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DETERMINATION OF IN-SITU COMPRESSIVE STRENGTH OF PRECAST CONCRETE GIRDERS

Final Report

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December 15, 2017

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Abstract

Verification of field compressive strength of precast concrete girders from 52 bridges in seven counties in California are presented. Non-destructive Testing (NDT) methods used are Proceq's Silver Schmidt Rebound Hammer and Ultrasonic Pulse Velocity (UPV) and James Instruments' Windsor Pin and Windsor Probe Systems. NDT tests were performed on concrete walls, slabs, and cylinders constructed under ambient and laboratory curing conditions at San Jose State University. Data from the laboratory testing in combination with data supplied by the manufacturer of the NDT equipment were utilized to develop strength prediction charts for the different bridge girders. Concrete cores from five selected bridges were taken, and compressive strength and NDT tests were performed and analyzed. Results obtained from the cores with the bridge prediction data were compared to verify accuracy of the predictions. The American Concrete Institute (ACI) 209 equation was utilized, and modified equations are proposed for more accurate bridge strength predictions.

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1.0 Problem Statement

Caltrans is seeking a way to verify field compressive strength of precast concrete girders from several bridges in the state of California. In-situ data will be used to obtain reliable estimates of concrete strengths needed to increase capacity recognition. Non-destructive Testing (NDT) methods and field core specimens will be utilized to evaluate the strength of the girders. Additionally, seismic/strengthening upgrades on bridges can be assessed more accurately with the field-testing data.

2.0 Executive Summary

This report summarizes tasks completed for the project “Determination of In-situ Compressive Strength of Precast Concrete Girders,” for the period 03/01/2016 to 12/31/2017.

52 bridges in seven counties in the state of California were selected in consultation with Caltrans. NDT methods were performed on the bridges, utilizing Proceq’s Silver Schmidt Rebound Hammer, Proceq’s Ultrasonic Pulse Velocity (UPV), James Instruments’ Windsor Pin Penetration System, and James Instruments’ Windsor Probe System to determine their compressive strength.

Concrete cylinders (6x12 in.), slabs (24x18x4 in. and 24x18x8 in.), and retaining walls (9 ft wide x 6 ft height x 8 in. thickness) were constructed at San Jose State University to calibrate the NDT equipment. The data collected from all the laboratory testing in combination with data supplied by the manufacturer of the NDT equipment were utilized to develop strength prediction charts for the different bridge girders. The specimens were cured under three different environments: engineering courtyard at ambient temperature, engineering structural laboratory at a controlled temperature of 71°F, and the concrete laboratory curing chamber at 71°F, and 100% relative humidity (RH). The specimens were periodically tested up to 180 days using the Silver Schmidt Rebound Hammer, UPV, Windsor Pin Penetration, and Windsor Probe to determine their compressive strength. Concrete cylinders (4x8 in. and 6x12 in.) and cores (3.75x8 in.) taken from concrete slabs were tested for their compressive strength.

Concrete cores from five selected bridges in Santa Clara County and San Bernardino County were taken, and compressive strength and NDT tests were performed and analyzed. Results obtained from the cores with the bridge prediction data were compared to verify accuracy of the predictions. The ACI 209 equation was utilized to check the accuracy of the strength predictions. Modifications to the ACI 209 equation are proposed for more accurate bridge strength predictions.

3.0 Literature Review

3.1 Ultrasonic Pulse Velocity Test

The UPV involves the measure of travel time of an ultrasonic pulse to pass through a known distance of concrete. This method is applied to determine the relative condition of concrete based on measured pulse velocity.

Unruh [1] states that there is currently no reliable nondestructive method for determining the strength of concrete. However, ultrasonic pulse velocity and rebound hammer are two methods that shown to be promising in estimating compressive strength.

Although the UPV test measures critical characteristics over the service life of a structure, there are a number of factors and conditions that can affect the accuracy of the results. The paper by Lorenzi [2] suggests the use of artificial neural networks as an easier, more accurate method of estimating concrete characteristics, density and compressive strength.

Trtnik [3] states that although the UPV method is used to assess concrete properties, it is very difficult to accurately evaluate the concrete compressive strength with this method since the ultrasonic pulse velocity values are affected by a number of factors, which do not necessarily influence the concrete compressive strength in the same way or to the same extent. These factors include the influence of aggregate, initial concrete temperature, type of cement, environmental temperature, and water to cement ratio. Artificial neural network modeling the velocity-strength relationship provides a more reliable estimate of the compressive strength of concrete by using only the ultrasonic pulse velocity value and some mix parameters of concrete.

Impact echo and ultrasonic pulse velocity tests were performed in investigating quality assurance of the repair done on an I-beam bridge girder on a concrete bridge located east of Interstate 70, east of Denver, Colorado. Promboon [4] preliminarily used impact echo to detect internal cracks at each test point. Then, once an internal crack was detected, the ultrasonic pulse velocity test with angular paths were performed to provide more information on the location and extent of the unfilled cracks. With a combination of both methods, concrete conditions can be rated on a more precise and accurate level, with more confidence.

Compressive strength cannot be assessed solely from the performance of the ultrasonic pulse velocity test due to the fact that too many factors affect the ultrasonic pulse velocity measurement. Some of these factors include moisture content, temperature of concrete, path length, shape and size of specimen, and effect of reinforcing bars. Combining the use of rebound hammer and the ultrasonic pulse velocity method can better predict the compressive strength of concrete [5].

In a study by Huang [6], when combining the rebound hammer and the ultrasonic pulse velocity methods, regression models are used to predict the compressive strength of the concrete. However, the available regression models are not sufficiently valid due to the limited range of data used for their calibration. This paper proposes a probabilistic multivariable linear regression model to predict the compressive strength using the measurements obtained from the combination of both methods and additional concrete properties.

In a study by Lin [7], the ultrasonic pulse velocity measurement and compressive strength tests were carried out at the concrete age of 1, 3, 7, 14, and 28 days for concrete specimens with different water-cement ratios and coarse aggregate content by weight. A clear relationship curve was drawn, verifying that is it suitable to predict concrete strength from the ultrasonic pulse velocity values.

3.2 Pull-out Test

The pull out test is based on the principle that the force required to pull out a cone of steel embedded in concrete is proportional to the strength of concrete.

As a result of much research throughout the past 30 years by many countries, such as Russia, the US, Canada and Denmark, it was discovered that there is a linear relationship between the pullout force and the compressive strength. Because of its usefulness, many countries have standardized the pullout test [8].

Various NDT tests were investigated to determine the best method to give the compressive strength of cores. The highest degree of correlation is for the pullout test followed by that for the CAPO (cut and pullout) test and rebound test, probe penetration test, and pulse velocity test [9].

The paper by Bishr [10] reports the results of a study carried out to estimate the accuracy and reliability of the pullout test for assessment of the in-situ compressive strength of concrete made with three water-cement ratios, two cement contents and two different types of aggregates. The compressive strength of both cast and cored cylindrical specimens was statistically correlated with the pullout force. It can be concluded that the linear relationship between the compressive strength and the pullout force was very significant and totally independent of the mixture design variables. There is a high potential of the pullout test to determine the compressive strength of concrete with a high degree of reliability.

3.3 Silver Schmidt Rebound Hammer Test

The Silver Schmidt Rebound Hammer Test involves a rebound hammer being pressed against the surface of a concrete structure. Thereafter, the hammer will read back the rebound number or index along a graduated scale, which assesses the surface hardness. The surface hardness is correlated with the compressive strength of the concrete. This correlation can be displayed graphically.

From studies undertaken in Australia and Scotland, it would appear that the combination of performing both the rebound hammer and ultrasonic pulse velocities tests, the confidence in estimating the strength of in-situ concrete is much higher [11].

The experimental investigation by Jaggerwal [12] showed that a good co-relation exists between compressive strength and rebound numbers/ index. As long as non-destructive testing is performed periodically and consistently on the same girder of a bridge, the confidence level of the compressive strength of that structure is much higher. A combination of multiple non-destructive tests helps further assess the strength and durability. The results of this experiment verified that there is a strong co-relation between compressive strength and the rebound hammer. Nevertheless, rebound hammer could be used alone to determine the compressive strength of the structures.

The nondestructive tests, rebound hammer, pulse velocity and core tests, were compared by Henao [13] in terms of correction factors for estimating compressive strength and the effect of variables, such as casting direction, sample location, core diameter, core moisture conditions, concrete strength, and congested reinforcement. The findings revealed significant differences in the way some of these variables and correction factors for estimating strength affect the strength measurements.

