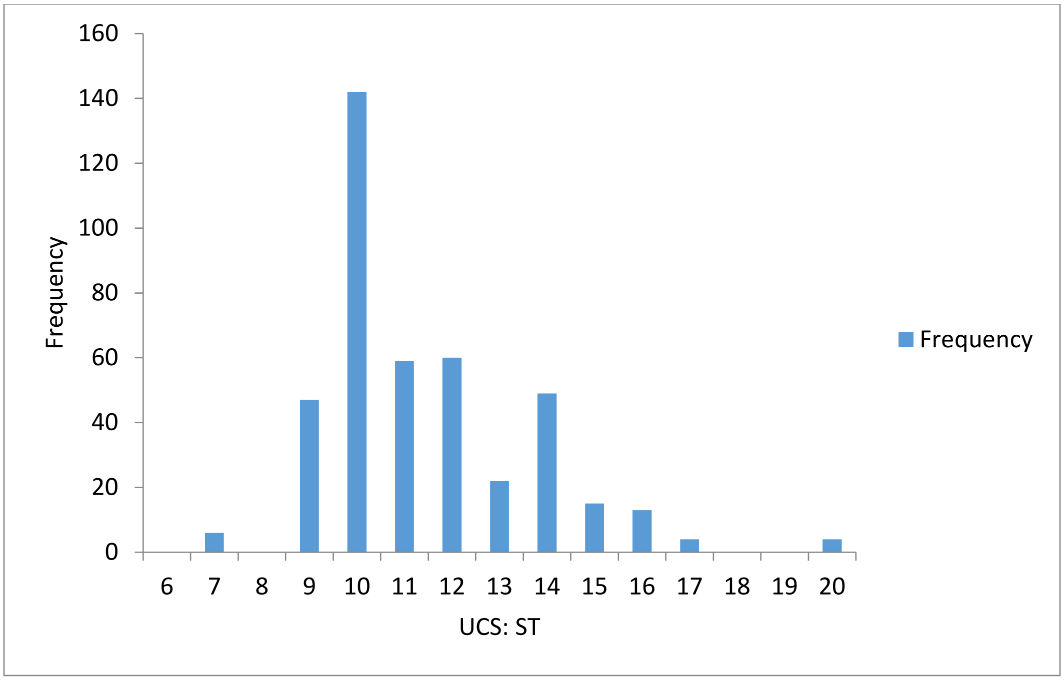

Figure 7 - Histogram of the ratio between uniaxial compressive and splitting tensile strengths (UCS/ST).

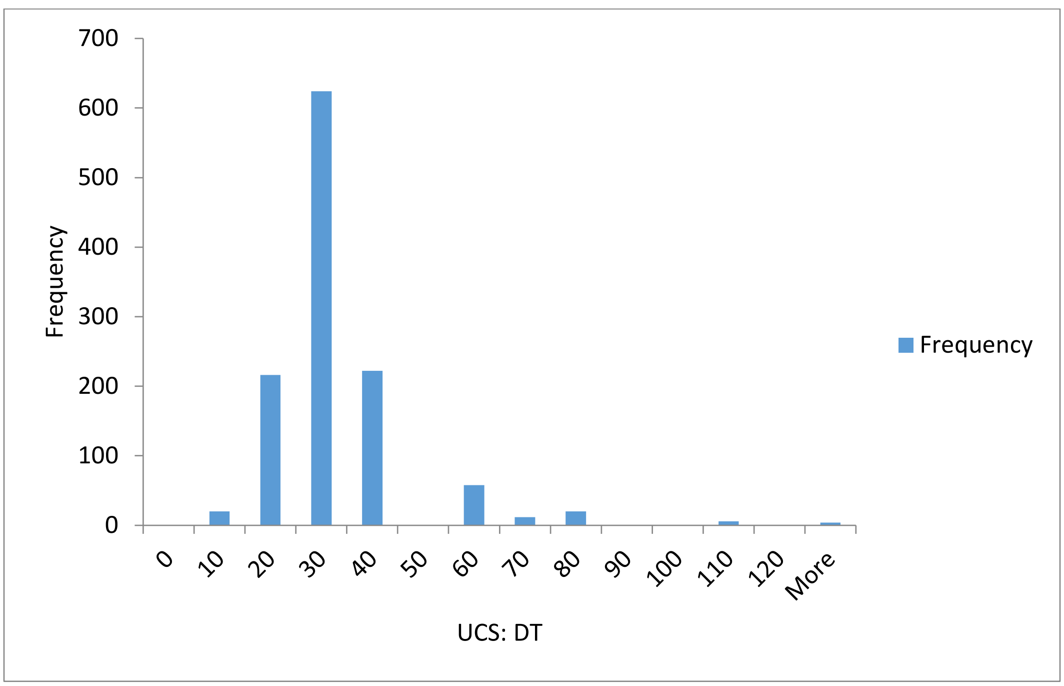

Figure 8 - Histogram of the ratio between uniaxial compressive and direct tensile strengths (UCS/DT).

Data obtained from this study points to the following relationships:

Splitting Tensile Strength: $f_{st} = 0.08f'_c$ (3)

Direct Tensile Strength: $f_{dt} = 0.03f'_c$ (4)

Splitting Tensile to Direct Tensile: $f_{dt} = 0.4f_{st}$ (5)

The figures and histograms presented above indicate that the ratios of direct and splitting tensile to uniaxial compressive strength for the projects included in this study are lower than those found for other Reclamation and TVA projects.

Break-Bond Shear Strength Correlations

All Data

Break-bond strength data from all tests, undifferentiated by type, project etc., is presented in Figure 9.

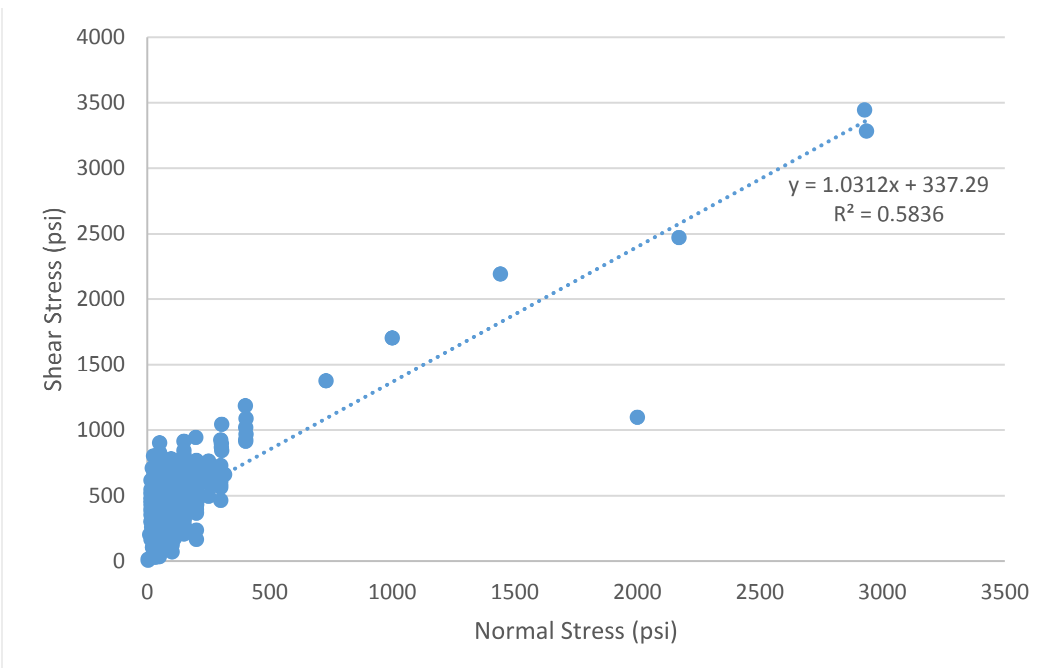

Figure 9 – All data break-bond test results. The average UCS = 4,239 psi, and the average ST = 359 psi.

The failure envelope shown in Figure 9 corresponds to a friction angle, φ, of 45.9° and a cohesion, c, of 337 psi. Note that the apparent cohesion intercept is quite nearly equal to $0.1f'_c$, and the average splitting tensile strength. This relationship was noted by McLean and Pierce (1988) as an assumption made for many of Reclamation's early design projects. Given the clustering of data at low normal stresses, the graph is broken out further in Figures 10 and 11, below.

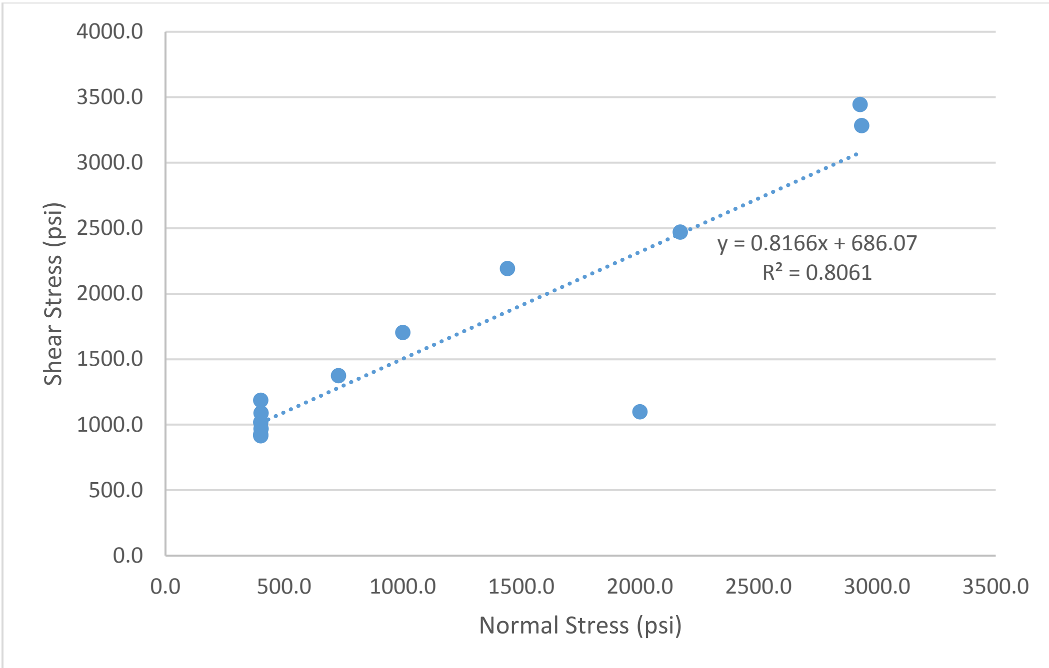

Figure 10 – All data break-bond test results including only specimens tested at normal loads greater than 400 psi.

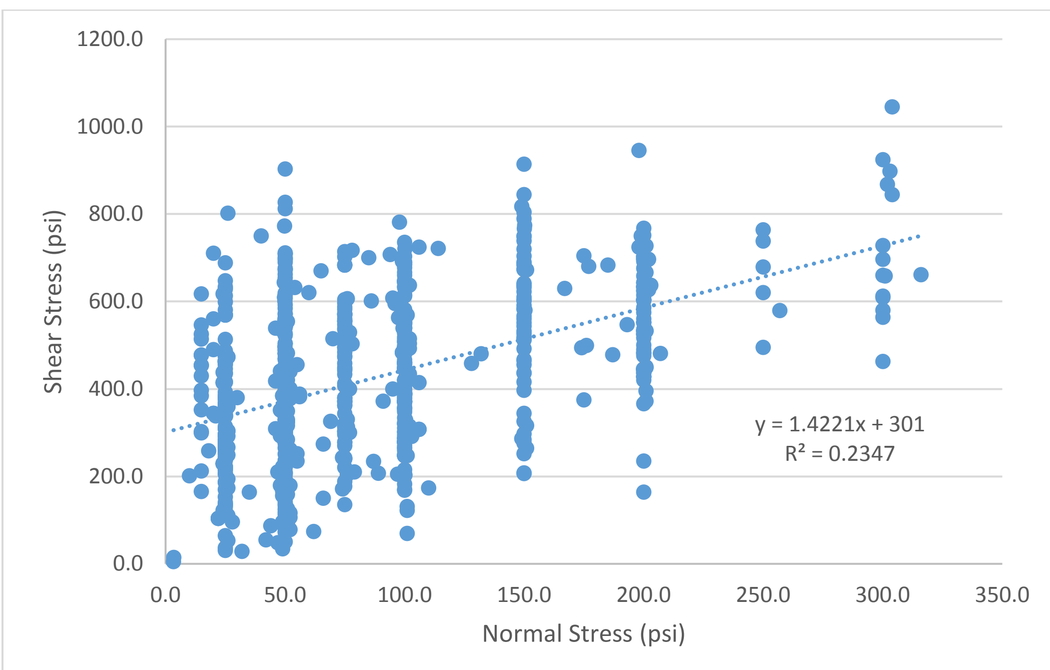

Figure 11 – All data break-bond test data including only specimens tested at normal loads less than or equal to 316 psi.

Figure 10 shows φ = 39.2°, and c = 686 psi, while Figure 11 displays φ = 54.9°, and c = 301 psi. It should be noted that there is increasing scatter with lower normal stresses for break-bond testing (shear stress ranges from about 10 to 900 psi at 50 psi normal), with the scatter likely due to concrete mix variation between projects. The reduced scatter at higher stresses is probably a relic of fewer tests performed at the higher stresses, with the higher stress tests all being performed for the same few projects.

The break-bond shear stress at failure was normalized by the normal stress to generate a stress ratio for each break-bond test (stress ratio = shear stress (τ) /normal stress (σ) at failure). The stress ratio points for each break-bond test are then plotted against corresponding DT, ST and UCS in the following figures.

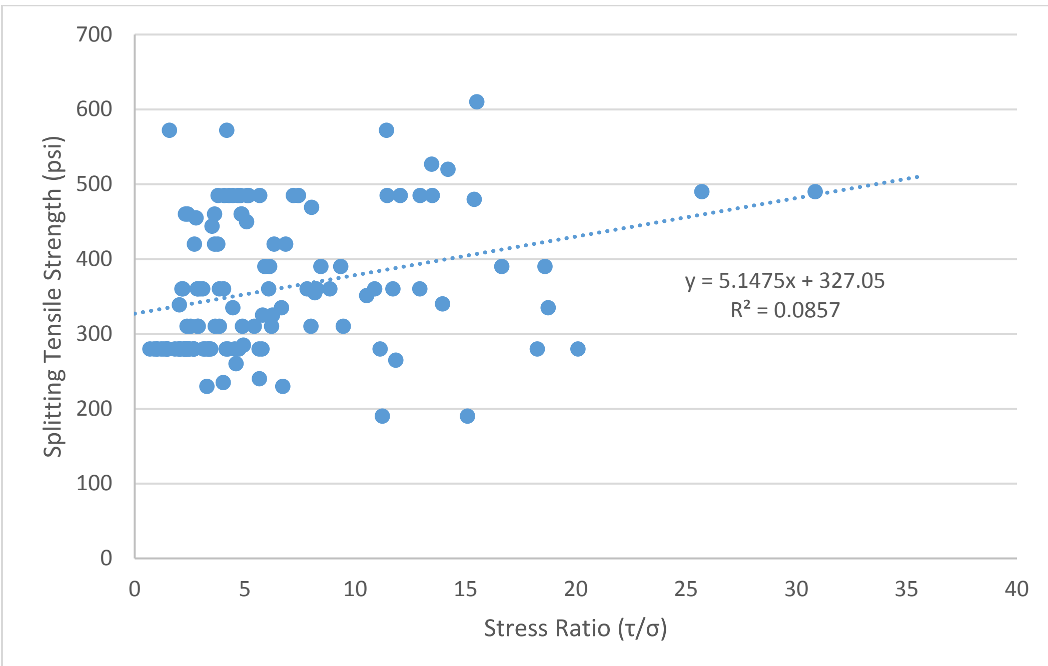

Figure 12 – All data break-bond splitting tensile versus stress ratio. The average splitting tensile strength is 359 psi.

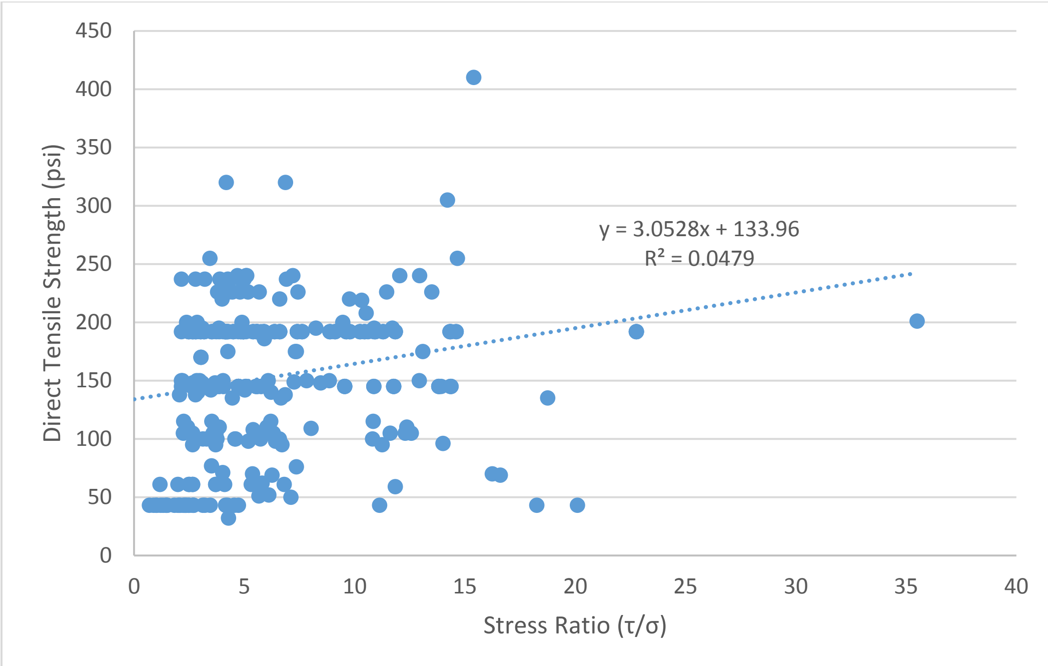

Figure 13 – All data break-bond direct tensile versus stress ratio. The average direct tensile strength is 154 psi.