3.4 Windsor Probe Test

The Windsor probe simulates a gun where a plug, resembling a bullet, is fired into the concrete and the distance into which the plug penetrates into the concrete is measured and correlated to the compressive strength of concrete.

After evaluating the use of the Windsor probe test on thirteen mixes with strength varying between 2240 and 18,820 psi, it was found that the Windsor probe test is capable of predicting the in situ compressive strength of normal and high strength concrete up to 17,080 psi [14].

3.5 Windsor Pin Penetration Test

The Windsor pin penetration test involves a spring loaded hammer that drives a small pin into a concrete surface and the depth the pin penetrates is correlated with the compressive strength of the concrete.

The paper by Masoumi [15] discusses visual inspections of 200 reinforced concrete bridges in Turkey and non-destructive testing applications performed on 10 bridges, which were most deficient. Penetration resistance, ultrasonic pulse velocity, rebar locator and reinforcement corrosion tests are performed on different elements of reinforced concrete bridges and the results are compared with the results of visual inspections. Almost perfect correlations are observed between results of nondestructive tests and condition states based on visual inspections. The Windsor pin test is applied 45 times on different bridge elements of 10 existing bridges. There is a good correlation between Windsor pin results and condition states which are obtained based on visual inspections.

After testing for compressive strength using the nail penetration method on 18 different concrete mixtures, the measured compressive strength values were compared to other NDT techniques; including Schmidt rebound hammer, ultrasonic pulse velocity, and Windsor probe. Selcuk [16] found that the nail penetration test can reliably estimate the compressive strength of a wide range of in-place concrete.

The pin penetration test was used to relate the early age strength of hardened concrete and mortar in the laboratory. It was found that the pin penetration tester can be used successfully, under laboratory conditions, to determine the compressive strength of concrete cylinders and mortar slabs at early age from 10 hours up to 28 days. For concrete and mortar cylinders, slabs and cubes with a compressive strength of up to 27.6 MPa (4000 psi), the pin penetration test readings were found to be linearly related to the compressive strength [17].

3.6 Impact Echo Test

The Impact Echo Test is based on the use of impact-generated stress (sound) waves that propagate through concrete and are reflected by internal flaws and external surfaces. Impact-echo can be used to determine the location and extent of flaws such as cracks.

In a study by Pessiki [18], the use of the impact-echo method to nondestructively estimate the in-place strength of concrete is more appropriately limited to the estimation of early-age strength. Operating experience with the impact-echo technique by Limaye [19] has shown that, within known limitations, the technique can provide a rapid nondestructive means for performing certain concrete condition surveys.

Impact-echo testing was performed by Tinkey [20] on the webs of two box girders with different amounts of deterioration. Because the P-wave peaks are determined by the persons performing the impact-echo test, the results come out to be biased. This method can be improved by coming up with and following a certain reliable standard that chooses the P-wave peaks to test. A more standard procedure for impact-echo testing should be further researched before implementation, since the test is subjective.

3.7 Selected NDT tests

After evaluating the six NDT tests, it was decided to use the following tests:
1. Silver Schmidt Rebound Hammer
2. Ultrasonic Pulse Velocity
3. Windsor Pin Penetration
4. Windsor Probe

The pull-out test was evaluated; however, it is not practical to use for bridge girders evaluation because of height accessibility limitations. The impact echo test was considered, however, it is not a proven method to determine in-situ compressive strength.

4.0 Description of Tasks

In situ NDT tests were performed on 52 bridge girders in Contra Costa County, Fresno County, Los Angeles County, Placer County, San Bernardino County, Santa Clara County, and Ventura County. Table 4 shows the number of bridge girders tested in each county. Four NDT tests that were performed to accurately calibrate for the concrete strength of the bridge girders were Proceq’s Silver Schmidt Rebound Hammer, Proceq’s Ultrasonic Pulse Velocity (UPV), James Instruments’ Windsor Pin Penetration System, and James Instruments’ Windsor Probe System.

A concrete mix was supplied by Star Concrete to cast a variety of specimens at San Jose State University. Table 1 shows the mix design used. Specimens constructed were concrete cylinders (6x12 in.), slabs (24x18x4 in. and 24x18x8 in.), and retaining walls (9 ft wide x 6 ft height x 8 in. thickness). 4x8 in. cores were taken from the 24x18x8 in. slabs, while NDT tests were performed on the 24x18x4 in. slabs, retaining walls, and cylinders.

Table 2 lists all the specimens on which the Silver Schmidt Rebound Hammer, UPV, Windsor Pin Penetration, and Windsor Probe tests were performed. Specimens in three Groups A, B, and C were cast and cured with different environmental conditions: Group A was cured at the SJSU building courtyard at ambient temperature, Group B was cured at the SJSU engineering structural laboratory at a controlled temperature of 71°F, and Group C was cured in the SJSU concrete laboratory at 71°F, and 100% relative humidity (RH).

Table 3 shows the frequency at which the NDT tests were performed. The collected data from all the specimens in Groups A, B, and C were combined with data supplied by the manufacturer of the NDT equipment to generate calibration charts for estimating the compressive strengths of the bridge girders.

Core samples were taken on three bridges in Santa Clara County and two bridges in San Bernardino County. Table 5 shows the schedule for taking cores on the five bridges. Compressive strength and NDT tests were performed on the core specimens to verify the NDT bridge compressive strength predictions.

To check the accuracy of the strength predictions, the existing ACI 209 equation was utilized. The equation will be described in Section 6.0.

5.0 Test Results for Laboratory Specimens, Calibration Charts for Bridges, and Core Specimens

Compression tests were performed over a period of 180 days on the 6x12 in. cylinders, 4x8 in. cylinders in Groups A, B, and C and 3.75x8 in. cores taken from the slabs in Groups A and C. NDT tests performed on all the cylinders, slabs, and walls were the Silver Schmidt Rebound Hammer, UPV, Windsor Pin Penetration, and Windsor Probe tests. Charts were developed for strength predictions for the Silver Schmidt Rebound Hammer, UPV, Windsor Pin Penetration, and Windsor Probe systems using the data collected from the laboratory testing and data supplied by the manufacturer for the NDT equipment.

5.1 Compressive Strength Test Results

Appendix A contains all compressive strength test results that were performed in accordance with ASTM C-39. Table A-1 contains the compression results for the 6x12 in. cylinders. Table A-2 contains the compression test results for the 4x8 in. cylinders. Outliers marked with the asterisk "*" were ignored when calculating the average compressive strength.

Figures A-1 and A-2 show the ratio between the strength of the 6x12 in. cylinders to the 4x8 in. cylinders. Figure A-3 shows the strength versus age of each tested cylinder in all three groups, while Figure A-4 shows the average strength versus age for each group. At 180 days, all cylinders had an average compressive strength ranging from 6,700 psi to 7,800 psi.

Table A-3 compares the average cylinder strengths to the core cylinder strength obtained from the slabs. The data from Table A-3 is also plotted in Figure A-5. In general, the 6x12 in. cylinders had a higher strength than the cores and 4x8 in. cylinders.

All strength data from this section in combination with data supplied by the manufacturer of the NDT equipment were utilized to develop strength prediction charts.

5.2 Rebound Hammer Test Results

Appendix B contains readings on cylinders (6x12 in.), slabs, and retaining walls obtained from the Proceq Silver Schmidt Rebound Hammer. Tables B-1 to B-3 contain the Rebound hammer test results from the cylinders, slabs, and retaining walls for Group A. Tables B-4 to B-6 contain the Rebound hammer results for cylinders, slabs, and the retaining wall for Group B. Tables B-7 and B-8 contain the Rebound hammer readings taken for cylinders and the slab in Group C. The data for the cylinders in Tables B-1, B-4, and B-7 were adjusted using the cylinder form factor (0.8) found in the Silver Schmidt Rebound Hammer user manual. Figures B-1 to B-8 show plots of the compressive strength versus the Rebound numbers for all tested specimens in all three groups with data provided by the Silver Schmidt Manufacturer Proceq. The Rebound values (Q) steadily increased for all plotted data in the range from 28 (Q) to 53 (Q), where the "Q"-value equals the rebound velocity divided by inbound velocity, which represents the physical rebound coefficient.

5.3 Ultrasonic Pulse Velocity Test Results

Appendix C contains readings on cylinders (6x12 in.), slabs, and retaining walls obtained from the Ultrasonic Pulse Velocity (UPV) tests. The tests were performed utilizing the Proceq Pundit 200 PL device. Tables C-1 to C-3 contain the UPV test results from the cylinders, slabs, and retaining walls for Group A. Tables C-4 to C-6 contain the UPV results for cylinders, slabs, and the retaining walls for Group B. Tables C-7 and C-8 contain the UPV readings taken for cylinders and the slab in Croup C.

The data from Tables C-1 to C-8 with the data provided by the manufacturer to aid in the estimation of the compressive strength are plotted in Figures C-1 to C-8. The UPV test results exponentially increased as compressive strength increased. The UPV values ranged from 14,000 ft/s to 16,400 ft/s.

5.4 Windsor Pin Penetration Test Results

Appendix D contains all the data gathered when performing Pin Penetration test using the James Instruments Windsor Pin Test System. The micrometer used to measure the depth of each pin penetration measures the exposed length of the pin. The readings were taken on cylinders (6x12 in.), slabs, and retaining walls in three groups. Tables D-1 to D-3 contain the pin penetration test results from the cylinders, slabs, and retaining walls for Group A. Tables D-4 to D-6 contain the pin penetration test results for cylinders, slabs, and retaining wall for Group B. Tables D-7 and D-8 contain the pin penetration test results taken from the cylinders and slab in Group C.

The data from Tables D-1 to D-8 with the corresponding compressive strength values obtained from the cylinders, slabs, and retaining walls are plotted in Figures D-1 to D-8. The trend for each of the set of results showed an increase in pin readings with time. After 180 days, the exposed pin readings ranged from 823×10^{-3} in. to 857×10^{-3} in. Results for the exposed pin readings for a given specimen at a given age often deviated by 3×10^{-3} in.

5.5 Windsor Probe Test Results

Appendix E contains the data gathered when performing the Windsor Probe test on the retaining walls cured in Groups A and B. The Windsor probe test measures the length of exposed probe after it has been embedded in the concrete.

Tables E-1 and E-2 contain the exposed probe and compressive strength for both retaining walls. Figure E-1 shows the exposed probe length (in.) versus specimen age in days, while Figure E-2 shows the average exposed probe length versus specimen age in days. Figure E-3 shows the relationship between time versus the compressive strength. Figures E-4 to E-6 show the relationship between exposed probe length (in.) and the compressive strength (psi) from the Windsor Probe Standard power table provided by James Instruments. Using the Windsor Probe Test, the compressive strength for the retaining walls A and B were both in the range of 5,900-6,400 psi. These compressive strength values are lower than those obtained from testing the 6x12 in. cylinders at the same age.

5.6 Strength Predictions for Bridges

Appendix F contains charts developed for strength predictions for the Silver Schmidt Rebound Hammer, the UPV, the Windsor Pin, and the Windsor Probe system. Data obtained from the laboratory testing in combination with the data supplied by the manufacturer for the NDT equipment were combined and utilized for strength prediction.

Figures F-1 to F-4 contain the charts showing equations from the Proceq's data, SJSU data, and their combination. Tables F-1 to F-7 contain strength predictions for all seven counties using the combined equation from the charts. The combined equations were used for all equipment, except for the Windsor Pin predictions. As shown in the tables, predicted UPV compressive strength data were in some cases below the design strength, as noted by "*". It is not clear why this problem occurs, however, it may be related to the reinforcement bar layout in the structure; even after bar scanning was performed. Therefore, UPV will not be included in the Mean strength calculations or in the Standard Deviation calculations, as noted by "**".

5.7 Core Samples

Core specimens were taken on selected bridges from two counties to further verify the accuracy of the compressive strength predictions made from the Silver Schmidt Rebound Hammer, UPV, Windsor Pin, and Windsor Probe Systems. Table 5 shows the list of selected bridges utilized. Tables F-8 to F-10 contain the compressive strength of core samples taken from three bridges in Santa Clara County. Tables F-11 and F-12 contain the compressive strength of core samples taken from two bridges in San Bernardino County. The percentage between parenthesis next to the compressive strength values for the core and all the NDT equipment predictions represent the percentage increase or decrease from the NDT bridge prediction. The percentage between parenthesis under the compressive strength values for the core and all the NDT equipment predictions represent the percent increase or decrease of the core from the individual equipment predictions.

A summary of the core specimen results is given in Table F-13. The table shows that the ratio of the average percent increase in strength of the bridge over the percent increase of the core was 1.30. Therefore, 70 percent of the predicted bridge NDT strength was calculated to make more realistic predictions, as seen in the far right column on Table F-13. Table F-14 shows the bridge NDT compressive strength predictions and their standard deviations of σ-2StDev, σ-StDev, σ+StDev, and σ+2StDev. Table F-14 shows that the average core compressive strengths fall between σ-StDev and σ+StDev of the averaged NDT compressive strength prediction. The UPV prediction results were below the design strength and they were excluded from the average. The UPV compressive strength values on the cores were more realistic than the predictions on the bridges, which mean the reinforcing strands may have some influence on the final value of the UPV prediction.

6.0 ACI 209 Equation and Modified Equations

In order to predict the strength of the bridges, the ACI 209 equation [21] was utilized to check the accuracy of the strength predictions over time for the bridge girders.

Figure F-5 shows the age ranges for the different bridges and the correlating percent increase in their design strength as predicted by the NDT tests. It can be observed that bridges around 10 years old showed at least 20 percent increase from their design compressive strength, and bridges around 50 years old showed at least 40 percent increase from their design compressive strength. A proposed equation, shown below, from ACI Committee 209 to predict compressive strength over time for concrete made with Type I cement and cured at 70°F was used to make strength predictions for the bridges:

= Compressive strength prediction
= Design strength of the bridge
t = Time in days

Figure F-6 shows the comparison of strength prediction versus age between 70%NDT and the ACI 209 equation. It can be observed that the ACI 209 equation is more accurate in predicting bridge strength older than 50 years, but not for younger bridges, where the strength predictions were over estimated.

After calibrating the data, the following two modified equations were proposed. The first modified equation was utilized to predict compressive strength of bridges younger than 15 years, while the other modified equation was utilized to predict compressive strength of bridges older than 15 years. The modified equations can be summarized as follows:

For bridges younger than 15 years:

For bridges older than 15 years:

This equation is based on limited data points for the ages between 15 to 50 years.

Figure F-7 shows the compressive strength predictions versus age from both modified equations. The equations were compared with the 70%NDT predicted compressive strength values. It can be observed that the compressive strength values obtained from the 70%NDT gives a better correlation with the modified equation predictions.

Figure F-8 shows the percent increase or decrease between the ACI 209 equation and the 70%NDT predictions, while Figure F-9 shows a similar comparison, but utilizing the modified ACI 209 equations. The values from Figures F-8 and F-9 were compared in Tables F-15 and F-16.

Table F-15 shows the percent increase or decrease of the ACI 209 equation compressive strength predictions from the 70%NDT strength predictions. The positive percentage represent an over estimation prediction while the negative percentage represents an under estimation prediction. The average percent for all the bridges at all ages was -1 percent, average for bridges younger than 15 years was 32 percent, average for bridges older than 15 years was -3 percent, and average for bridges older than 50 years was 1 percent. The 32 percent average over estimation for bridges younger than 15 years confirms that the ACI 209 equation is not the best choice to use for younger bridges. On the other hand, the 1 percent average over estimation for bridges over 50 years shows that the ACI 209 equation is useful for predicting compressive strength for older bridges.

Table F-16 shows the percent increase or decrease of the modified ACI 209 equation compressive strength predictions from the 70%NDT strength predictions. The average percent for all the bridges at all ages was 1 percent, average for bridges younger than 15 years was 6 percent, average for bridges older than 15 years was 2 percent, and average for bridges older than 50 years was 6 percent. The 2 percent average over estimation for bridges over 15 years confirms that the modified ACI 209 equation is a better choice to use for bridges older than 15 years. The

6 percent average over estimation for bridges younger than 15 years shows that the modified ACI 209 equation is also a better choice to use for younger bridges.

Finally, Table F-17 shows the summary percentage values from Tables F-15 and F-16. The table shows that the ACI 209 equation can give a good compressive strength prediction for bridges older than 50 years. On the other hand, the modified ACI 209 equations can be a better choice for predicting compressive strength for bridges at all ages. There was limited data to evaluate bridges between 15 and 50 years old, and therefore, the modified ACI 209 equations can be further improved if data are available for this age range.

7.0 Conclusions

The following conclusions can be made from this study:

(1) In several cases, the UPV prediction results were below the design strength. Therefore, they were excluded from the analysis.