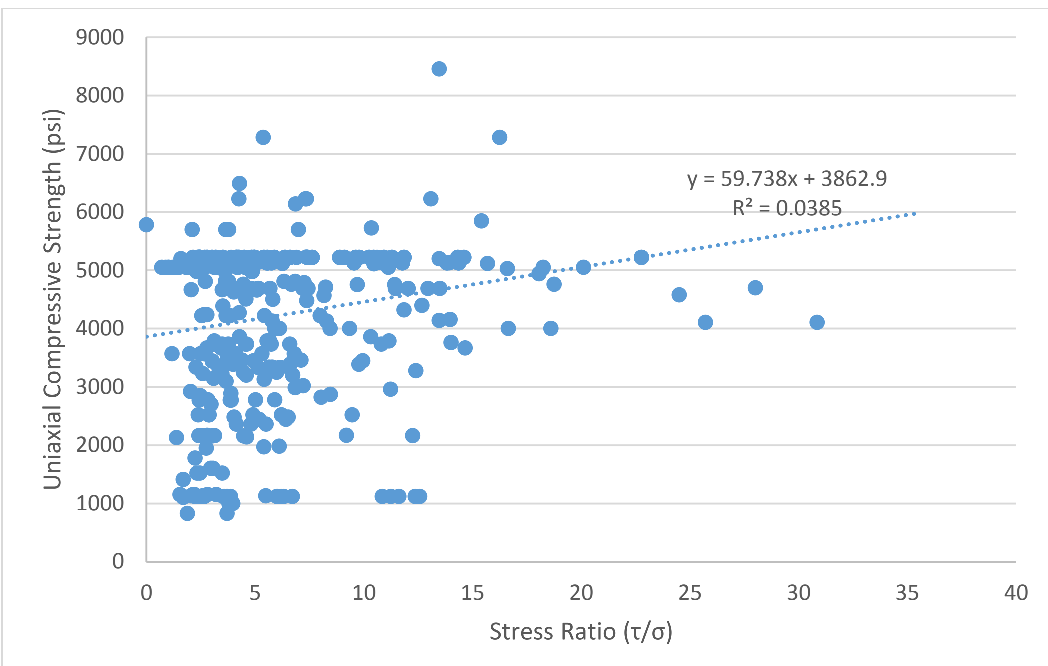

Figure 14 – All data break-bond uniaxial compressive strength versus the stress ratio. The average uniaxial compressive strength is 4,239 psi.

Note that there does not appear to be any correlation between ST, DT or UCS and the stress ratio at failure. For each graph, the y-intercept is nearly equal to the average y-axis parameter, indicating that the best fit linear regression line is nearly horizontal. The horizontal banding in the graphs is caused by the use of average parameters from ACIS; many of the break-bond tests were assigned the same, average strength parameters.

Figure 15 shows a histogram distribution of the stress ratio at failure for all break-bond tests, indicating that the majority of tests had a stress ratio between 4 and 6 at failure.

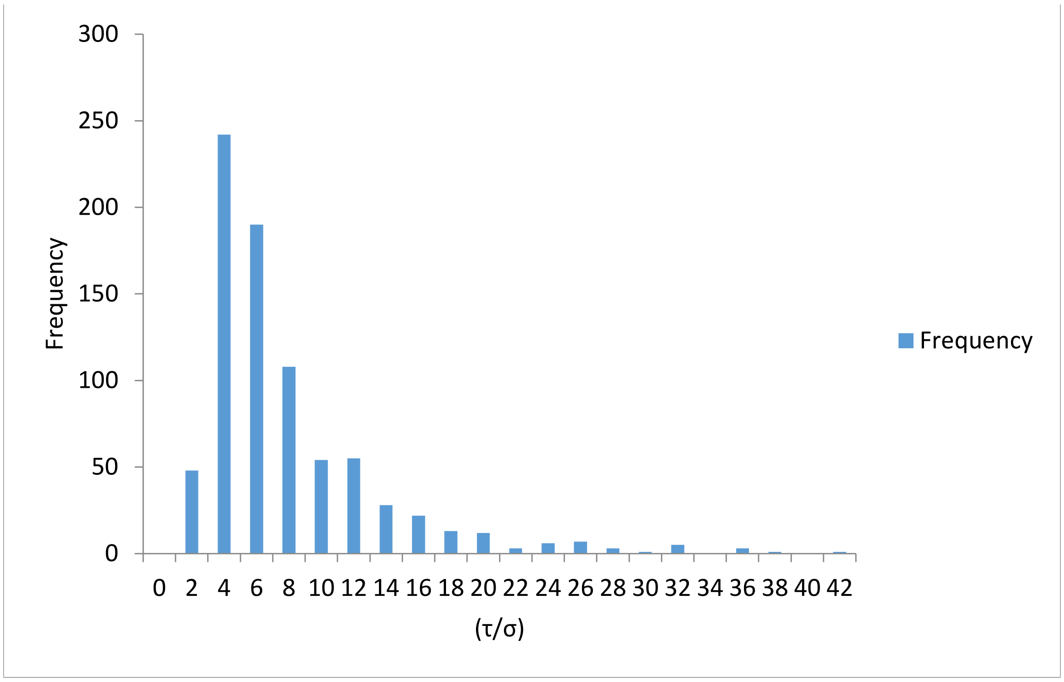

Figure 15 - Histogram of the stress ratio at failure.

Well-Constrained Data

Where compressive/tensile strength data could be obtained for individual specimens located within 5 feet of a direct shear specimen, these data were labeled as “Well-Constrained Data.” The data is presented below in a similar format to the previous section but does not include any comparisons of compressive/tensile strength test data.

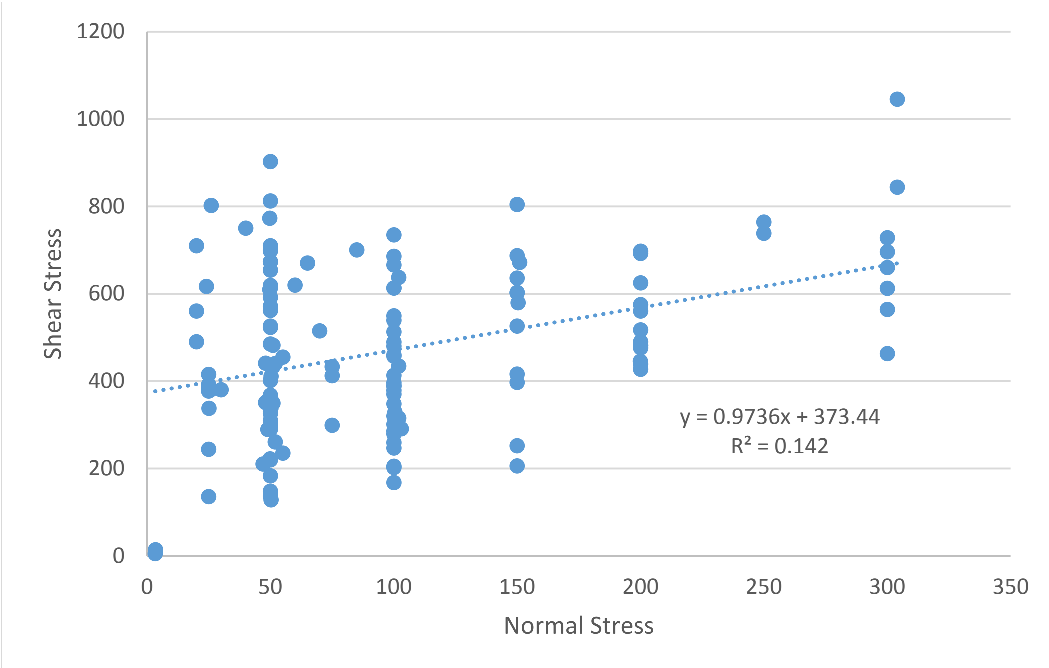

Figure 16 – Well-constrained data break-bond test results. The average UCS = 3,397 psi, and the average ST = 374 psi.

Figure 16 indicates φ = 44.2° and c = 373 psi. While there is a great deal of scatter in Figure 16, this again points to the relationship of the apparent cohesion intercept being 0.1f'$_c$, and equal to the splitting tensile strength.

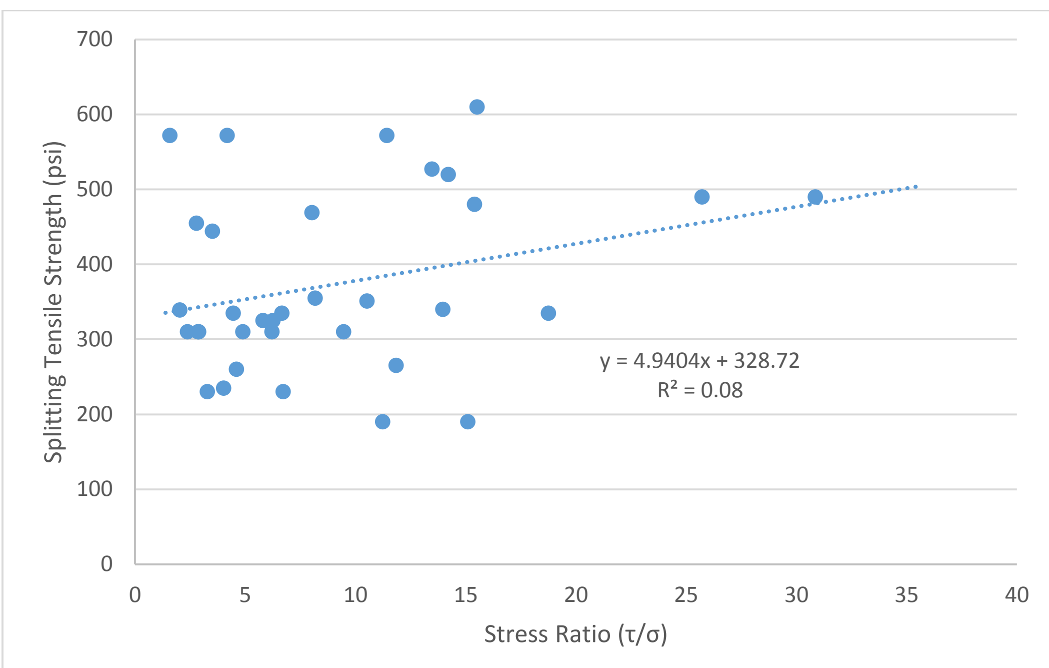

Figure 17 - Well-constrained data break-bond splitting tensile versus stress ratio. The average splitting tensile strength is 374 psi.

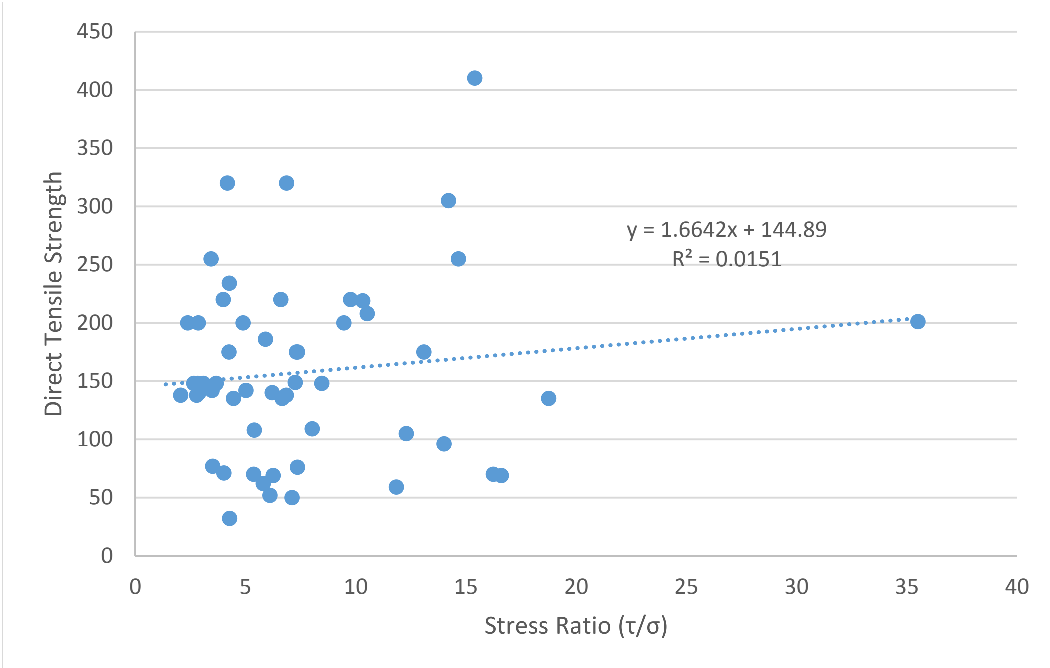

Figure 18 - Well-constrained data break-bond direct tensile versus stress ratio. The average direct tensile strength is 158 psi.

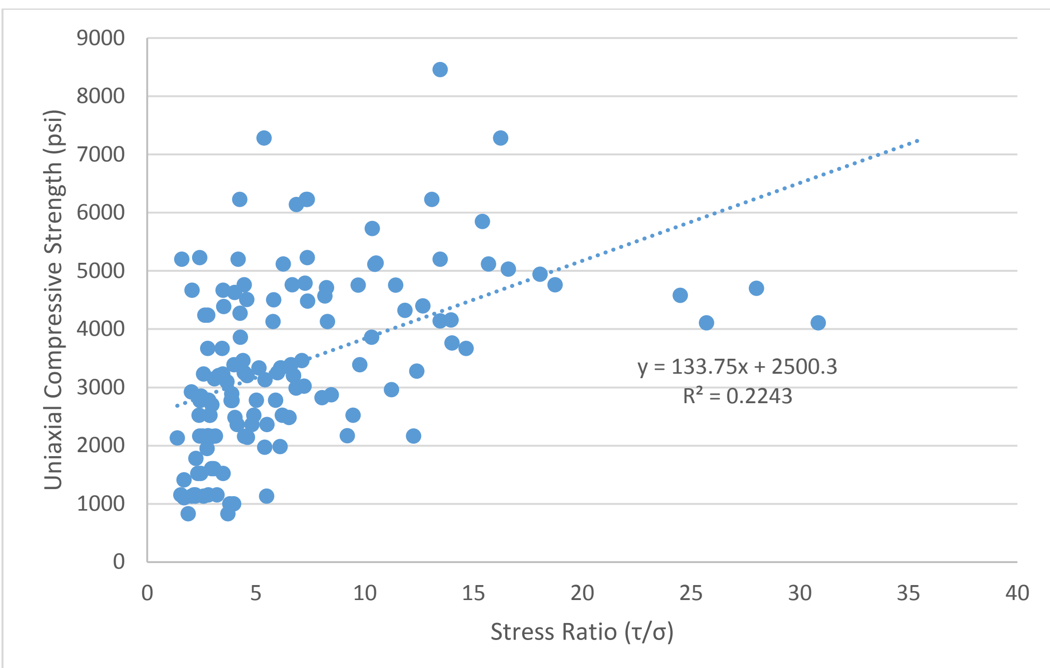

Figure 19 - Well-constrained data break-bond uniaxial compressive strength versus stress ratio. The average uniaxial compressive strength is 3,397 psi.

Figures 17 through 19 again indicate a lack of good correlation between the direct shear stress ratio at failure and any compressive/tensile strength parameters.

The “Well-Constrained” data set was then parsed into bins by UCS to determine if variations in compressive strength affected the break-bond direct shear strength.