(2) Core compressive strength values of the cores taken from five selected bridges fell between mean-StDev and mean+StDev of the predicted averaged NDT bridge values, excluding the UPV.

(3) The Windsor Probe strength prediction was typically higher than those strengths obtained from the Silver Schmidt and Windsor Pin predictions on the bridges.

(4) The percentage increase in strength of the bridges can be better predicted with core compressive strength values when taking 70% of the averaged compressive strength predictions obtained from the Silver Schmidt, Windsor Probe, and Windsor Pin tests.

(5) In-situ precast concrete girders that were approximately 10 years old exhibited at least 20% increase in their design compressive strength.

(6) In-situ precast concrete girders that were approximately 50 years old exhibited at least 40% increase from their design compressive strength.

(7) The following modified equations are proposed for bridge compressive strength predictions:

Modified ACI 209 Equations		Younger than 15 years
		Older than 15 years

(8) Caltrans is seeking a way to verify field compressive strength of precast concrete girders from several bridges in the state of California. In-situ testing data and modified prediction equations, obtained from this study, will help Caltrans to reliably estimate the concrete strength needed to increase capacity recognition of the bridges. Additionally, seismic/strengthening upgrades on bridges can be assessed more accurately with the field-testing data provided.

Table 1: Ready Mix Design Ordered from Star Concrete

STAR — Ready Mixed Concrete — Quality Concrete

San Jose Plant • 1404 So. 7th St., San Jose, CA 95112

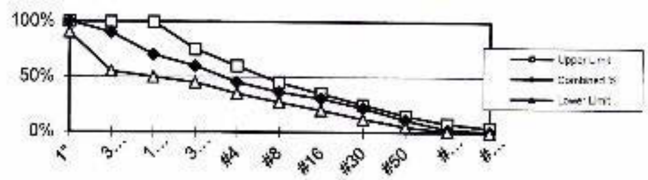
Ph: (408) 947-0669 • Fax: (408) 947-0434

Contractor:	San Jose State	**Concrete Mix Design:**	10.2 sk 1/2"
Project:		**Mix Design Number:**	10212WR
		Date:	9/14/2016
Use :	High Strength		
Plant:	San Jose, CA		

Mechanical analyses percent passing U.S. standard sieves

Sieve	11/2"	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
1" x #4	100%	100%	82%	46%	27%	1%	0%	0%	0%	0%	0%	0%
Concrete Sand	100%	100%	100%	100%	100%	99%	81%	68%	49%	25%	6%	2%
Combined	100%	100%	90%	70%	60%	45%	36%	31%	22%	11%	3%	1%

Sack Content:	10.20 sk equiv.
Specified Strength:	High Strength
W/Cm Ratio:	0.34
Slump:	4.00 +/-1"
Cement Type:	Type II/V



Material		Specific Gravity	Density lb/ft³.	S.S.D. Weight	Vol. ft³
1/2" X #4	60.0%	2.88	179.71	1752 lb	9.75
Concrete Sand	40.0%	2.78	173.47	1128 lb	6.50
Cement, Type II/V	89%	3.15	196.56	853 lb	4.34
Slag, 120 Grade	0%	2.92	182.21	0 lb	0.00
Pozzolan, Class F Ash	11%	2.32	144.77	105 lb	0.73
39.5 Gallons Water		1.00	62.40	329 lb	5.27
Entrapped Air	1.5%				0.41
322N				31 oz/yd	
Admix 2				0.0 oz/yd	
Admix 3				0 oz/yd	
Total	Unit Weight =	154.4 pcf		4168 lb	27.00

Table 2: List of Specimens Tested

Specimen	Group A (Courtyard)	Group B (Lab)	Group C (Humidity Room)	Total Quantity
Retaining Wall	1	1	0	2
6x12 in. Cylinders	36	36	36	108
4x8 in. Cylinders	36	36	36	108
24x18x4 in. Slabs	3	3	3	9
24x18x8 in. Slabs	1	1	1	3

Table 3: NDT Testing Schedule

Date	Concrete Age (days)
10/18/2016	1
10/20/2016	3
10/24/2016	7
10/31/2016	14
11/7/2016	21
11/14/2016	28
11/21/2016	35
11/28/2016	42
12/12/2016	56
1/15/2017	90
2/14/2017	120
4/15/2017	180

Table 4: NDT Tests Performed on Bridges in Seven Counties

County	Number of Bridge Girders Tested	Number of Cores Taken
Contra Costa	7	-
Fresno	6	-
Los Angeles	8	-
Placer	7	-
San Bernardino	8	4 – (Two Bridges)
Santa Clara	9	6 – (Three Bridges)
Ventura	7	-
	Total = 52	Total = 10

Table 5: Core Samples Schedule

Date	Bridge No.	County
6/1/2017	37C0031	Santa Clara
6/13/2017	37 0218	Santa Clara
6/21/2017	37 0149	Santa Clara
7/27/2017	54 1277L	San Bernardino
7/27/2017	54 1278R	San Bernardino

Appendix A

Compression Test Results for Cylinders and Cores

Table A-1: 6x12 in. Cylinder Compression Strengths

	Group A 6x12 in. Cylinders			Group B 6x12 in. Cylinders			Group C 6x12 in. Cylinders		
	Strength (psi)	**Average (psi)**	**Std. Dev.**	**Strength (psi)**	**Average (psi)**	**Std. Dev.**	**Strength (psi)**	**Average (psi)**	**Std. Dev.**
1	2608*	3219	405	3655	3487	157	2750*	3269	334
	3021			3463			3121		
	3417			3344			3417		
3	4598	4648	209	4804	4833	130	4826	4622	181
	4469			4975			4479		
	4878			4720			4563		
7	5502	5484	99	5365	5150	191	5243	5059	357
	5378			5000			5285		
	5573			5085			4648		
14	5883	5680	276	5460	5715	505	5357	5383	44
	5366			6297			5433		
	5791			5389			5359		
21	6445	6322	194	6103	6226	169	6203	5789	362
	6423			6419			5533		
	6099			6155			5631		
28	6185	6356	257	6394	6403	113	6539*	6034	317
	6232			6597*			6156		
	6651			6411			5911		
35	6549	6425	146	5994*	6314	192	5982	6346	395
	6463			6260			6766		
	6264			6368			6291		
42	6351*	6474	280	6594	6460	269	5905*	6574	475
	6203			6635			6297		
	6745			6150			6851		
56	7003	6621	455	6834	6910	225	7058	6925	167
	6742			7163			7100*		
	6117			6732			6792		
90	7239	7045	168	7014	7065	287	7044	6993	76
	6947			7554*			6941		
	6948			7116			6896*		
120	7275	7207	171	6919	7054	269	7579	7382	330
	7012			6651*			7185		
	7333			7189			7841*		
180	7431	7880	397	7817	7835	113	7297	7501	211
	8023			7641			7704		
	8185			7852			7406		

*Outlier not plotted or used to calculate average

Table A-2: 4x8 in. Cylinder Compression Strength

	Group A 4x8 in. Cylinders			Group B 4x8 in. Cylinders			Group C 4x8 in. Cylinders		
	Strength (psi)	Average (psi)	Std. Dev.	Strength (psi)	Average (psi)	Std. Dev.	Strength (psi)	Average (psi)	Std. Dev.
1	3470	3284	454	3180	3357	176	2300*	3334	642
	2566*			3533			3570		
	3099			3356			3099		
3	3140*	4610	849	4228	4071	282	4662	4628	44
	4586			3746			4643		
	4635			4240			4579		
7	4791	4891	183	4613	4551	274	4723	4851	186
	4780			4789			5065		
	5103			4252			4766		
14	5338	5503	155	5086	5335	226	5542	5430	98
	5527			5395			5387		
	5645			5525			5360		
21	6251*	5899	223	6659*	6271	254	6478	6329	212
	5989			6389			6590*		
	5808			6152			6180		
28	5450*	5844	273	5442*	6081	369	6224	6181	61
	5692			6059			6111		
	5995			6102			6209		
35	6098	6175	187	2594**	6240	2112	5911*	6175	207
	6252			6068			6315		
	5880*			6412			6034		
42	6487	6462	75	6181	5931	221	6124	6219	360
	6437			5765			6617		
	6585*			5846			5917		
56	6502	6377	452	5864	5942	125	6284	6162	142
	6252			6086			6007		
	5625*			5877			6196		
90	6783*	6557	186	6842	6303	475	6704	6688	352
	6690			5947			7032		
	6424			6120			6328		
120	6156	6587	427	6473	6506	592	6685	7075	346
	6595			5931			7197		
	7010			7113			7344		
180	6731	7055	706	6635	6793	357	7514	7495	70
	7864			6542			7554		
	6569			7201			7418		

* Outlier not plotted or used to calculate average

**Specimen failed at Cap

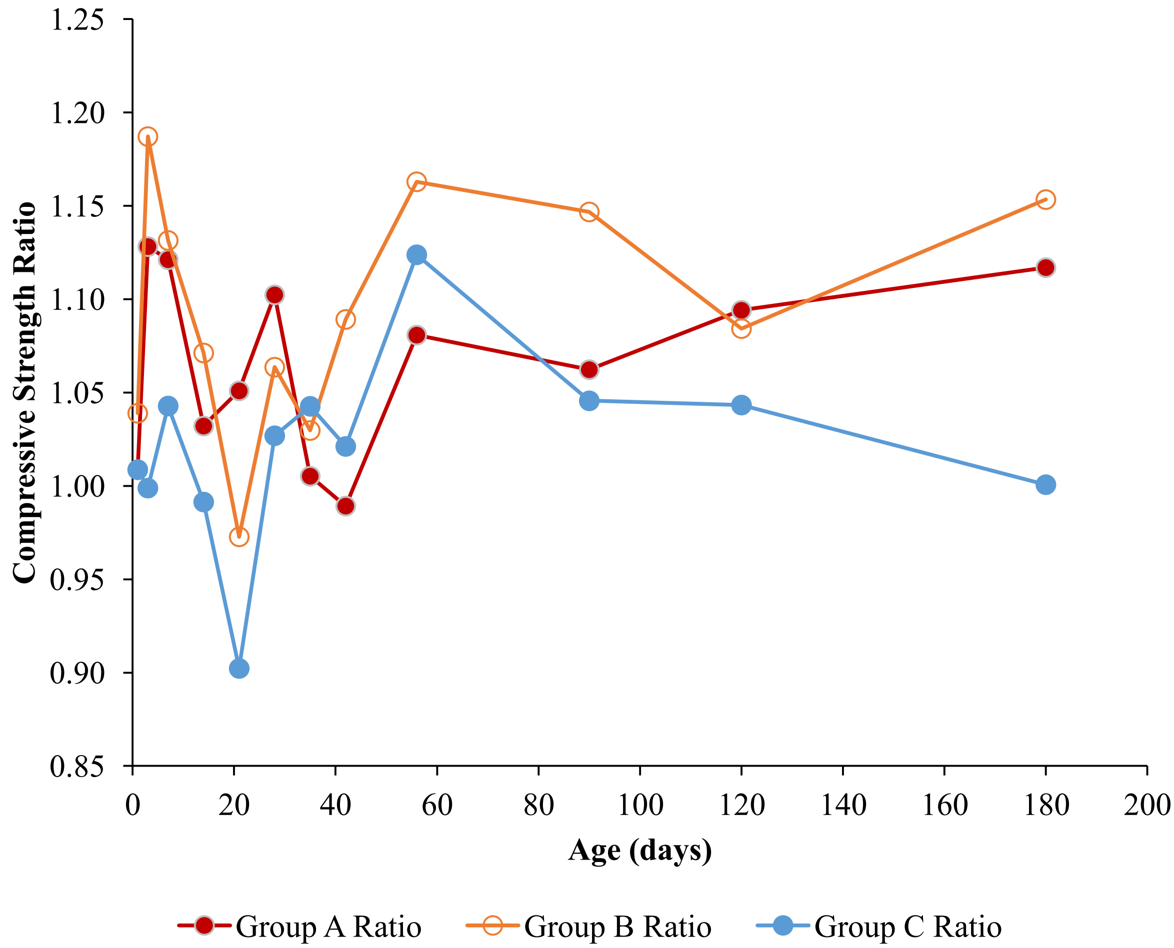


Figure A-1: Ratio of 6x12 in./4x8 in. Cylinder Strength vs. Age (days)

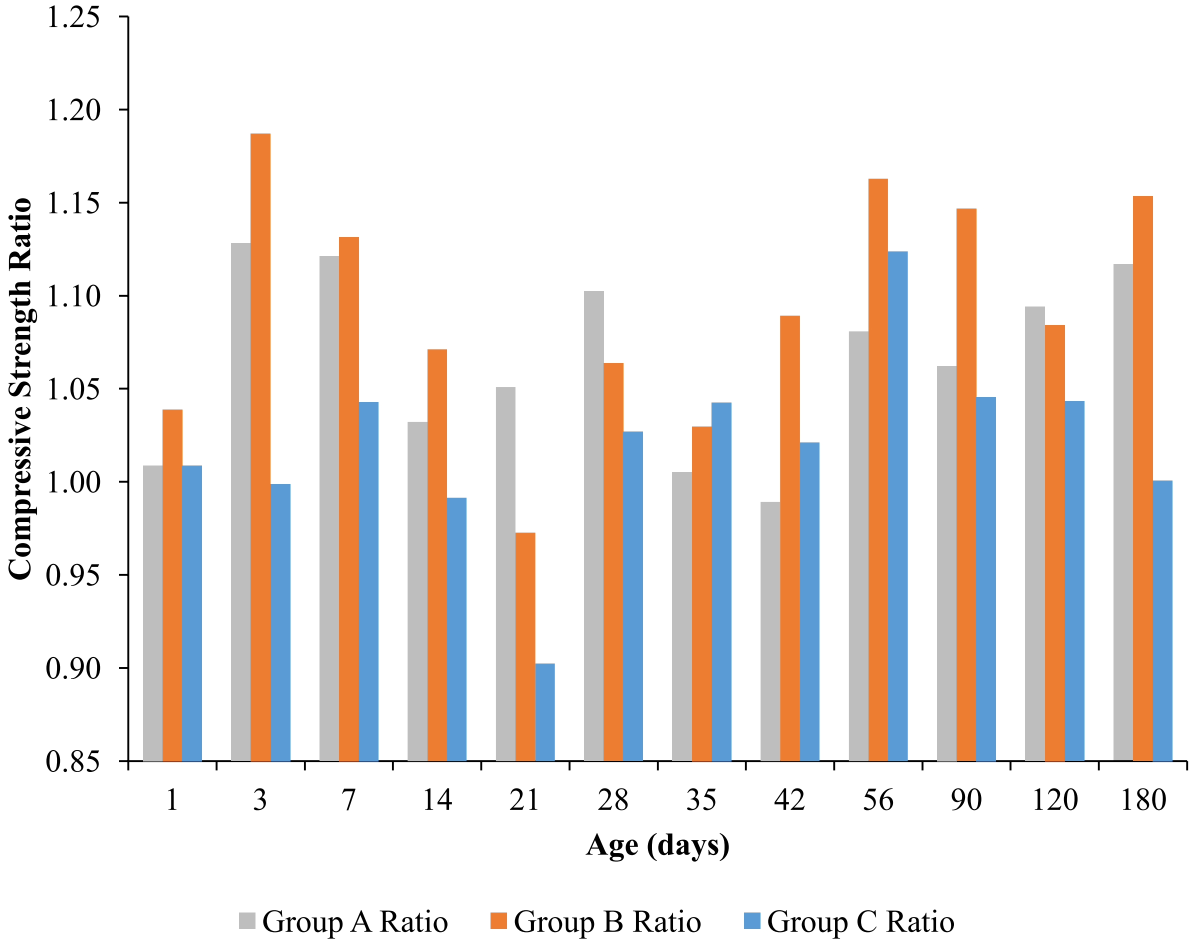


Figure A-2: Ratio of 6x12 in./4x8 in. Cylinder Strength vs. Age (days)