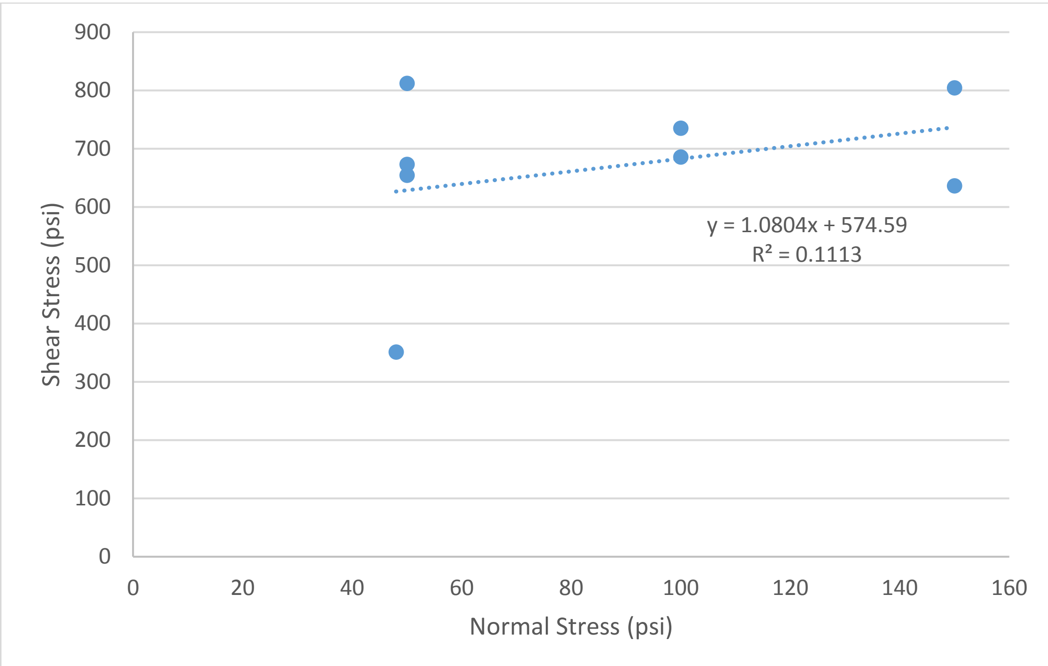

Figure 20 – Well-constrained data break-bond strength with UCS>6,000 psi. Average UCS = 6,760 psi.

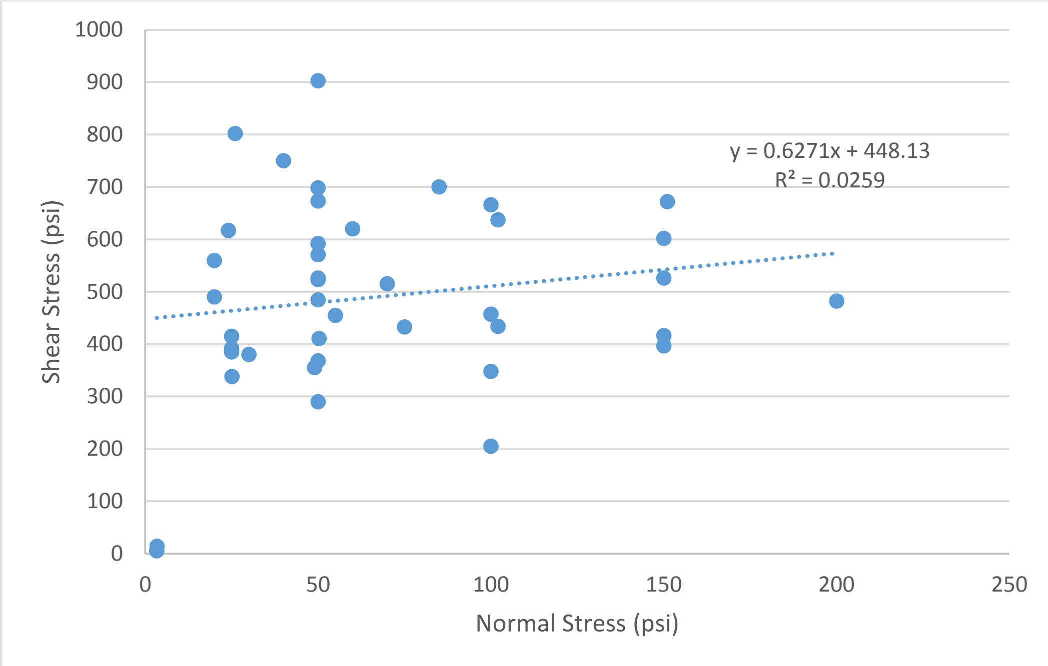

Figure 21 – Well-constrained data break-bond strength with 4,000 psi<UCS<6,000 psi. Average UCS = 4,715 psi.

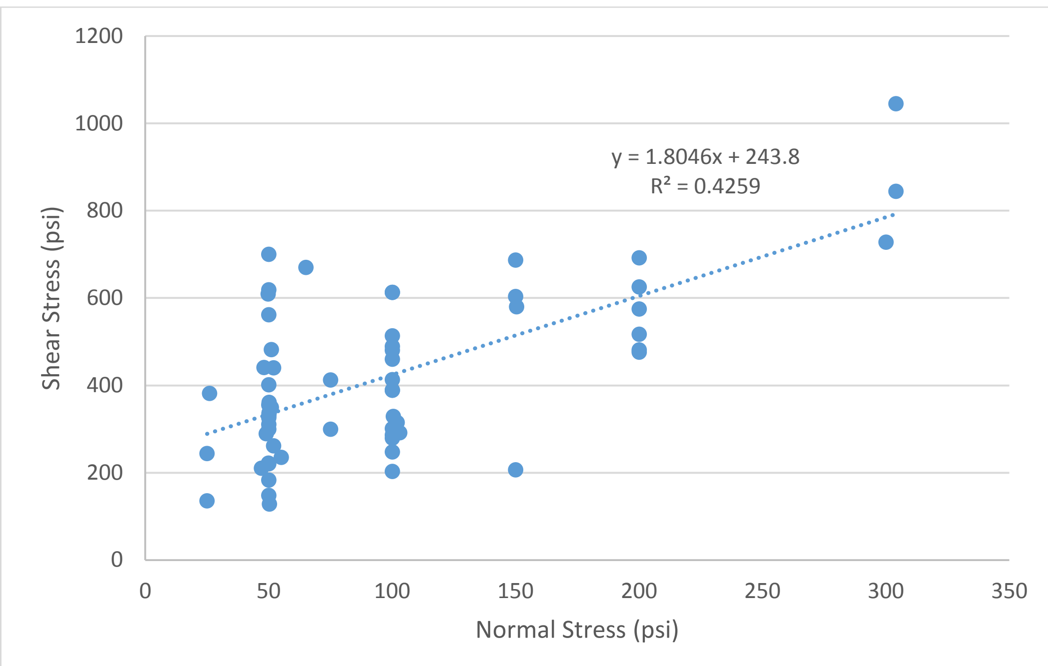

Figure 22 – Well-constrained data break-bond strength with 2,000<UCS<4,000 psi. Average UCS = 2,893 psi.

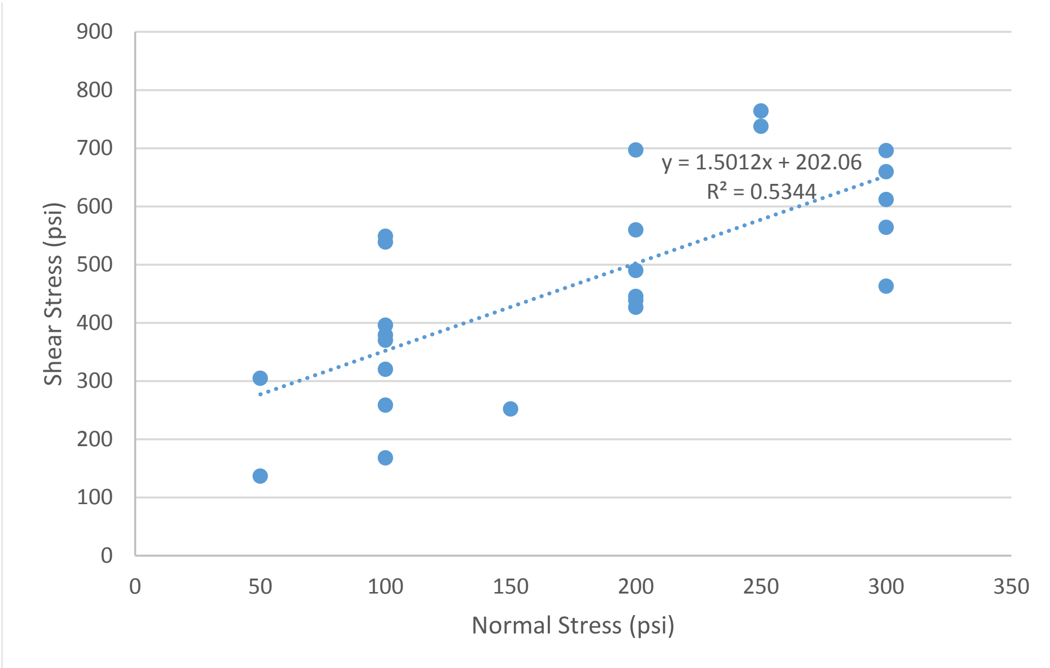

Figure 23- Well-constrained data break-bond strength with UCS<2,000 psi. Average UCS = 1,328 psi.

Note that while there is no trend in friction angle with UCS, the cohesion intercept decreases with decreasing uniaxial compressive strength and generally follows the 0.1f'$_c$ relationship discussed earlier.

Conclusions

Both the "All Data" and "Well-Constrained Data" data sets found wide scatter in the break-bond strength test results, particularly at low normal stresses. The only correlation observed in the data was confirming the general assumption presented in McLean and Pierce (1988) where the apparent cohesion is about 0.1f'$_c$ and is approximately equal to the splitting tensile strength. Note that this relationship is rough with wide scatter in the data. No relationship for predicting the friction component of shear strength was observed in the data. The stress ratio at failure for the break-bond tests is most commonly between 4 and 6, but there is also wide scatter in this data with many data points representing higher stress ratios.

Sliding Shear Strength Correlations

Sliding shear strength parameters and their corresponding strength parameters were collected and analyzed in a similar manner to those for the break-bond tests. Figure 24 presents the results from all sliding friction tests included in this study.

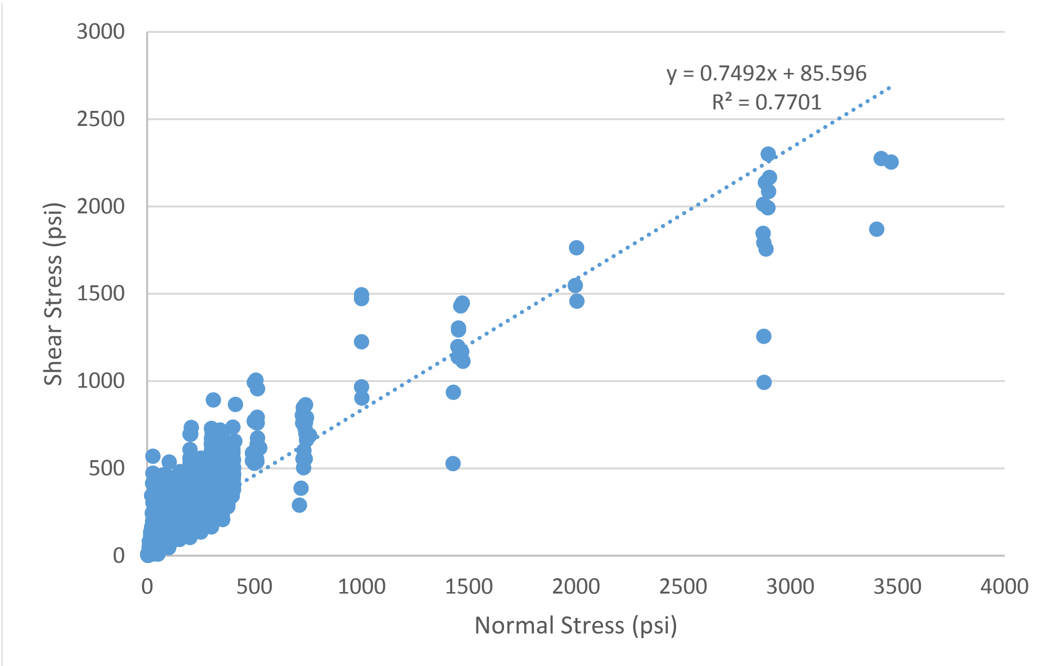

Figure 24 – All data sliding shear strength test data.

Figure 24 shows a linear failure envelope with φ = 36.8° and c = 85.6 psi.

The Angle-Envelope Method (Reclamation, 1976) predicts that the friction angle for both the break-bond and sliding shear strength tests should be similar, with the break-bond shifted "up" at a parallel slope to intercept the y-axis at the cohesive strength (Figure 25).

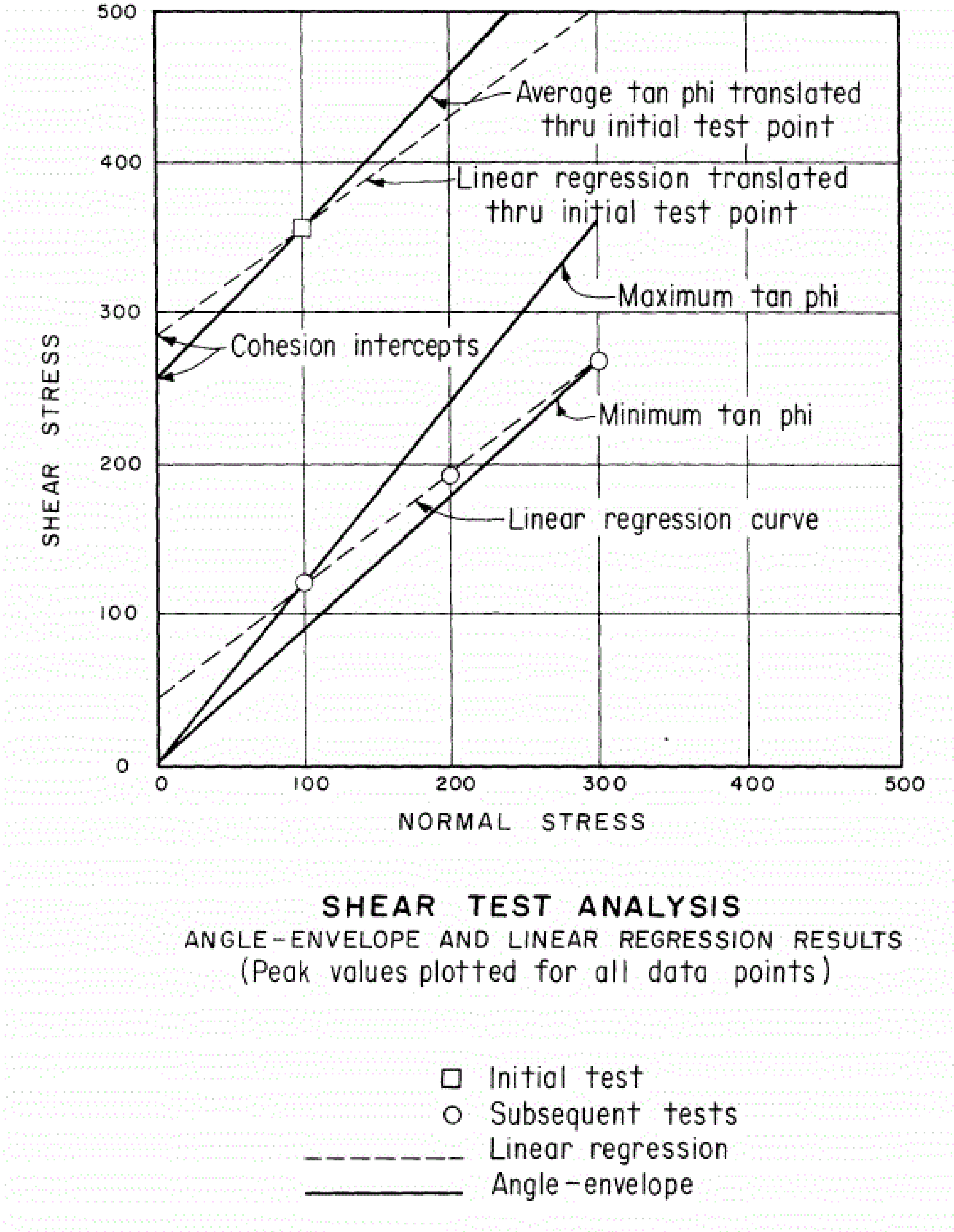

Figure 25 - Depiction of the Angle-Envelope Method (from Reclamation, 1976).

The break-bond friction angle is greater than the sliding friction angle by nearly 10°, likely due to the larger number of high normal stress tests performed under the sliding boundary condition.

Sliding Strength Binned by Normal Stress

Given the large amount of scatter at low normal stresses, the data presented in Figure 24 was parsed by normal stress to generate Figures 26 through 28.