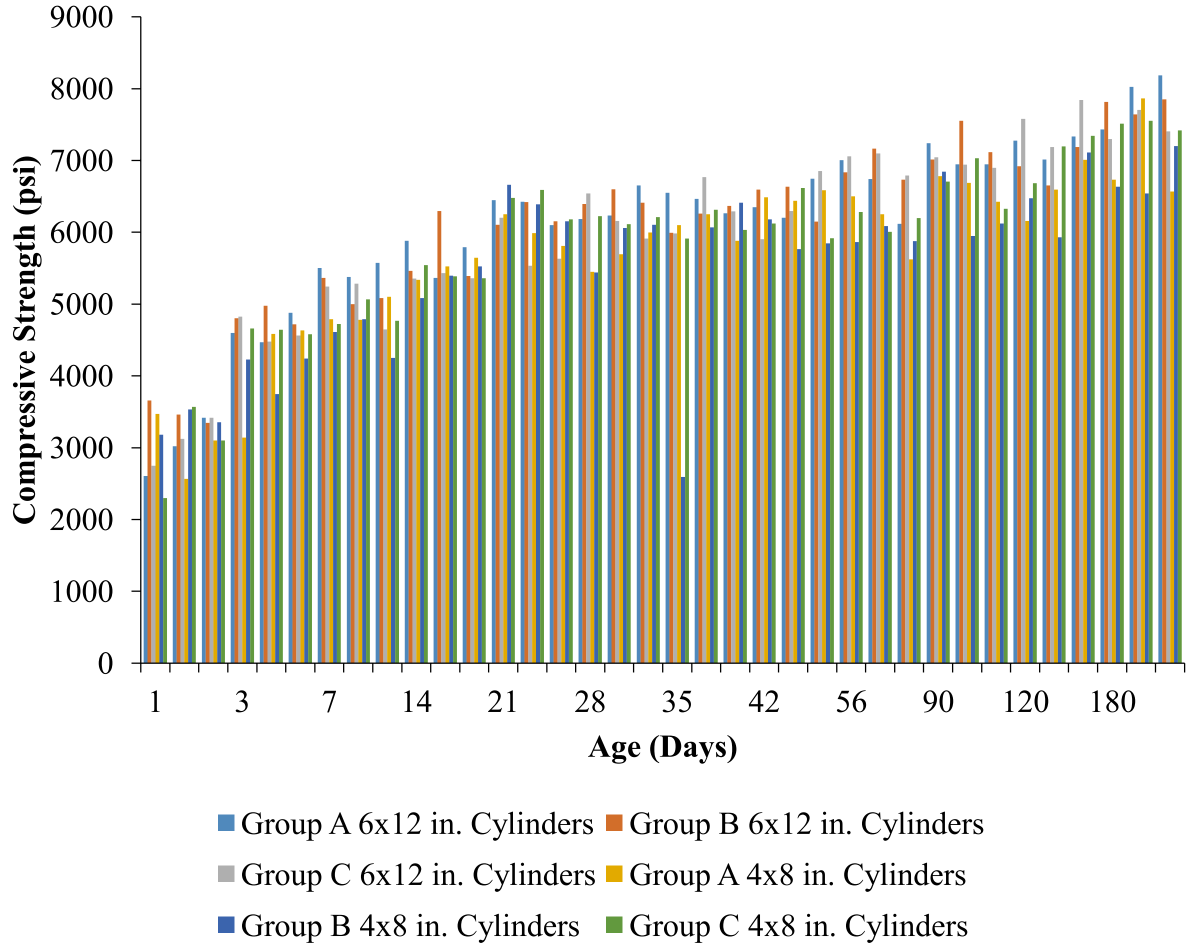


Figure A-3: Compressive Strength for all Cylinders (psi) vs. Age (days)

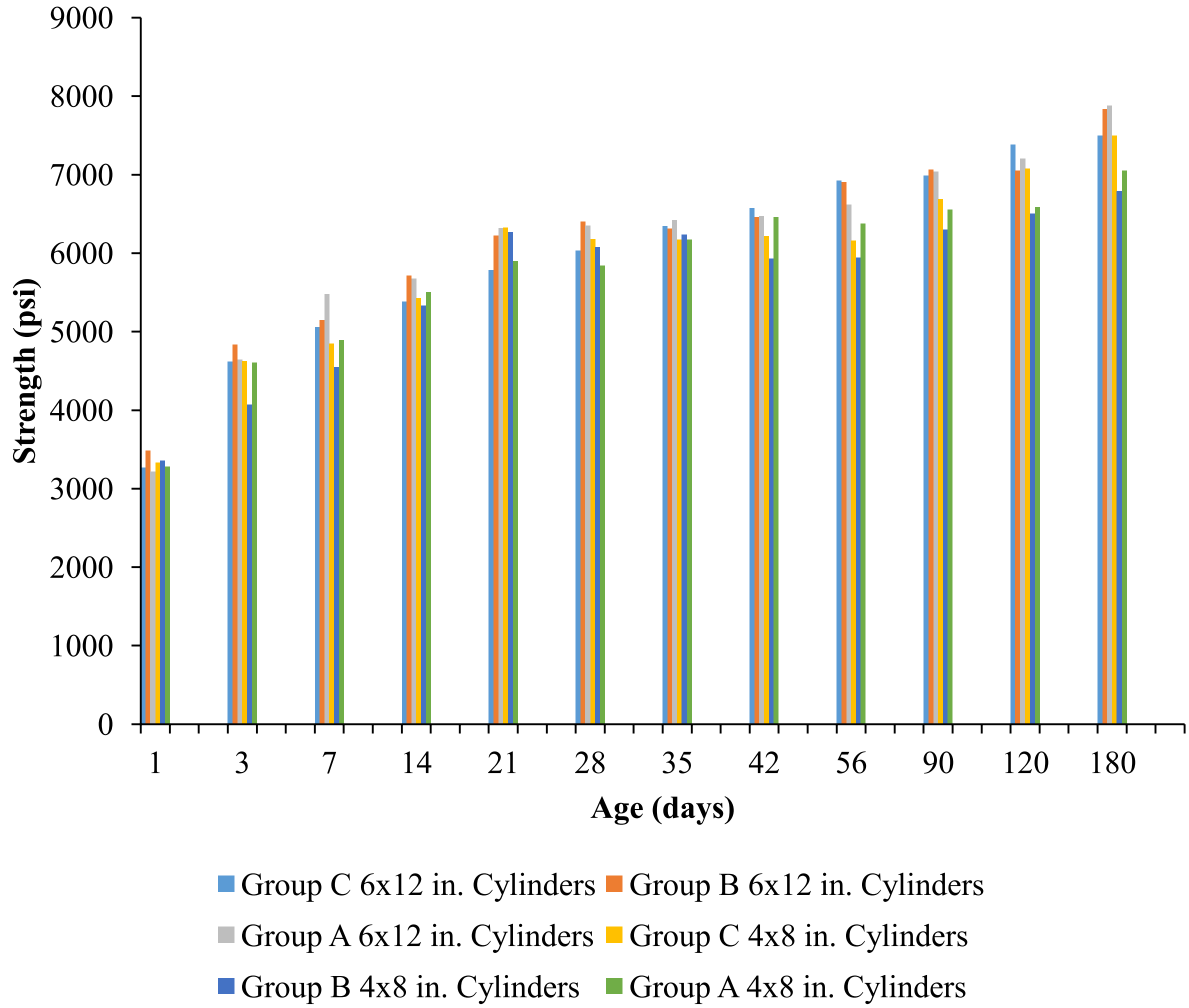


Figure A-4: Average Compressive Strength for all Cylinders (psi) vs. Age (days)

Table A-3: Slabs Core Strength & Cylinder Strength

Age (Days)	Group A Slab Core (psi)	Group C Slab Core (psi)	Group A 6x12 in. Cylinder (psi)	Group C 6x12 in. Cylinder (psi)	Group A 4x8 in. Cylinder (psi)	Group C 4x8 in. Cylinder (psi)
14	4487	4580	5680	5383	5503	5430
21	4740	5401	6322	5789	5899	6329
35	5522	5685	6425	6346	5844	6175
56	6303	5719	6621	6925	6377	6162
90	6865	6328	7045	6993	6557	6688
120	5791	5953	7207	7382	6587	7075
180	6624	7187	7880	7501	7055	7495

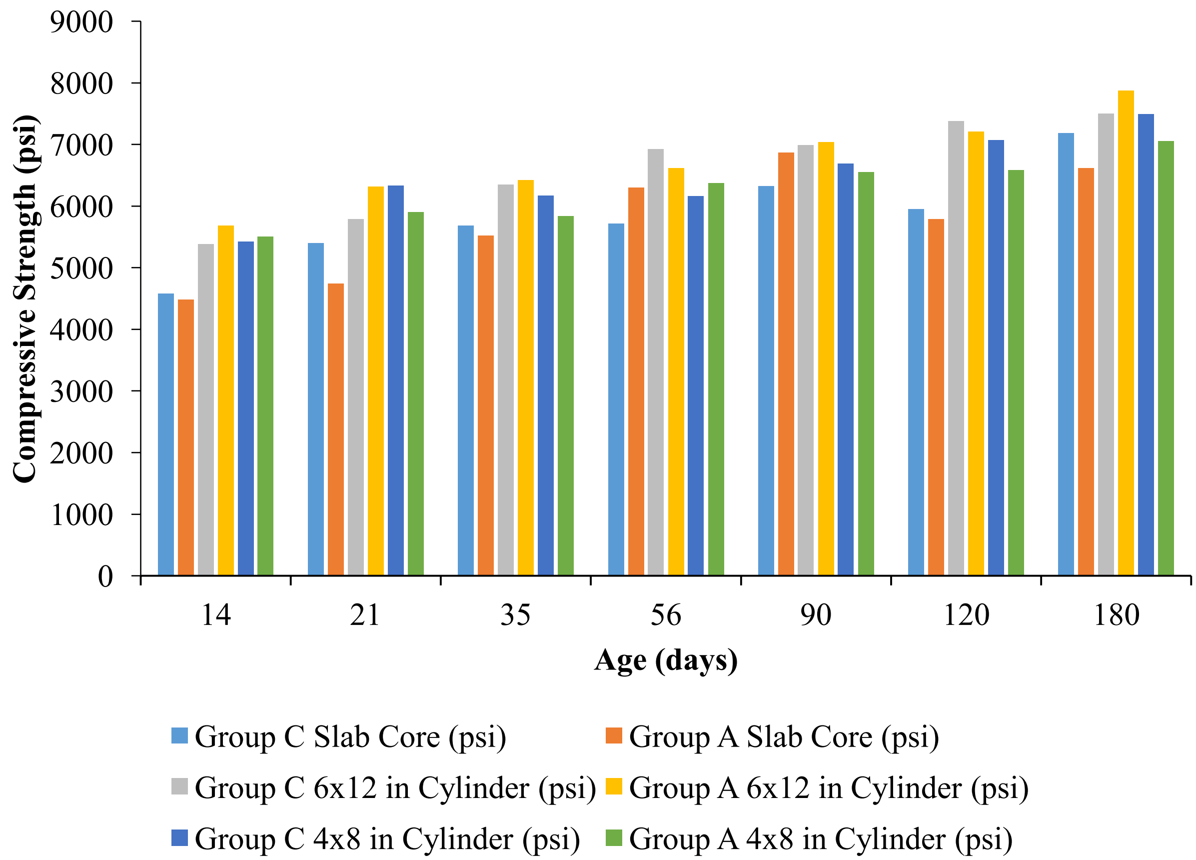


Figure A-5: Core and Cylinder Compressive Strength (psi) vs. Age (days)

Appendix B

Rebound Hammer Test Results for Cylinders, Slabs, and Retaining Walls

Table B-1: Rebound Values for 6x12 in. Group A Cylinders

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str. (psi)	3219	4648	5484	5680	6322	6356	6549	6463	6264	6594	6635	6150	7003	6742	6117	7239	6948	6947	7275	7012	7333	7431	8023	8185
	39.0	51.5	45.5	57.5	57.5	57.5	60.5	61	60	61.0	61.5	60.5	62.5	63.5	63.0	65.5	63.5	65.0	60.0	64.5	63.5	65.5	64.5	61
	45.0	53.5	57.5	55.5	54	58.0	62.5	60.5	57	65.5	62.5	62.0	63.0	61.5	63.0	63.5	67.5	61.0	61.5	62.0	63.5	64	64.5	64.5
	40.0	51.0	58.5	59.0	57.5	56.0	65.5	59.5	61.5	55.5	65.0	60.5	62.5	62.5	61.0	61.5	64.0	64.0	59.5	66.5	63.0	66.5	66	67
	41.5	53.5	55.0	60.5	57	59.0	6	60.5	58.5	64.5	62.5	62.0	59	61.5	60.5	58.5	64.5	62.5	62.5	64.0	61.0	69.5	68.5	64.5
	46.0	49.5	53.5	55.5	56.5	58.0	57.5	62	66	60.0	63.5	62.5	62.5	59.0	62.0	61.0	63.5	65.0	64.5	65.0	59.5	67.5	64	64.5
	42.0	51.0	53.0	53.0	59.5	58.0	57	61	63	66.0	62.5	60.0	61	59.5	62.5	65.0	60.5	64.0	63.0	64.0	62.0	65.5	65	67
	48.5	50.5	52.0	54.5	56	57.5	61.5	60	59	62.5	64.0	61.0	59	62.5	68.5	60.0	60.5	64.0	63.5	62.5	62.0	62	64	66
	43.5	51.0	52.0	57.0	51	57.0	63	56.5	61	60.0	63.0	63.0	64	59.0	61.5	59.5	59.0	62.5	62.5	62.5	65.5	63	66	66
	42.5	48.5	53.5	56.0	57.5	54.0	61	57.5	61.5	61.0	61.5	62.0	59	62.5	63.5	64.0	64.0	63.0	64.5	63.0	61.5	66	65	63.5
	46.5	50.5	56.5	59.5	56.5	55.5	58.5	57.5	61.5	60.0	62.5	61.0	60	60.5	63.0	62.5	69.5	61.0	62.5	65.0	61.5	68	64.5	64
	41.0	49.5	61.0	58.0	60	56.0	59.5	58.5	58.5	60.5	63.0	64.5	60.5	65.5	63.0	63.5	60.0	60.0	62.5	64.5	64.0	64	65	62.5
	41.0	53.5	50.5	58.0	61.5	57.0	57	61	60.5	61.5	61.0	63.0	62	59.0	62.5	61.0	57.5	59.5	61.0	63.5	59.0	67	62	66
	44.0	51.0	53.0	58.0	54.5	57.5	60	61	61	62.5	61.0	59.0	68	59.0	62.5	57.5	59.5	62.0	63.5	60.0	60.0	67	63.5	64.5
	44.0	48.5	56.0	56.0	58	56.0	60	61.5	61	63.0	62.0	61.5	61.5	63.0	64.5	63.5	63.0	61.5	60.0	63.0	61.5	64	67	63.5
	41.5	52.0	57.0	58.5	57.5	58.0	58	59.5	58.5	61.0	61.0	60.5	60	63.0	63.0	62.5	56.0	62.5	69.0	61.0	60.0	67.5	65	65
***Average**	43.1	51.0	54.3	57.1	57.0	57.0	56.5	59.8	60.6	61.6	62.4	61.5	61.6	61.4	62.9	61.9	62.2	62.5	62.7	63.4	61.8	65.8	65.0	64.6
****Adjusted Average**	34	41	43	46	46	46	45	48	48	49	50	49	49	49	50	50	50	50	50	51	49	53	52	52