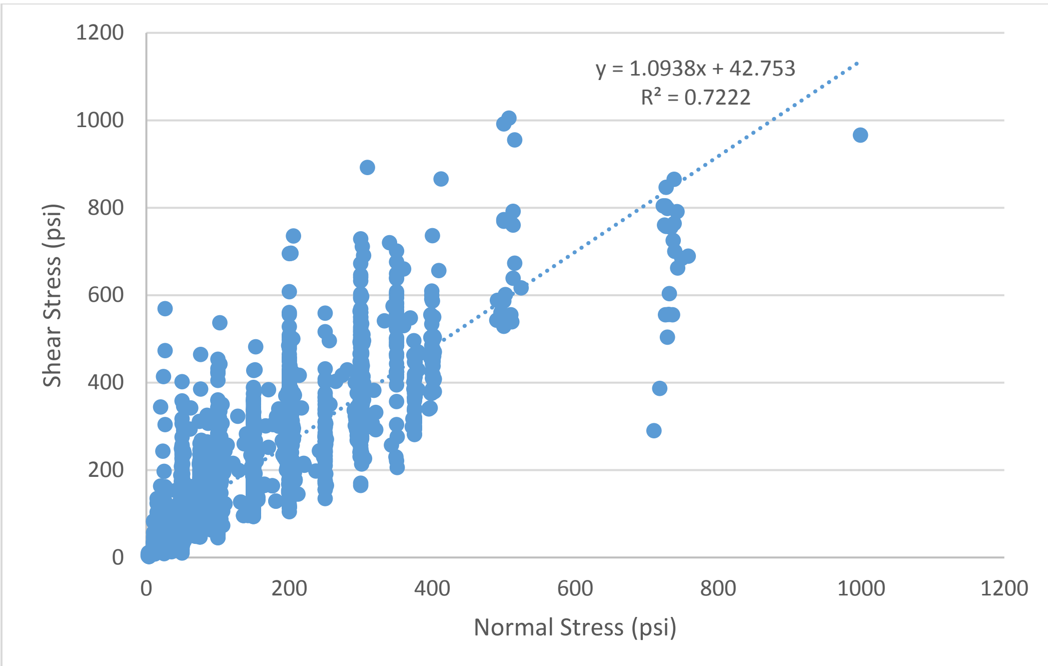

Figure 26 – All data sliding shear strength test data with the normal stress less than 1,000 psi.

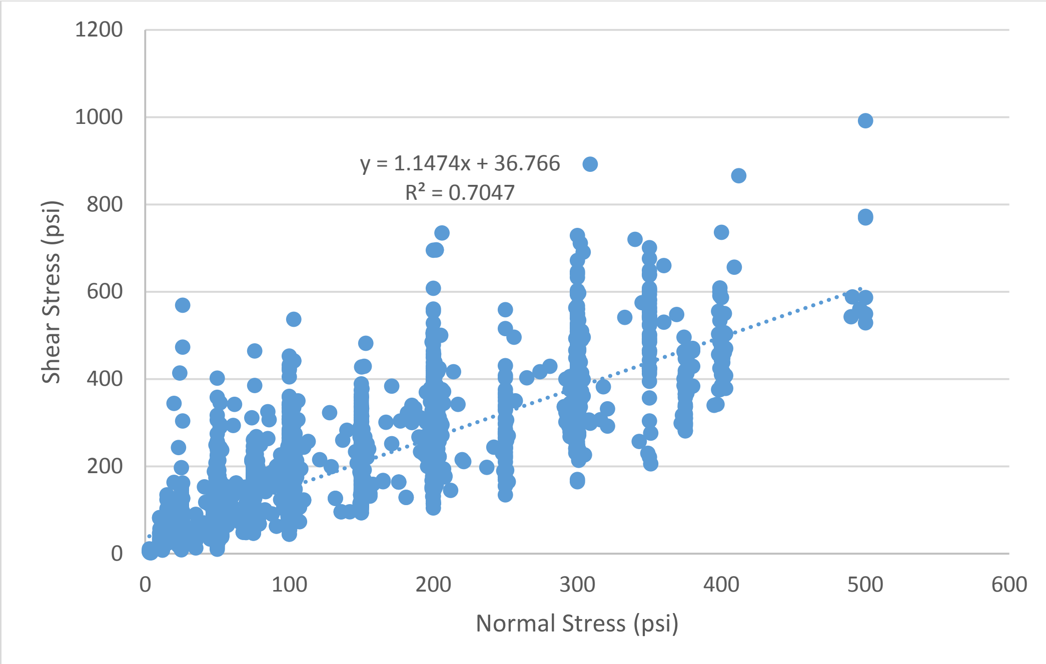

Figure 27 – All data sliding shear strength test data with the normal stress less than or equal to 500 psi.

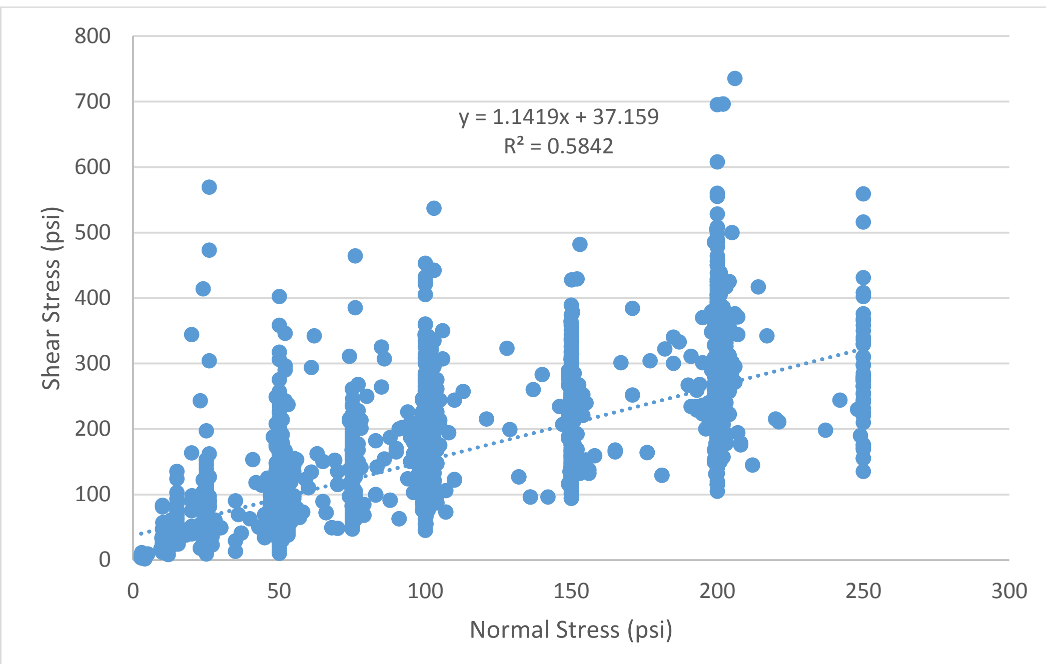

Figure 28 – All data sliding shear strength test data with the normal stress less than or equal to 250 psi.

Figures 26 through 28 show a general increase in friction angle from 36.8° to 48.8° as the higher normal stress points are removed from the failure envelope. The cohesion intercept also generally decreased, from 85.6 psi to 37.2 psi. Note that at normal stresses less than or equal to 250 psi (Figure 28), the data becomes very scattered, indicating that at typical engineering stresses, the friction angle and apparent cohesion can vary widely. Friction angles in Figures 27 and 28 (φ = 48.9° and 48.8°, respectively) are generally more consistent with the friction angle for the "All Data" break-bond test results (φ = 45.9°). This result is consistent with the assumptions for the Angle-Envelope Method (Reclamation, 1976)

Correlations to Strength Parameters

Stress ratio (τ/σ) values at failure generated from sliding friction tests were compared to other strength parameters (ST, DT and UCS) in the same manner as was done for the break-bond tests. Figures 29 through 31 present the compressive/tensile strength parameters plotted against the stress ratio.

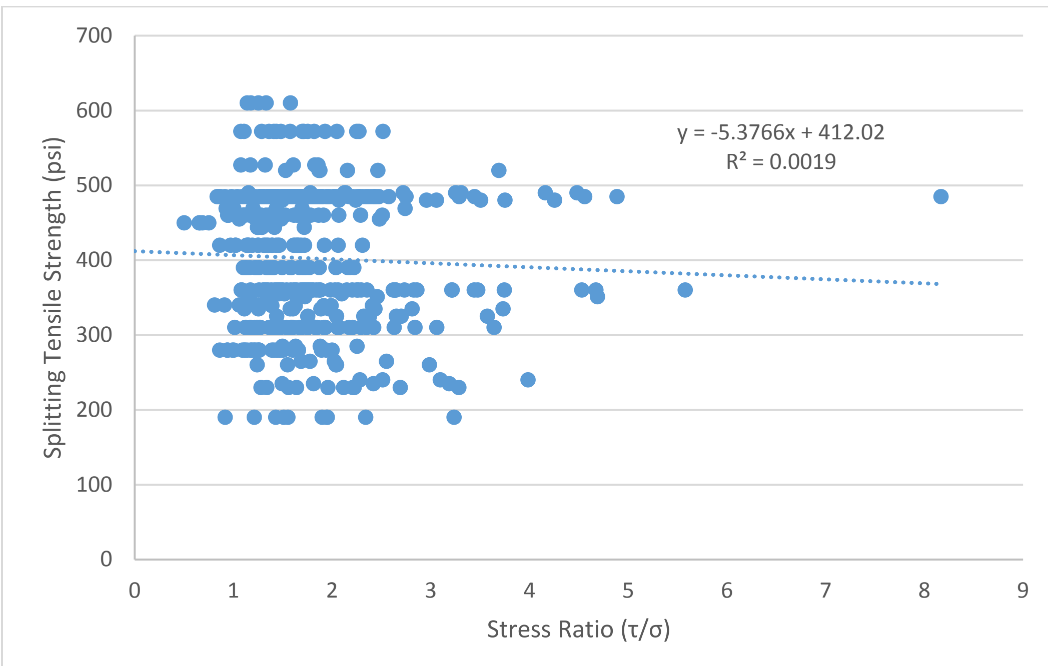

Figure 29 – All data sliding shear strength, splitting tensile strength versus stress ratio.

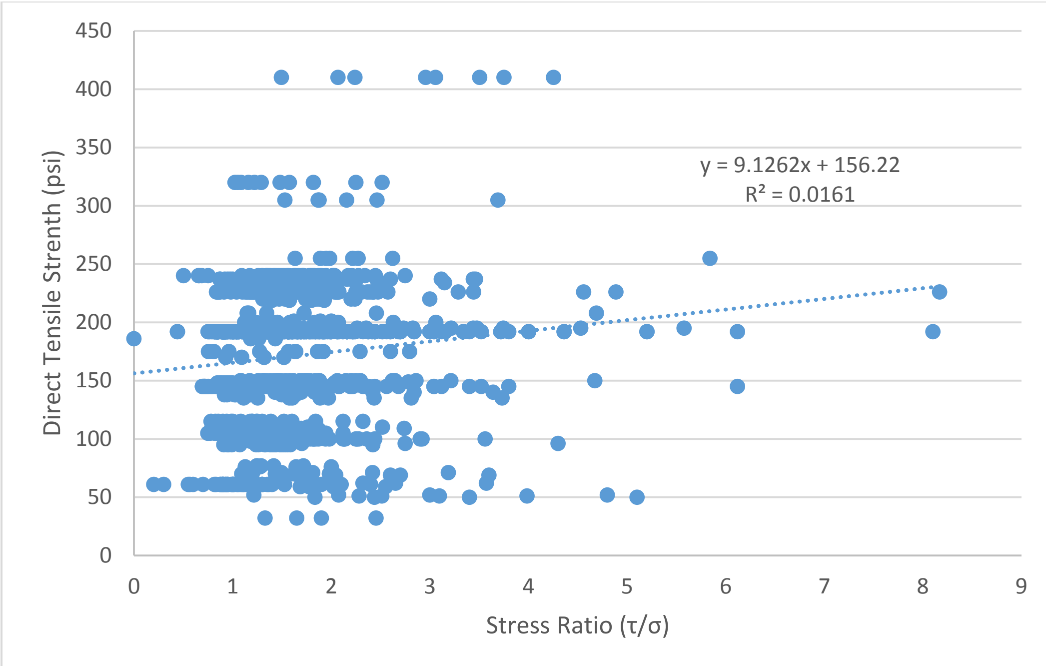

Figure 30 – All data sliding shear strength, direct tensile strength versus stress ratio.

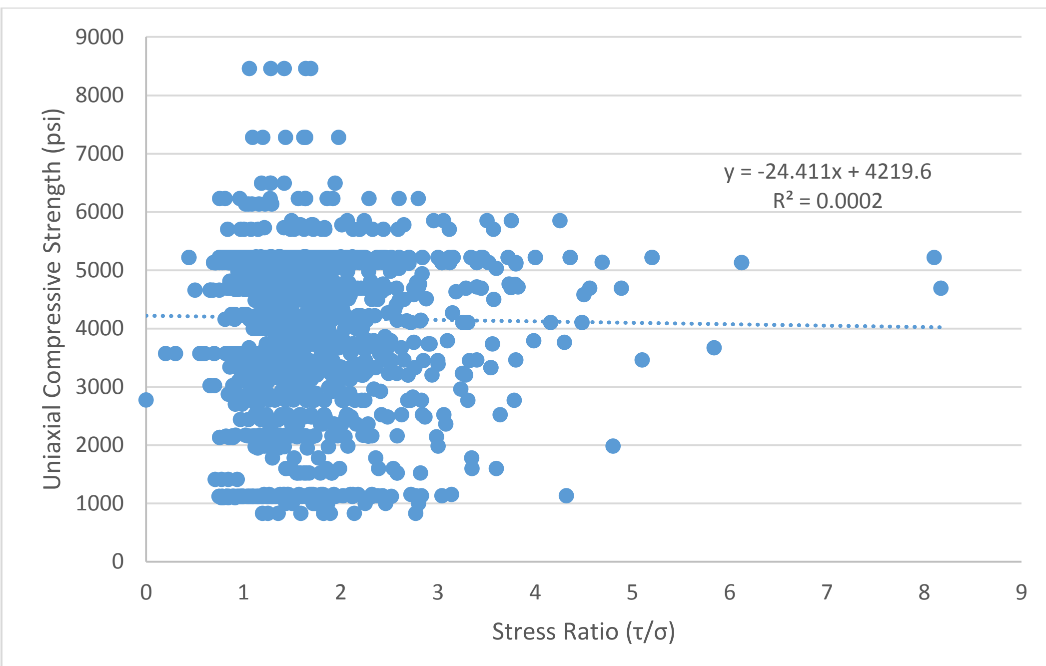

Figure 31 – All data sliding shear strength, uniaxial compressive strength versus stress ratio.

Note the lack of correlation between any of the strength parameters and the stress ratio. Horizontal lines in the graphs are due to average strength values from ACIS being assigned to multiple sliding shear tests.

Stress ratio values are presented in a histogram in Figure 32 below.

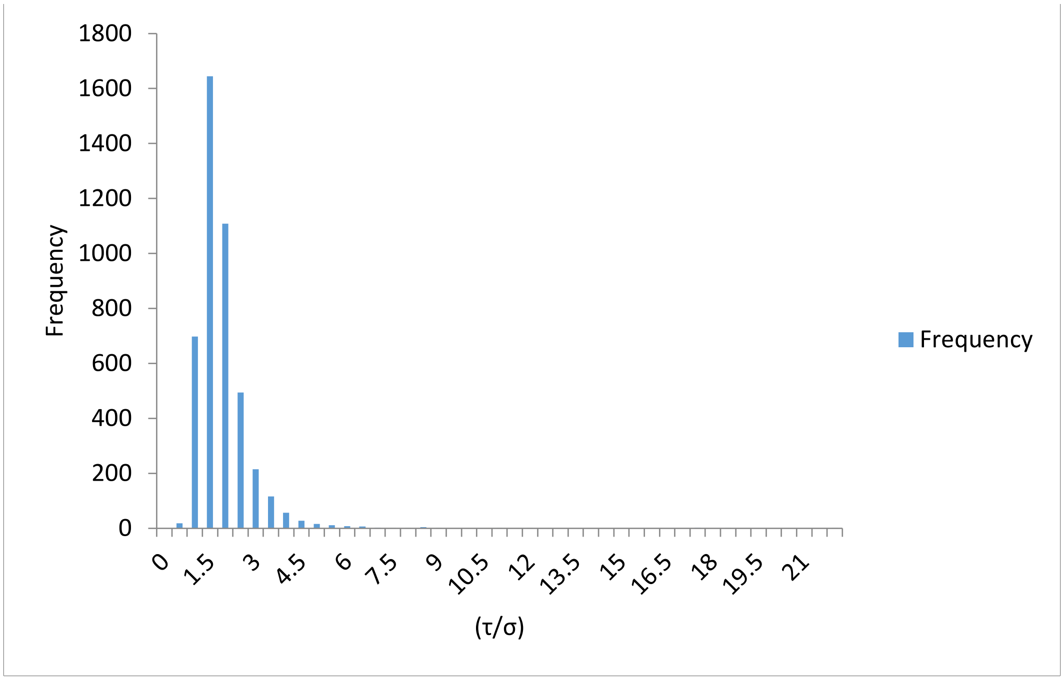

Figure 32 - Histogram of stress ratio at failure for all data sliding shear strength tests.

Figure 32 indicates the majority of sliding friction tests had strength ratios between 1.5 and 2.5, corresponding to secant friction angles of 56.3° and 68.2°, respectively. These friction angles are much higher than those found in the sliding friction plots (Figures 26 through 28) likely capturing the variability in stress ratio values for low normal stress conditions.

Sliding Friction Tests Binned by Compressive/Tensile Strength Parameters

The sliding friction test values were binned by types of strength data and then by values within those strength data bins. Figure 33 presents the sliding friction failure envelope for all data where corresponding UCS tests exist. Figures 34 through 37 show sliding friction data binned by UCS values. Note that the data used to generate the figures in this section were only from direct shear tests with corresponding compressive strength data; previous plots included direct shear data with no corresponding compressive strength data.

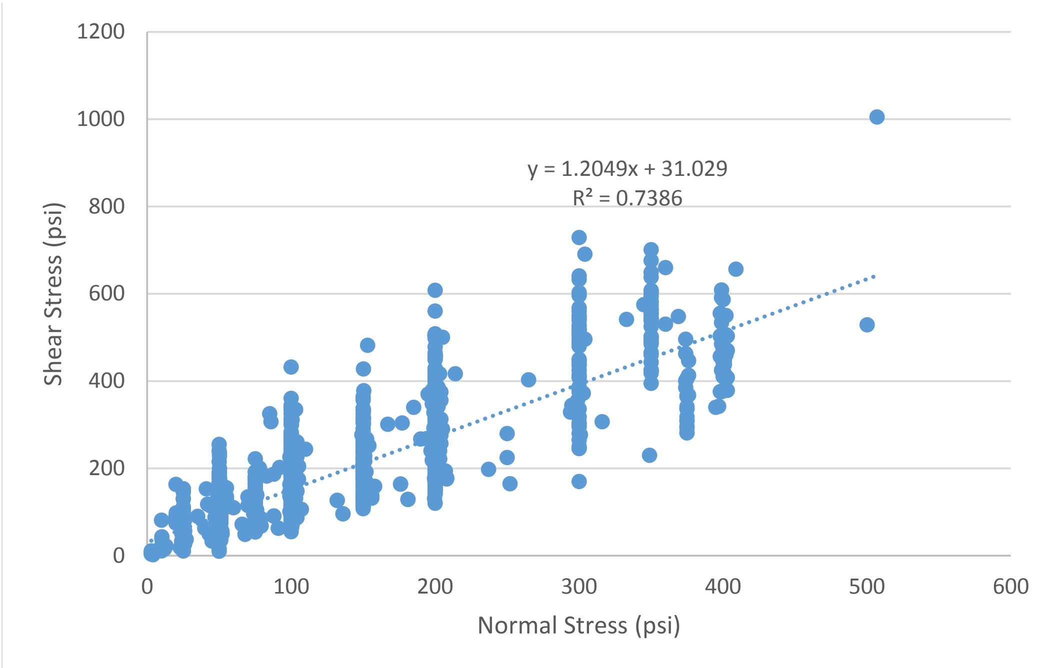

Figure 33 - Sliding shear strength test results only for specimens that had accompanying UCS values. Average UCS = 4,180 psi.

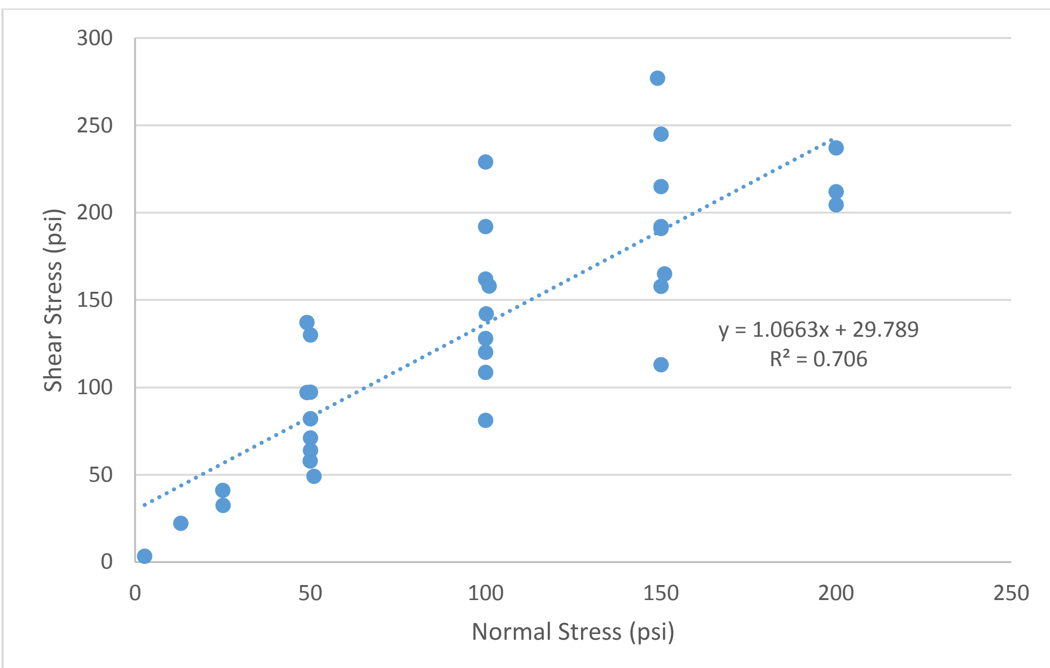

Figure 34 - Sliding shear strength test results binned by UCS, with UCS>6,000 psi. Average UCS = 6765 psi.

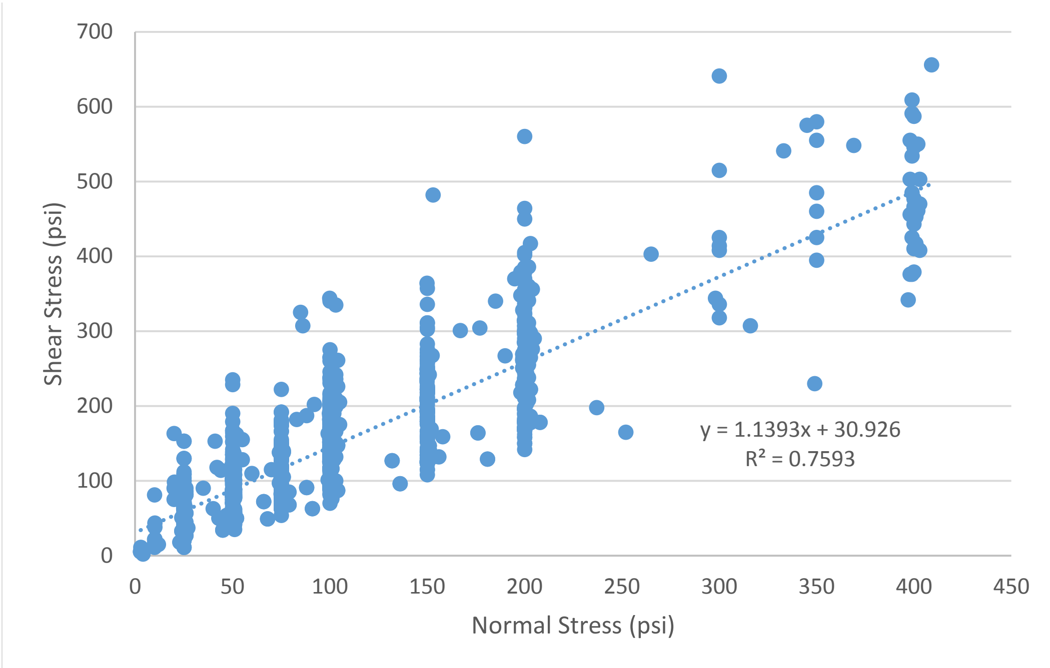

Figure 35 - Sliding shear strength test results binned by UCS, with 4,000 psi<UCS<6,000 psi. Average UCS = 5,000 psi.

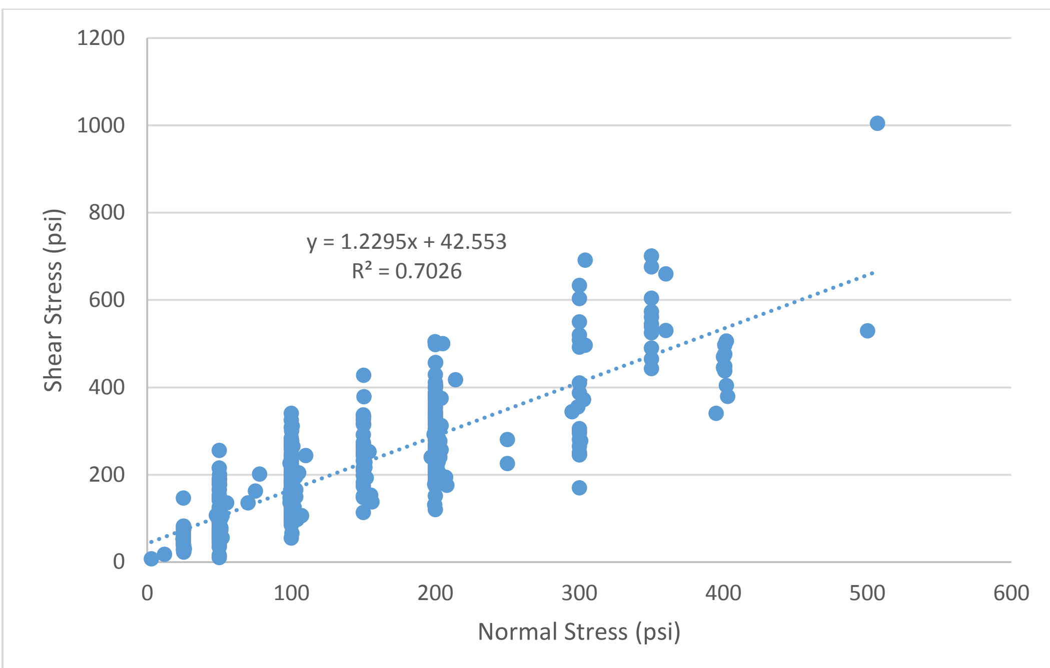

Figure 36 - Sliding shear strength test results binned by UCS, with 2,000 psi<UCS<4,000 psi. Average UCS is 3,140 psi.

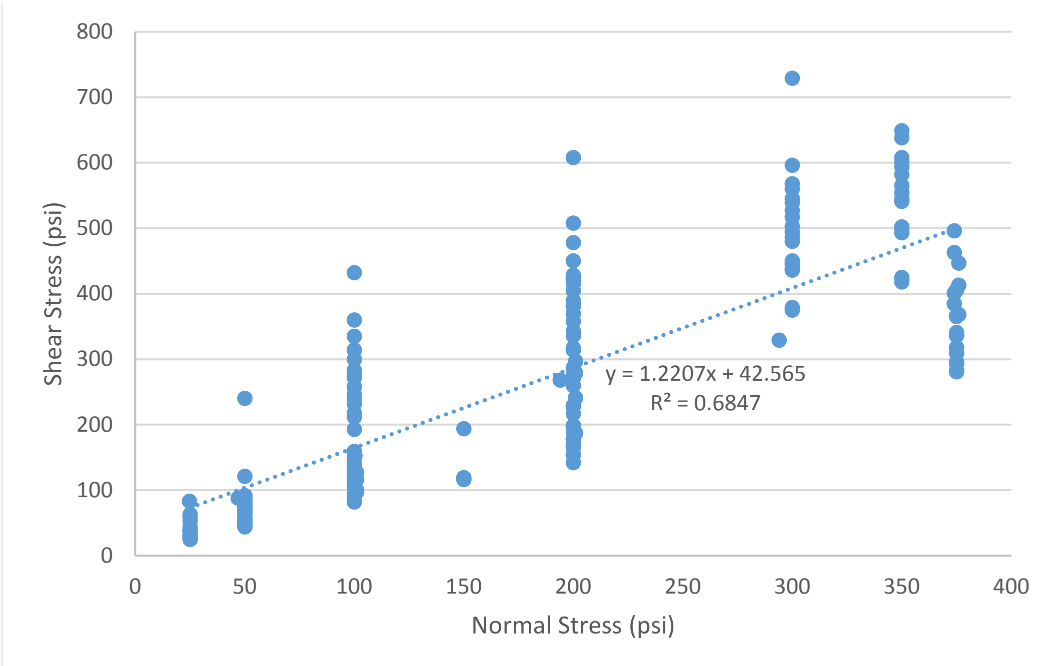

Figure 37 - Sliding shear strength test results binned by UCS, with UCS<2,000 psi. Average UCS is 1,226 psi.

Failure envelope parameters for Figures 33 through 37 were all very similar, therefore no observable predictive relationship between UCS and sliding shear strength was noted. This same analysis was repeated for both splitting tensile and direct tensile strengths, with the same null result. The sliding shear strength data binned by splitting tensile and direct tensile strengths are not presented in this report.

Conclusions

No reliable predictive relationships were found between sliding shear strength and any other strength parameters. The scatter in sliding shear strengths at low normal stresses indicates that shear strengths can be highly variable. Attempting to predict the strengths without laboratory testing is challenging and will result in a great deal of uncertainty.

Conventional Concrete Lift Lines

Data from a number of projects where conventional concrete lift lines were tested for both break-bond and sliding shear strength were collected and analyzed. For this data set, only specimens that were identified as lift lines from existing dams with no noted AAR issues were included (i.e. no parent concrete or research studies). Projects included in this data set were: Altus Dam, Arrowrock Dam, Deadwood Dam, Dworshak Dam, East Canyon Dam, Elephant Butte Dam Folsom Dam, Gerber Dam Glen Canyon Dam, Horse Mesa Dam, Minidoka Dam, Monticello Dam, Ochoco Dam, Owyhee Dam, Stewart Mountain Dam, Stoney Gorge Dam, Theodore Roosevelt Dam, and Warm Springs Dam.

Strength Property Correlations

Compressive/tensile strength test results were plotted against each other in Figures 38 through 40, similar to as was presented previously for the "All Data" and "Well-Constrained Data" data sets.

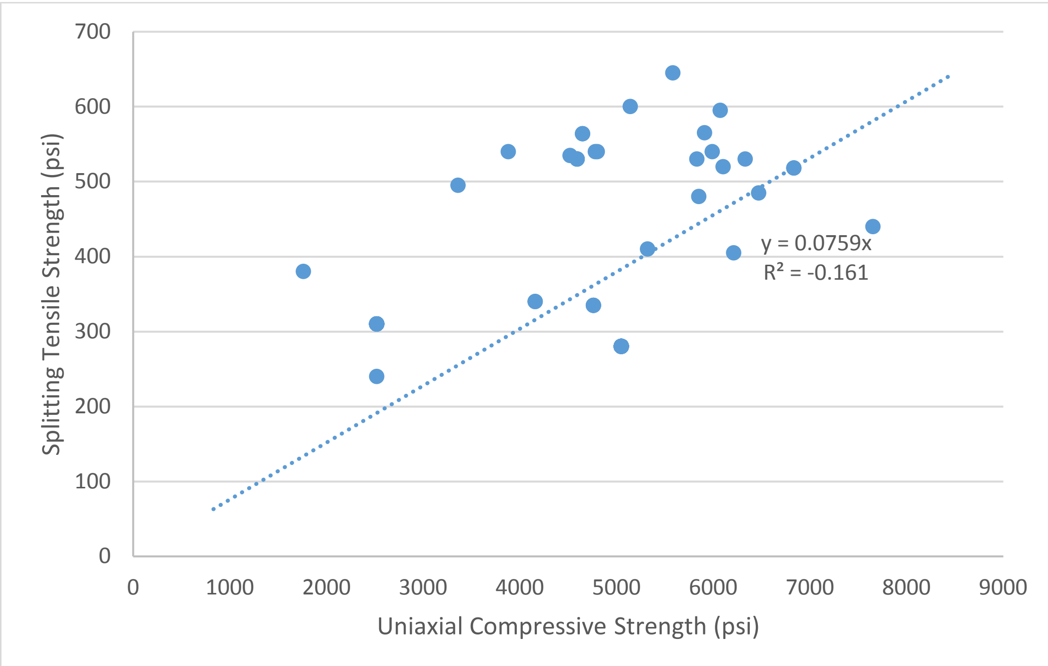

Figure 38 - Conventional concrete lift line, splitting tensile versus uniaxial compressive strength.

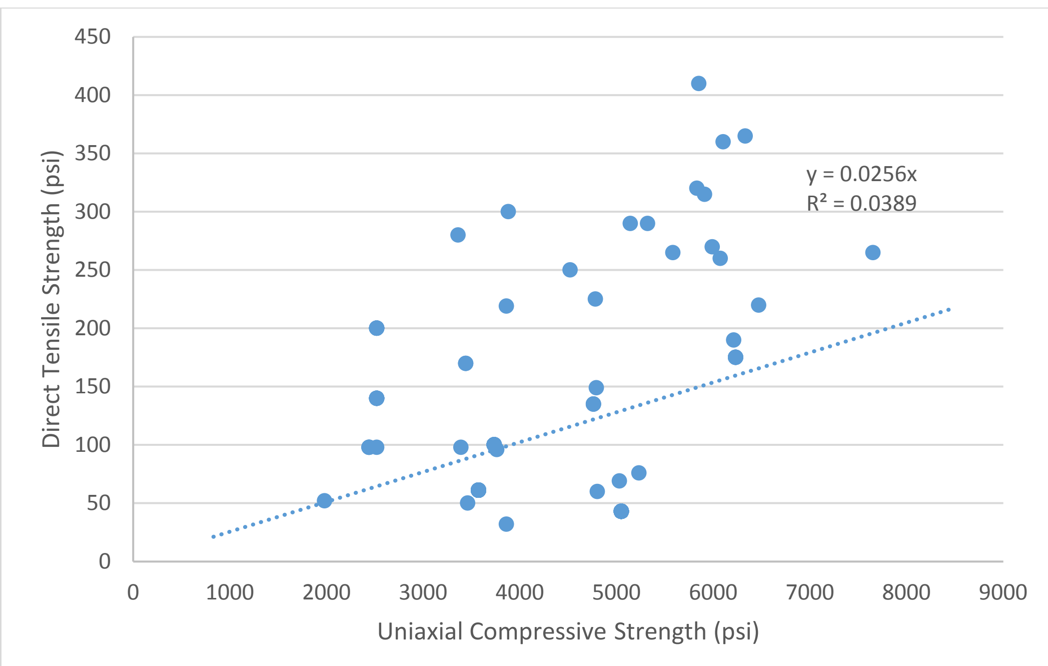

Figure 39 - Conventional concrete lift line, direct tensile versus uniaxial compressive strength.

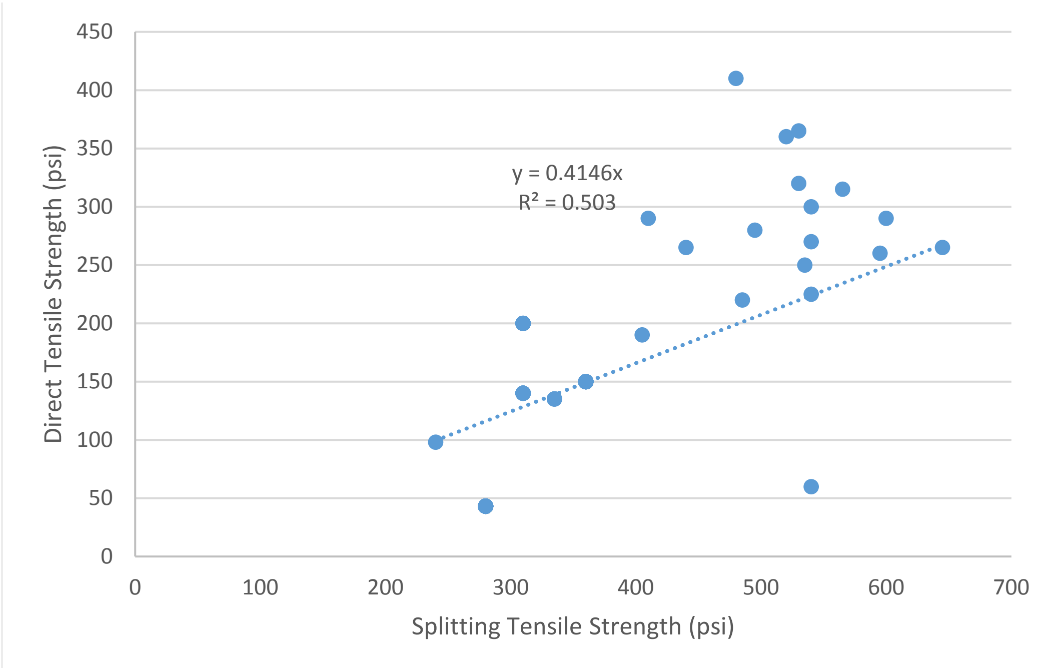

Figure 40 - Conventional concrete lift line, direct tensile versus splitting tensile strength.

Data obtained from this study points to the following relationships for conventional concrete lift lines or material in close proximity to lift lines:

Splitting Tensile Strength: $f_{st} = 0.08f'_c$ (6)

Direct Tensile Strength: $f_{dt} = 0.03f'_c$ (7)

Splitting Tensile to Direct Tensile: $f_{dt} = 0.4f_{st}$ (8)

These values are the same as those presented in Equations 3 through 5, for all of the strength data in the "All Data" data set.

Break-Bond Strength Correlations

Break-bond strength data is presented in Figure 41 below for all conventional concrete lift line specimens.

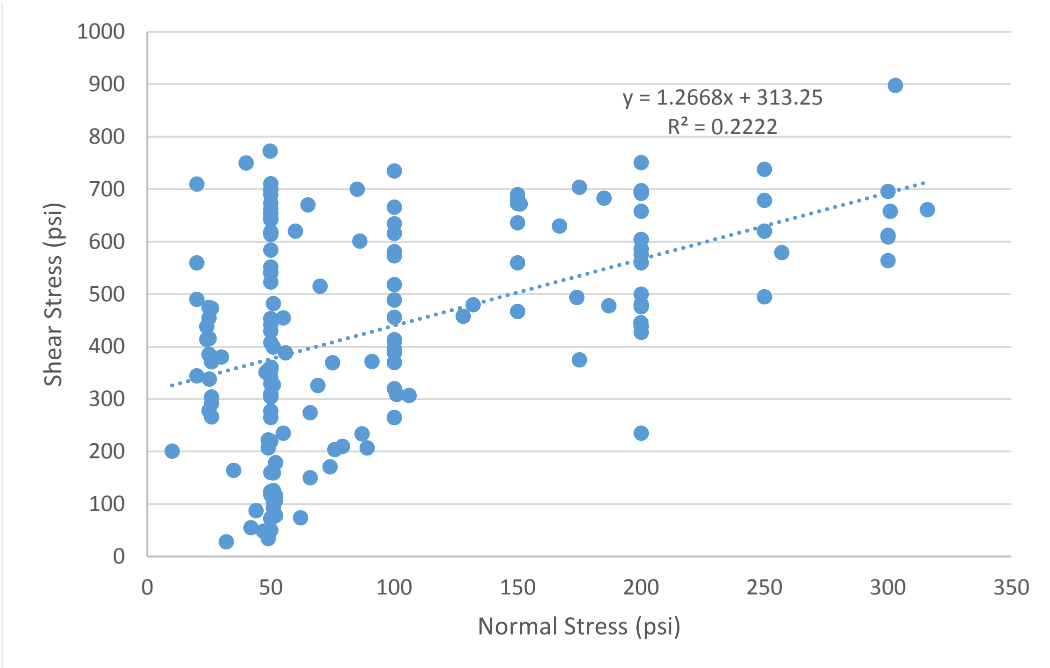

Figure 41 – Conventional concrete lift line break-bond shear strength. Average UCS = 4188 psi, and average ST = 382 psi.

Figure 41 shows φ = 51.7° with c = 313.3 psi. It can be seen that this data fits the pattern identified earlier where c ≈ 0.1f'c ≈ splitting tensile strength.

The break-bond shear stress at failure for conventional concrete lift lines was normalized by the normal stress at failure to generate a stress ratio at failure for each break-bond test. The stress ratio points for each break-bond test are then plotted against ST, DT and UCS in the following figures.

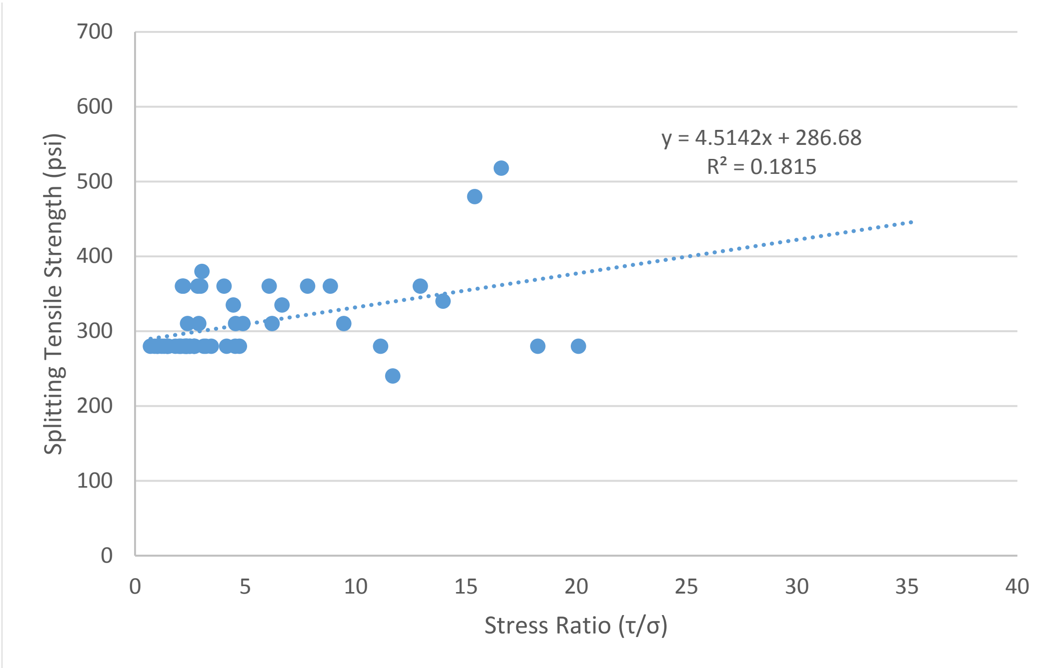

Figure 42 - Conventional concrete lift line break-bond data showing splitting tensile strength versus stress ratio.

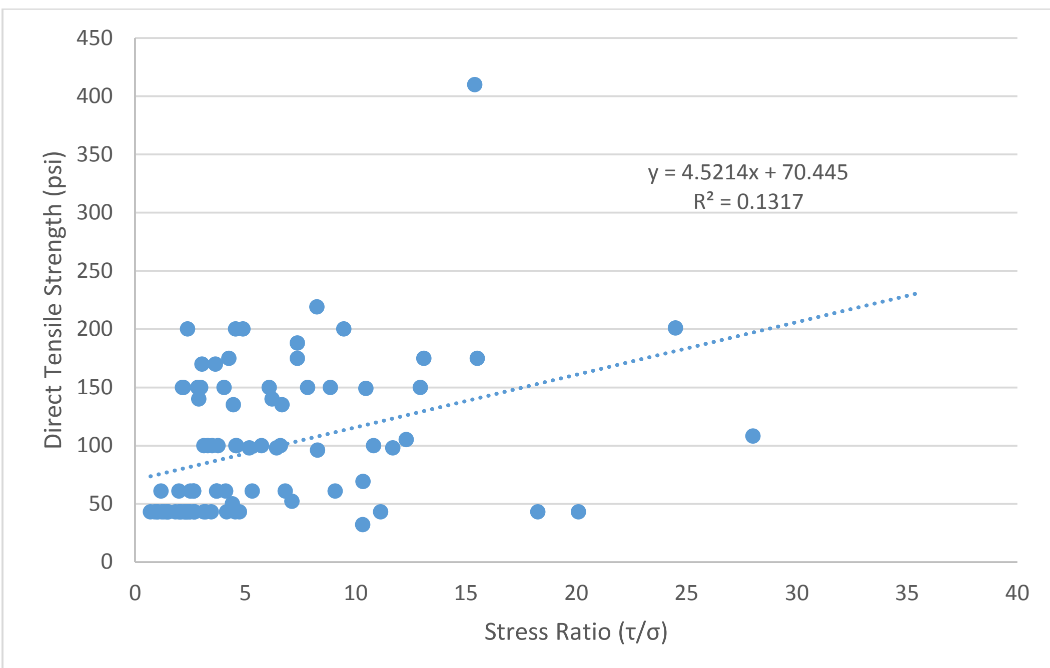

Figure 43 - Conventional concrete lift line break-bond data showing direct tensile strength versus stress ratio.

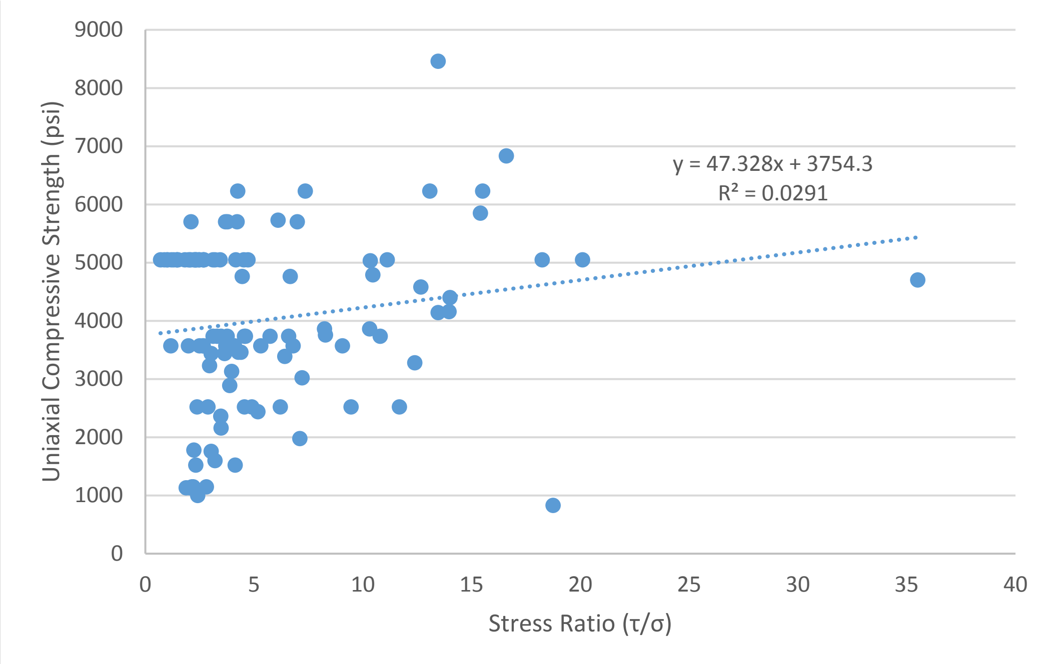

Figure 44 - Conventional concrete lift line break-bond data showing uniaxial compressive strength versus stress ratio.

As was seen in the earlier sections, Figures 42 through 44 indicate little correlation between ST, DT or UCS and stress ratio at failure for the break-bond tests.

Sliding Shear Strength

Sliding shear strengths for all of the conventional concrete lift line direct shear tests are shown in Figures 45 and 46 below.

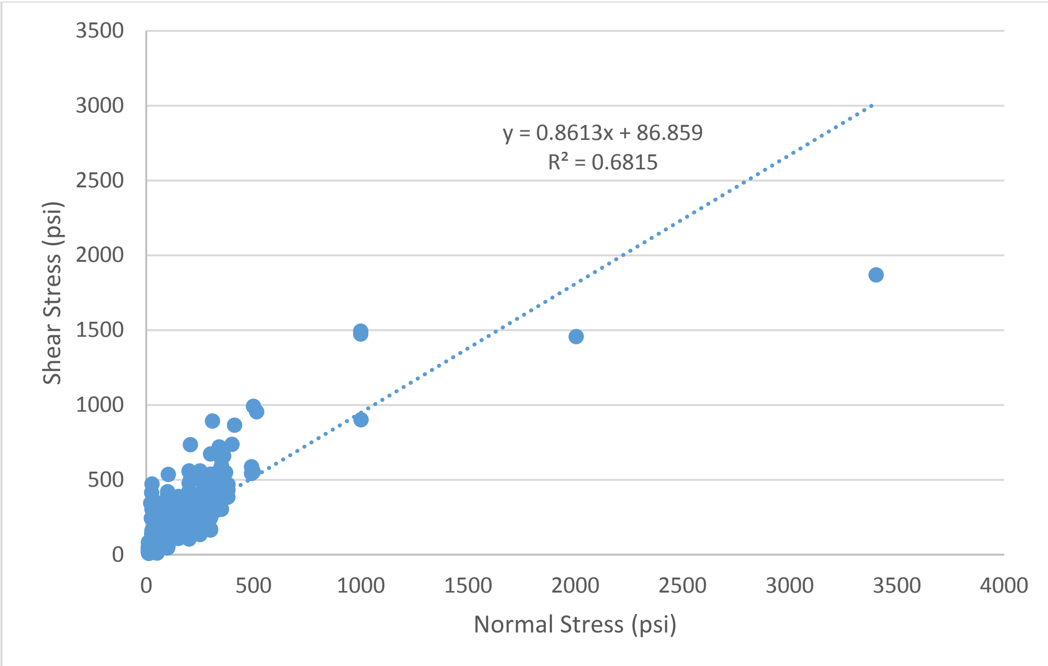

Figure 45 - Conventional concrete lift line sliding shear strength.

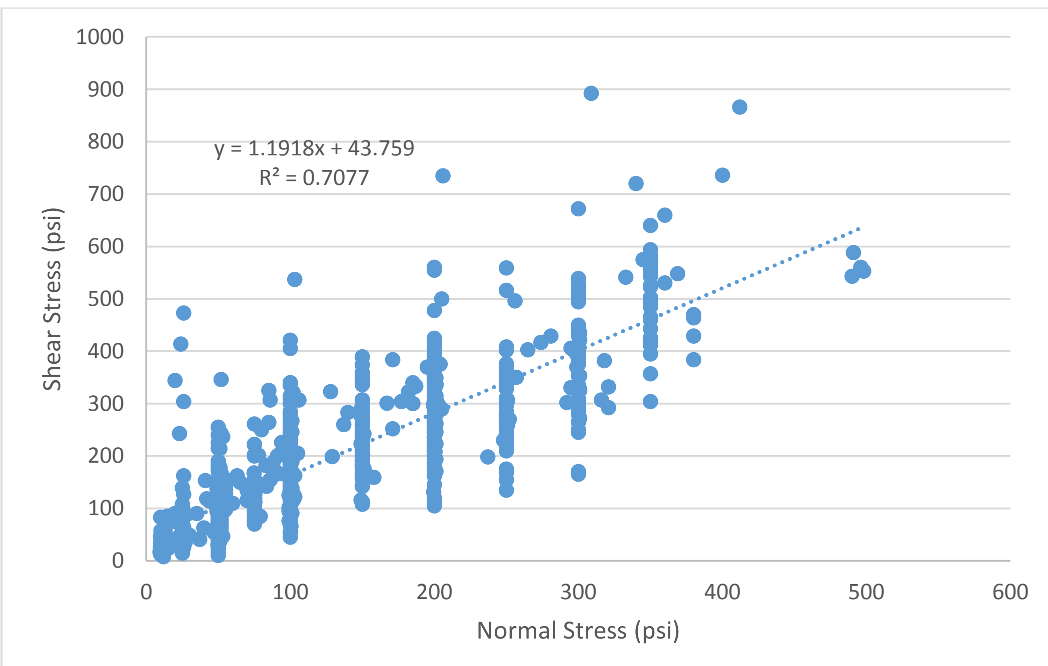

Figure 46 - Conventional concrete lift line sliding shear strength with normal stress less than 500 psi.

The linear failure envelope shown in Figure 45 indicates $\varphi = 40.7°$ and $c = 86.9$ psi, while the failure envelope in Figure 46 indicates $\varphi = 50.0°$ and $c = 43.8$ psi. As noted previously, the low normal stress data tends to have higher shear strengths than the higher normal stress data; Figure 46 illustrates this observation and also shows the scatter at low normal stresses. The friction angle found in Figure 46 is in general agreement with the friction angle found for the break-bond test results ($\varphi = 51.7°$). This follows the same pattern as for the "All Data" data set and is consistent with the assumptions made for the Angle-Envelope Method (Reclamation, 1976).

Conclusions

Conventional concrete shear strength data appears to be very similar to the "All Data" data set, likely due to the "All Data" data set being primarily composed of conventional concrete data. The cohesion intercept for the break-bond testing is close to $0.1f'_c$ and the splitting tensile strength, although there is significant scatter in the data. The friction angle for the break-bond tests and the lower normal load sliding tests are in good agreement, as predicted by the Angle-Envelope Method (Reclamation, 1976).

RCC Lift Lines

Data from a number of projects where RCC lift lines were tested for both break-bond and sliding shear strength were collected and analyzed. For this data set, only specimens that were identified as lift lines from existing dams with no noted AAR were included (i.e. no parent concrete or research studies). Projects included in this data set were: Galesville Dam, Pajarito Dam, Theodore Roosevelt Dam (RCC placed on existing concrete), and Upper Stillwater Dam.

Compressive/Tensile Strength Property Correlations

Only one project (Upper Stillwater Dam) had ST, DT and UCS values to compare, and the only values for this project were averages from ACIS. The following relationships were determined for RCC lift lines from Upper Stillwater Dam:

Splitting Tensile Strength: $f_{st} = 0.1f'_c$ (9)

Direct Tensile Strength: $f_{dt} = 0.05f'_c$ (10)

Splitting Tensile to Direct Tensile: $f_{dt} = 0.5f_{st}$ (11)

Equations 9 through 11 show higher ratios of splitting and direct tensile strengths to the uniaxial compressive strength and a higher ratio of splitting tensile to direct tensile strength than found in the conventional concrete data set, but of similar magnitude to those noted in Curtis et al. (2017) and Reclamation (2005).

Break-Bond Strength Correlations

Break-bond strength data is presented in Figure 47 below for all RCC lift line specimens.

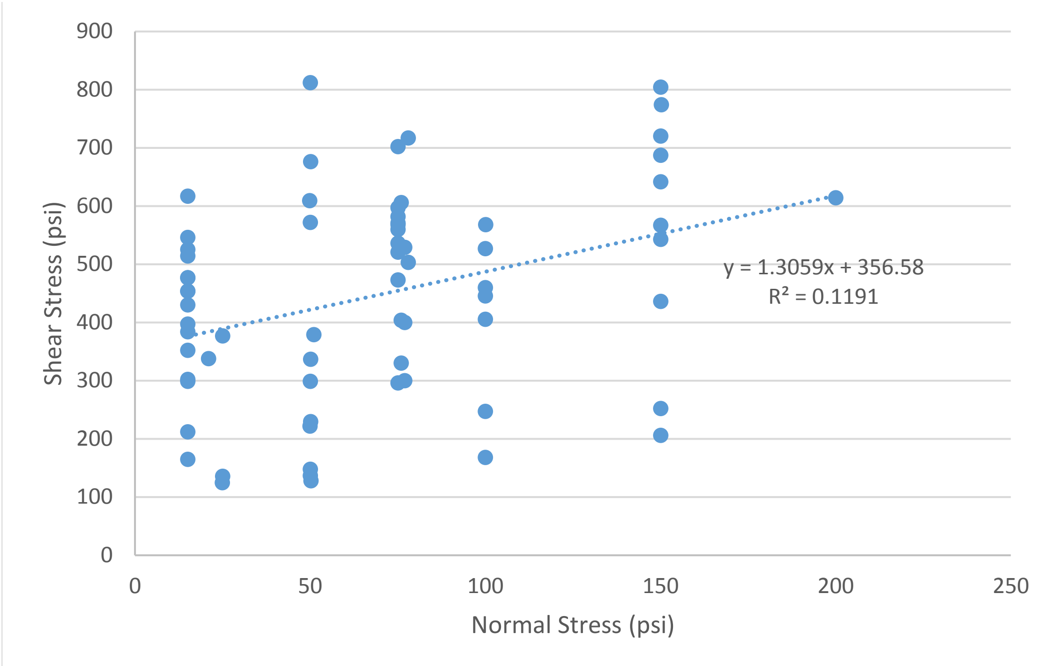

Figure 47 - RCC lift line break-bond shear strength. Average UCS = 4,014 psi, and average ST = 485 psi.

Figure 47 shows $\varphi = 52.6°$ and c = 357 psi. Note that $0.1f'_c$ and the splitting tensile strength are of a similar magnitude to the apparent cohesion, as was seen with data presented previously; although the linear regression does not fit the data well, as seen by the low R^2 value.

The break-bond shear stress at failure for RCC lift lines was normalized by the normal stress at failure to generate a stress ratio for each break-bond test. The stress ratio points for each break-bond test are then plotted against the UCS in the Figure 48.

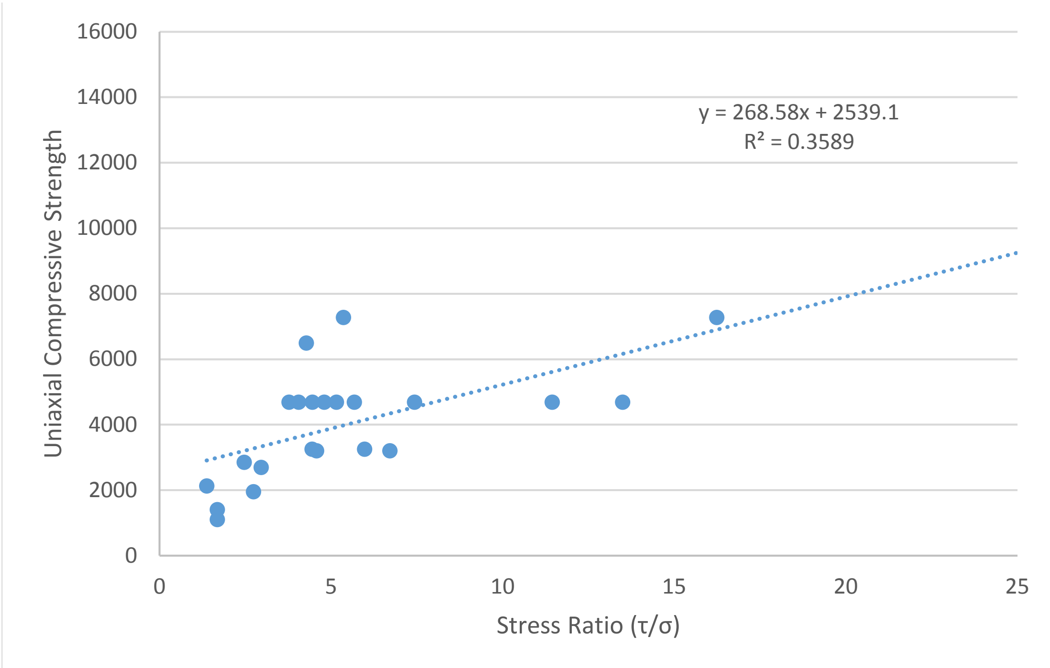

Figure 48 - RCC lift line break-bond. Uniaxial compressive strength versus stress ratio.

From Figure 48, it can be seen there is a weak correlation between UCS and strength ratio. This is likely due to most of the UCS test values coming from one project.

Sliding Friction Strength

Figure 49 presents all of the RCC sliding shear strengths plotted to determine a failure envelope.

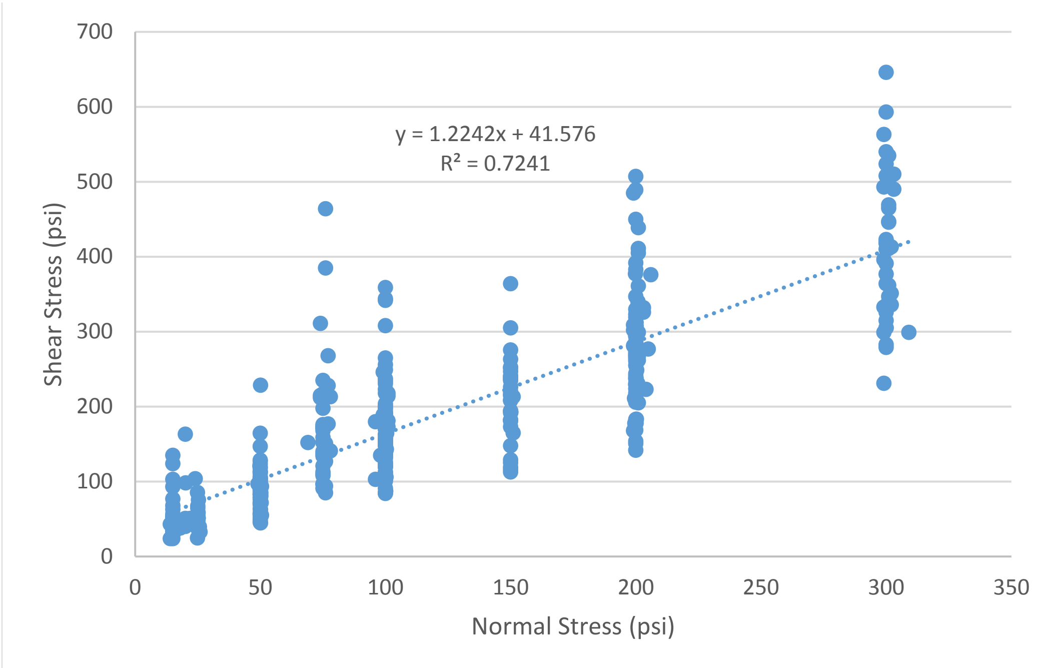

Figure 49 - RCC lift line sliding shear strength.

The sliding friction parameters for the best fit regression line in Figure 49 are φ = 50.8°, with c = 41.6 psi. The linear failure envelope parameters are in close agreement with those found for conventional concrete at similar normal stresses. The friction angles for the sliding tests and the break-bond tests are in good agreement, again confirming the assumptions made in the Angle-Envelope Method (Reclamation, 1976).

Conclusions

RCC lift line shear strength data appears to be similar to the "All Data" data set. The cohesion intercept for the break-bond testing is close to $0.1f'_c$ and the splitting tensile strength, although there is significant scatter in the data. The friction angle for the break-bond and the sliding tests are in good agreement, as predicted by the Angle-Envelope Method (Reclamation, 1976).

AAR Lift Lines

Data from concrete lift lines at a number of projects where AAR issues have been recognized were collected and analyzed. For this data set, only specimens that were identified as lift lines from existing dams were included (i.e. no parent concrete or research studies). Projects included in this data set were: Black Canyon Dam, Olympus Dam, Parker Dam, and Seminoe Dam.

Compressive/Tensile Strength Property Correlations

Figures 50 through 52 present strength property correlations for the concrete lift lines at dams with noted AAR issues.

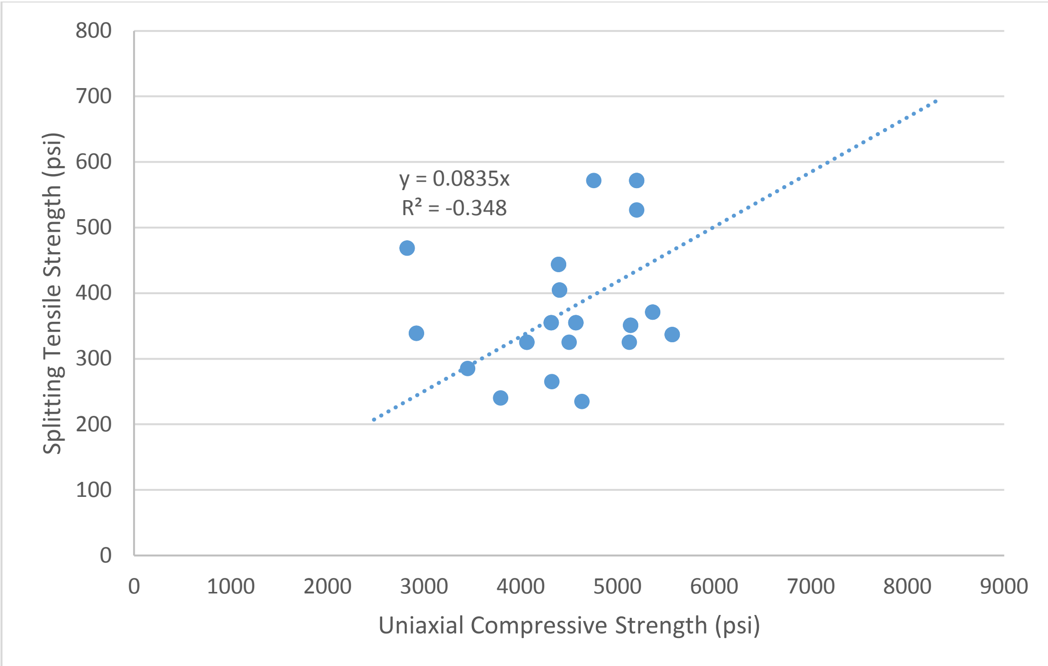

Figure 50 - Concrete lift lines with AAR issues. Splitting tensile versus uniaxial compressive strengths. The trend line is poor and likely not valid.

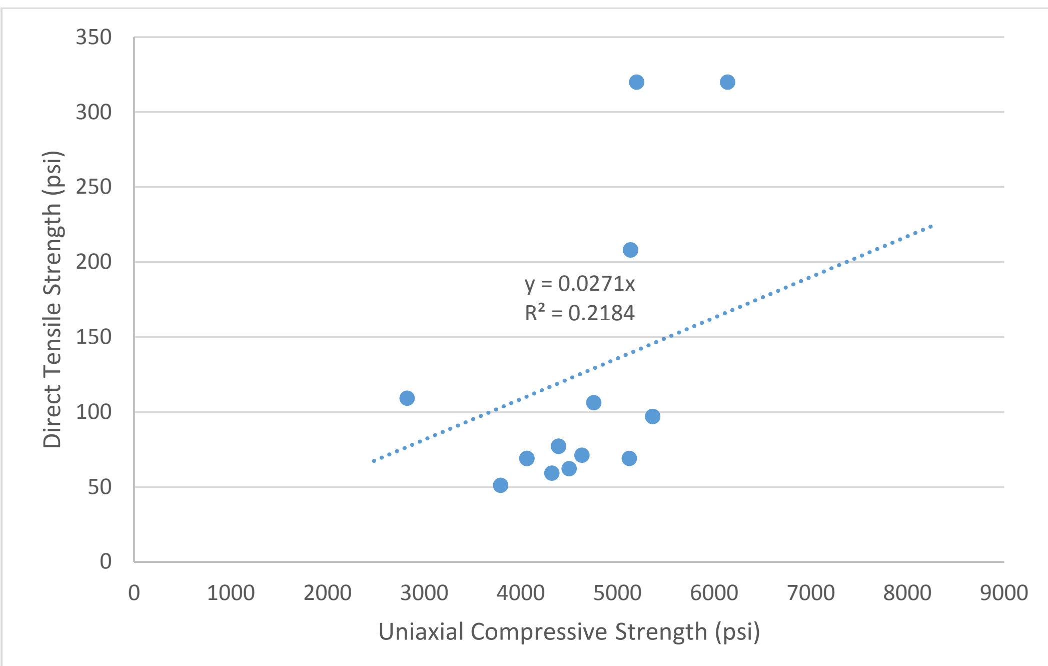

Figure 51 - Concrete lift lines with AAR issues. Direct tensile versus uniaxial compressive strength.

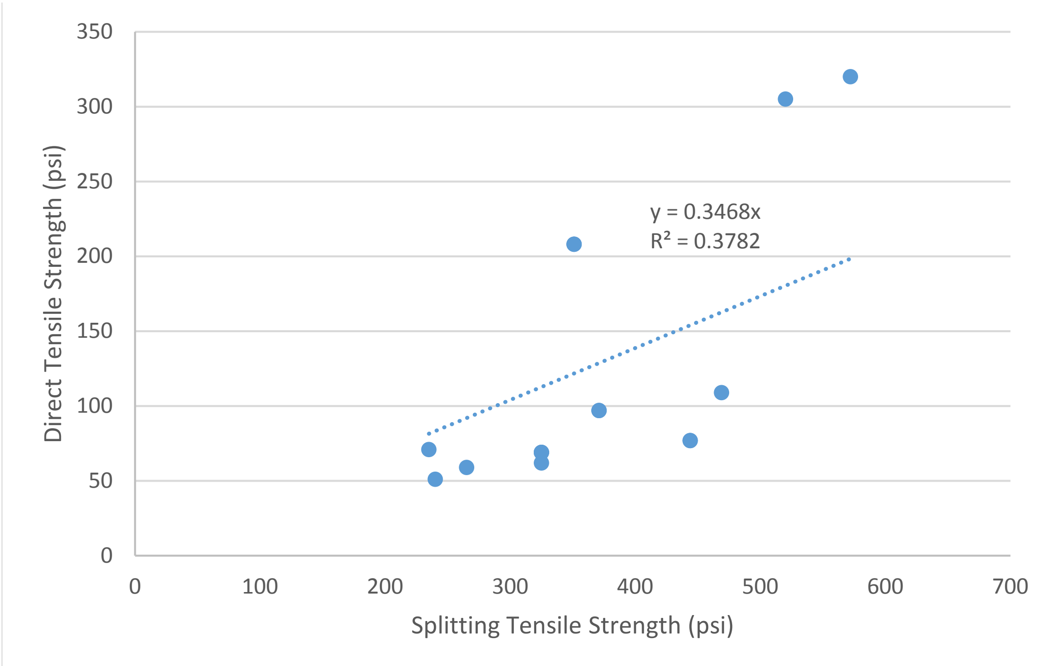

Figure 52 - Concrete lift lines with AAR issues. Direct tensile versus splitting tensile strength.

The following equations were determined concrete lift lines with AAR issues:

Splitting Tensile Strength: $f_{st} = 0.08f'_c$ (12)

Direct Tensile Strength: $f_{dt} = 0.03f'_c$ (13)

Splitting Tensile to Direct Tensile: $f_{dt} = 0.3f_{st}$ (14)

Equations 12 through 14 indicate lower direct tensile strengths relative to the uniaxial or splitting tensile strengths found in the previous data sets, or in Curtis et al. (2017) and Reclamation (2005). Equation 12 is based on a poor quality trend line, and may not be valid based on the R^2 value and visual appearance of fit through the data. This may be caused by AAR creating more fractures that coalesce more readily in tension, while the fractures are not as easily joined in compression.

Break-Bond Correlations

Break-bond strength data is presented in Figure 53, below, for all lift line specimens with AAR issues.

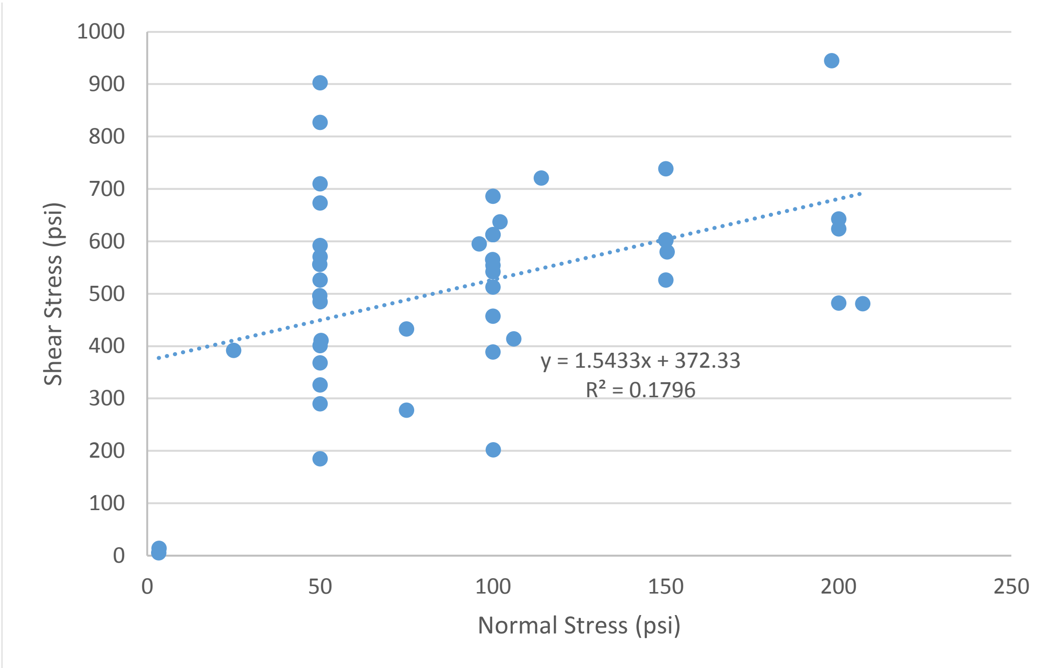

Figure 53 - Concrete lift lines with AAR issues, break-bond shear strength data. Average UCS = 4,196 psi and average ST = 389 psi.

Figure 53 shows φ = 51.1° and c = 372 psi. The friction angle for the break-bond testing in this data set is higher than any of the previous data sets, and higher than the average of all strength data. This may be a relic of most of the data coming from one project that may have used either larger aggregate or higher strength aggregate than other projects. A similar relationship between the apparent cohesion intercept, and the uniaxial and splitting tensile strengths noted in the previous data sets can be observed in Figure 53. Note the large amount of scatter in the data at a normal stress of 50 psi (shear strength ranging from about 185 to 900 psi).

The break-bond shear stress at failure for concrete lift lines with AAR issues was normalized by the normal stress at failure to generate a stress ratio for each break-bond test. The stress ratio points for each break-bond test are then plotted against ST, DT and UCS in the following figures.

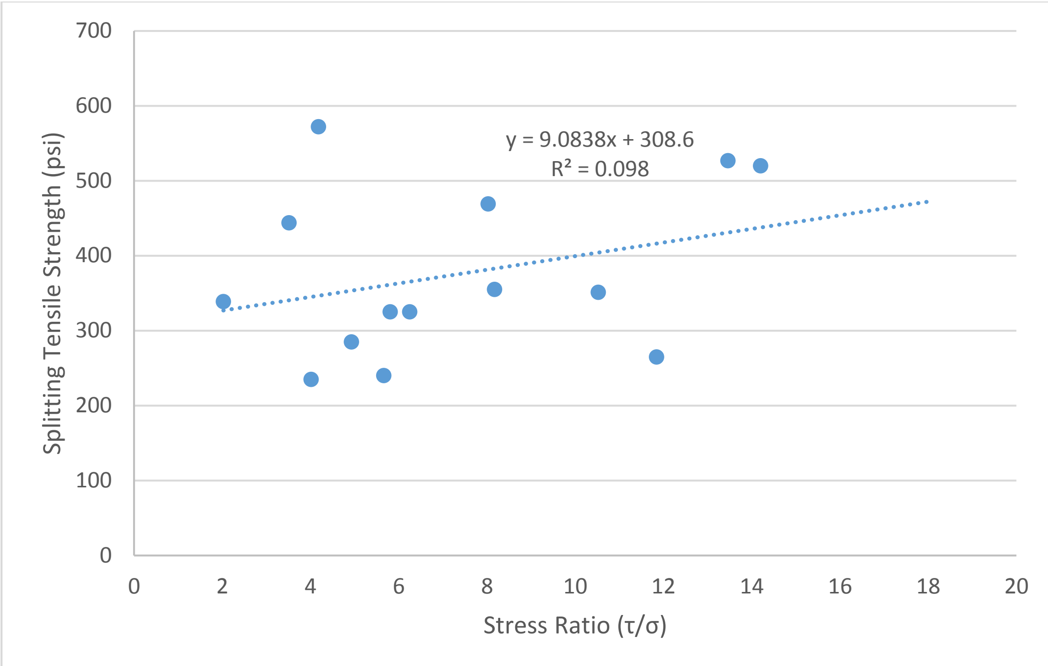

Figure 54 - Concrete lift lines with AAR issues break-bond. Splitting tensile strength versus stress ratio.

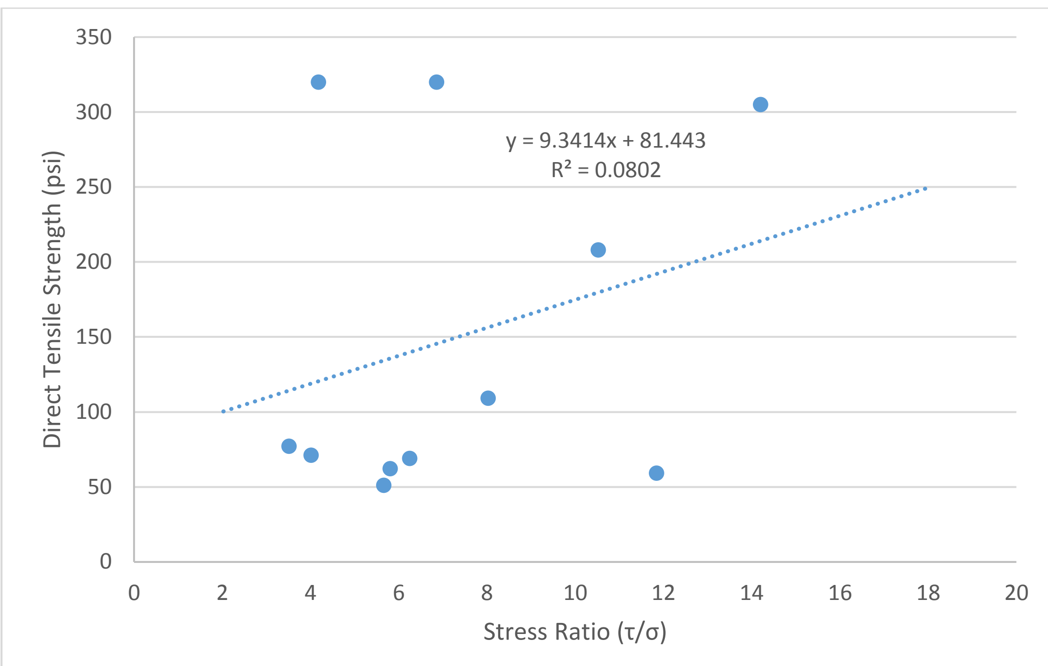

Figure 55 - Concrete lift lines with AAR issues break-bond. Direct tensile versus stress ratio.

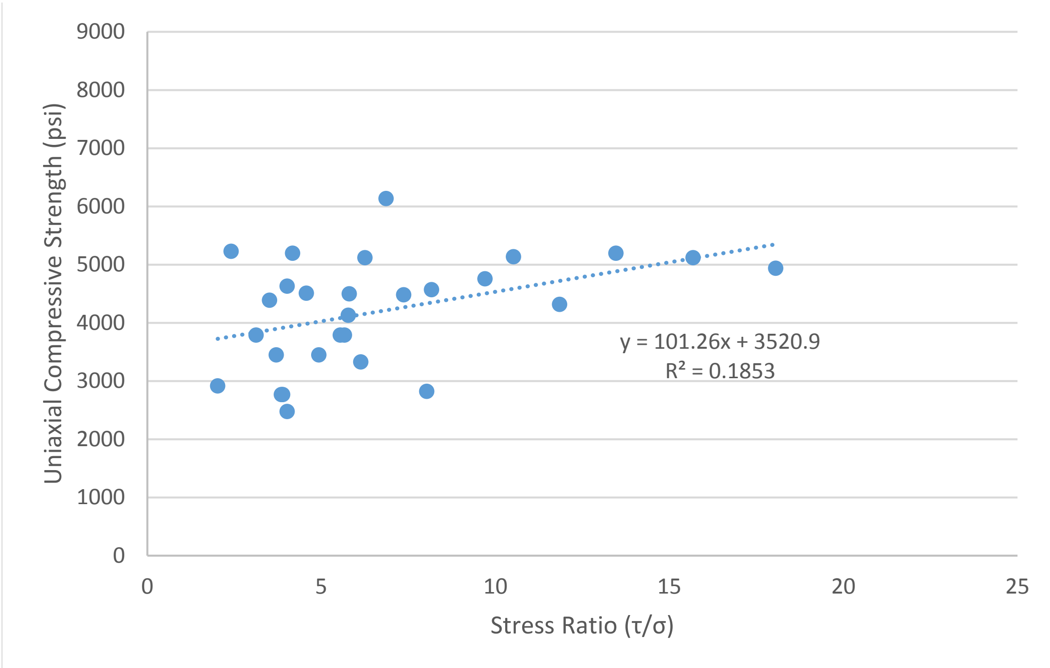

Figure 56 - Concrete lift lines with AAR issues break-bond. Uniaxial compressive strength versus stress ratio.

Figure 56 shows a weak correlation between UCS and stress ratio, while Figures 54 and 55 show little correlation.

Sliding Shear Strength

Sliding shear strength of all AAR lift line specimens is plotted in Figure 57, below.

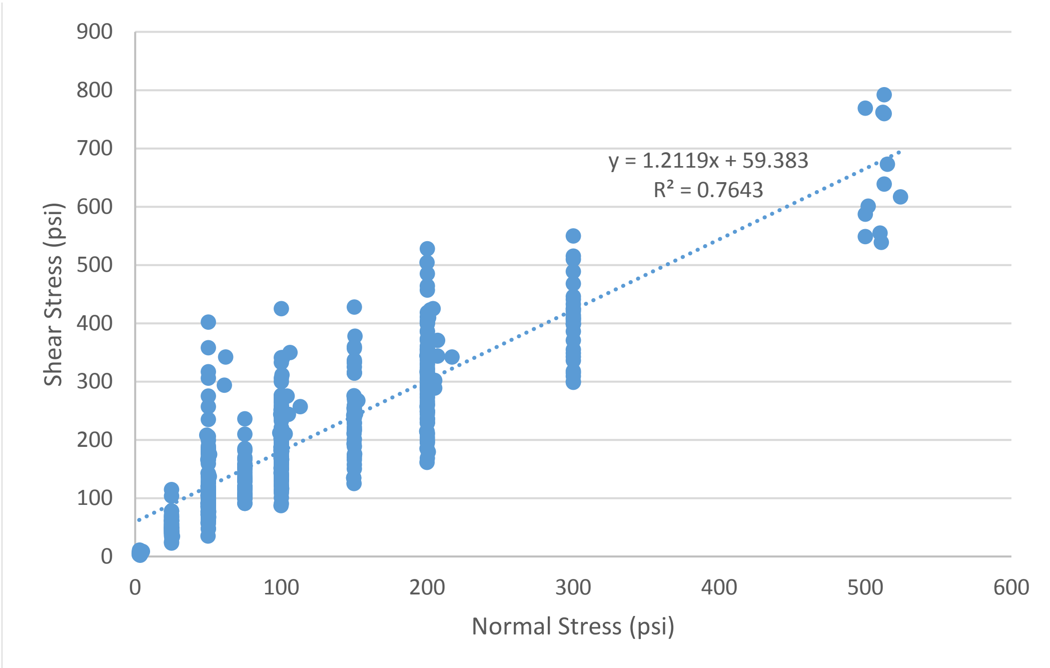

Figure 57 - Concrete lift lines with AAR issues, sliding shear strength data.

The linear failure envelope shown in Figure 57 indicates φ = 50.5°, and c = 59.4 psi. The friction value for sliding is in good agreement with that found for the break-bond tests, confirming the assumptions made for the Angle-Envelope Method (Reclamation, 1976).

Conclusions

The direct tensile strength of AAR concrete lift lines relative to splitting tensile or uniaxial compressive strength was lower than the other types of concrete. This may be a result of pre-existing fractures caused by the AAR. AAR lift line shear strength data has a slightly higher friction angle than the "All Data" data set, potentially due to most of the testing coming from one particular project. The cohesion intercept for the break-bond testing is close to $0.1f'_c$ and the splitting tensile strength, although there is significant scatter in the data. The friction angle for the break-bond and the sliding tests are in good agreement, as predicted by the Angle-Envelope Method (Reclamation, 1976).

Summary and Conclusions

While no clear correlation was found between any of the compressive/tensile and/or direct shear strength parameters, a number of trends could be noted. The ratios of splitting tensile: uniaxial compressive strength, direct tensile: uniaxial compressive strength, and splitting tensile: direct tensile were generally similar between all types of concrete (all data, conventional concrete lift lines, RCC lift lines and AAR lift lines) with only a few exceptions. The RCC lift lines tended to have higher splitting and direct tensile strengths relative to the compressive strength, and the AAR lift lines tended to have lower direct tensile strength relative to splitting tensile or uniaxial compressive strength.

For appraisal level design, the apparent cohesion intercept for break-bond can be approximated as either as 10% of the uniaxial compressive strength ($0.1f'_c$) or as the splitting tensile strength. The failure envelope for the break-bond strength can be approximated using the Angle-Envelope Method (Reclamation, 1976) with data from sliding friction tests. It should be noted that a great deal of uncertainty must be incorporated into a design using these relationships. It is the author's recommendation that for anything but appraisal level design, actual laboratory testing be performed at the anticipated normal stresses to develop a mix-specific understanding of direct shear strength. This same recommendation holds true for evaluations of existing structures.

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