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

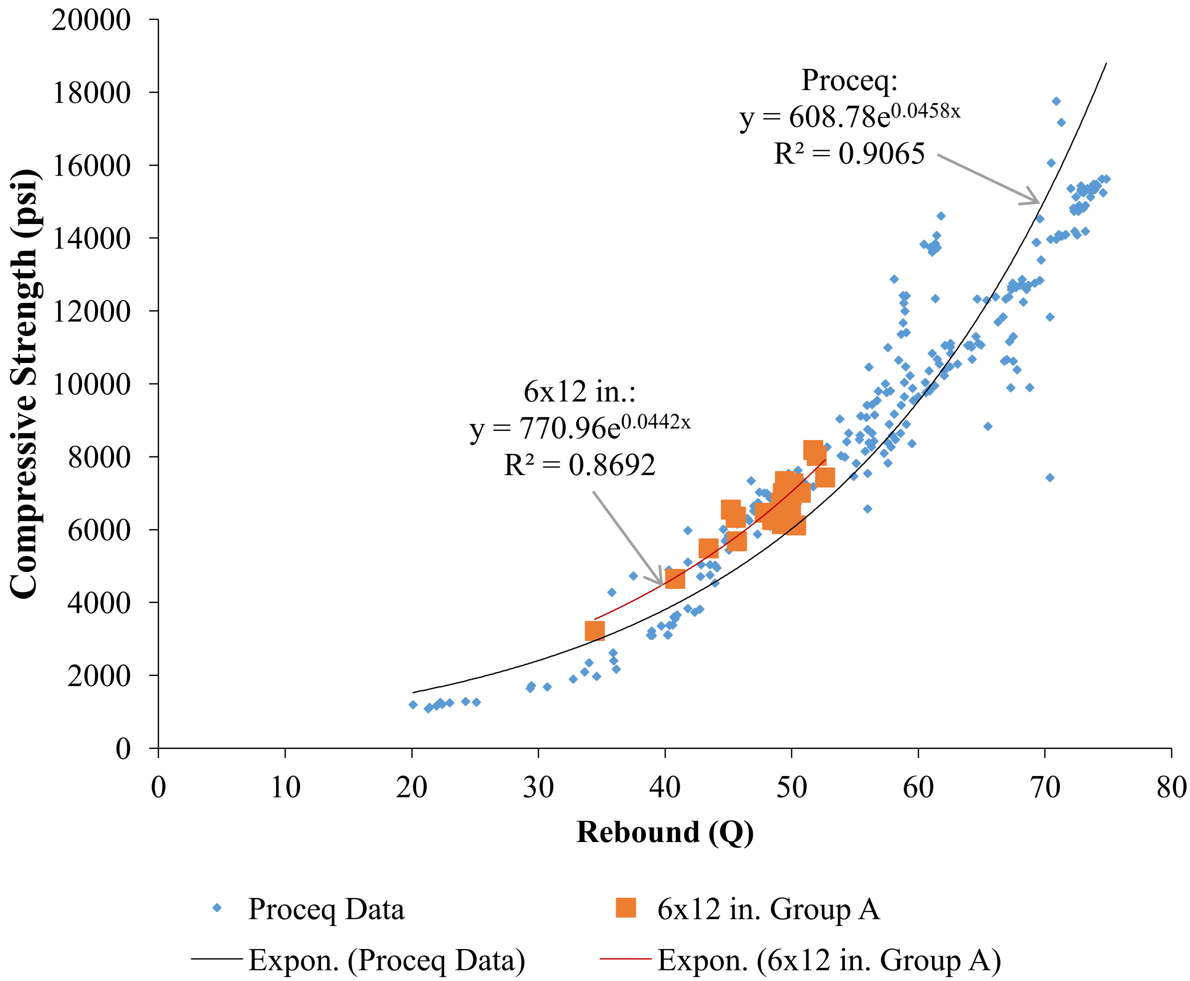


Figure B-1: Rebound Value (Q) vs. Compressive Strength (psi) for Group A 6x12 in. Cylinders

Table B-2: Rebound Values for 24x18x4 in. Slab A

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3219	4648	5484	5680	6322	6356	6474	6621	7045	7207	7880
Core Str. (psi)				4487	4740			6303	6865	5791	6624
	40.0	48.0	46.5	61.5	43.5	55.0	61.5	56.5	62.5	62.0	56
	43.0	46.0	49.5	54.5	43	55.5	59.5	57.5	61.5	61.0	57
	41.0	49.5	56.0	54.5	48	55.5	58.5	60.5	60.0	60.5	59.5
	43.5	47.0	54.0	56.5	43	58.0	60.0	56.0	60.5	51.0	61
	40.0	45.5	56.0	49.0	44.5	52.0	58.0	56.0	61.0	60.5	55.5
	42.0	42.0	49.0	49.5	45	55.5	57.5	60.0	57.5	59.5	64
	44.0	45.0	44.5	49.5	45.5	52.0	57.5	61.5	60.5	60.5	61.5
	42.0	45.0	54.0	56.5	45.5	55.5	58.0	57.0	61.5	59.5	56
	42.5	47.5	56.0	45.5	52.5	52.0	61.5	58.5	66.0	62.0	64
	39.5	40.5	50.0	51.5	46.5	55.5	57.0	59.0	62.0	59.5	63
	41.0	45.5	52.5	46.0	43	56.5	58.0	62.5	57.0	61.0	56
	41.0	41.5	49.0	50.0	45	54.0	62.0	54.0	62.0	56.5	62
	44.0	46.0	50.0	56.0	45	53.5	60.0	60.0	60.0	58.0	64.5
	38.0	47.5	53.0	55.5	47	51.5	61.0	58.5	59.0	58.5	60
	43.5	48.0	2.5	55.5	47		57.0	56.0	57.0	58.5	61
***Average**	41.7	45.6	48.2	52.8	45.6	54.4	59.1	58.2	60.5	59.2	60.1
****Adjusted Average**	33	37	39	42	36	44	47	47	48	47	48

*Average = Rebound Value (Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

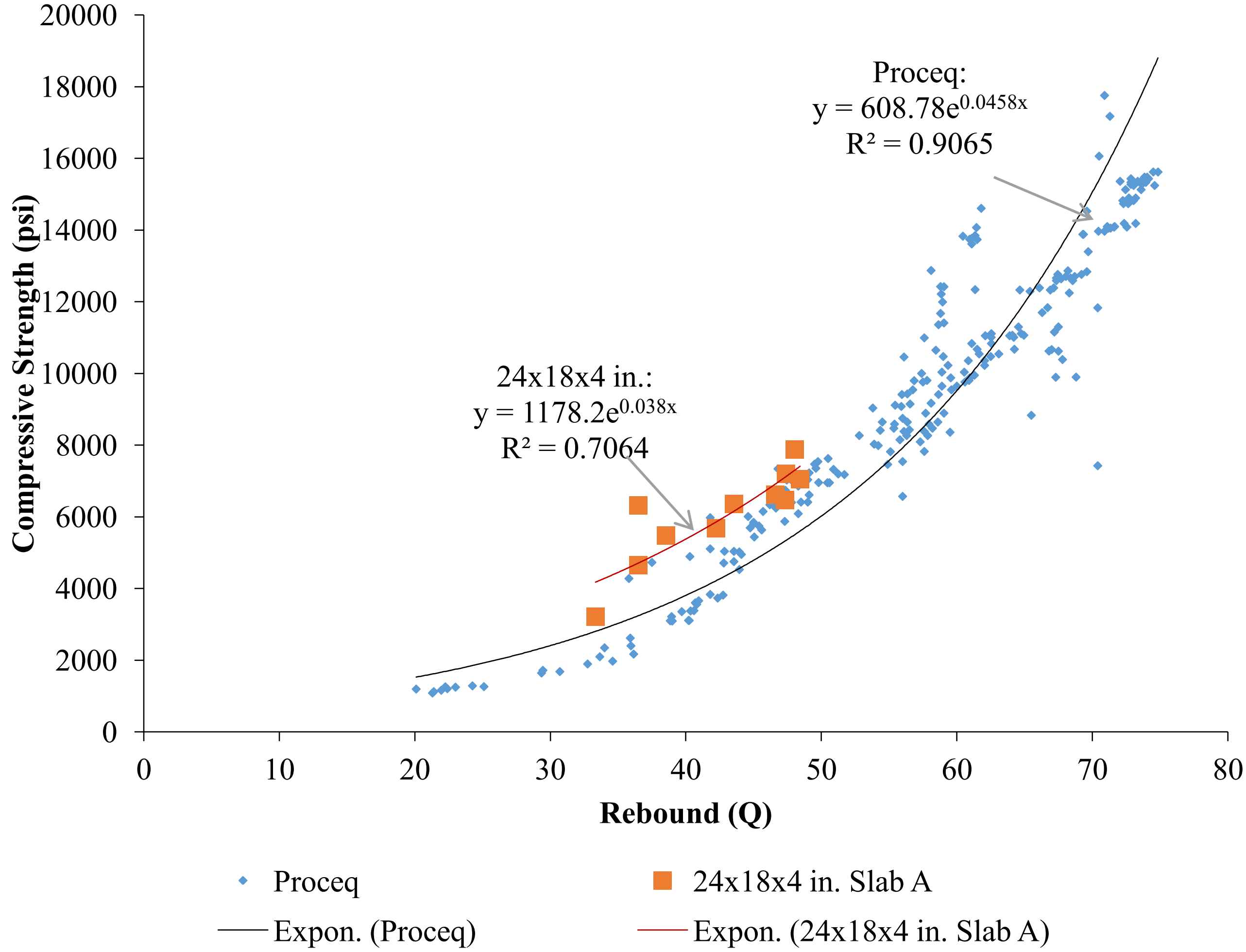


Figure B-2: Rebound Value (Q) vs. Compressive Strength (psi) for 24x18x4 in. Slab A

Table B-3: Rebound Values for Retaining Wall A

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3219	4648	5484	5680	6322	6356	6474	6621	7045	7207	7880
	34.0	50.5	46.5	43.5	44.0	45.0	50.0	49.5	51.5	53.0	53
	35.5	42.0	40.5	49.0	46.0	44.5	49.5	54.0	51.5	54.5	55.5
	36.5	39.5	46.5	42.5	47.0	44.5	52.0	48.0	53.0	57.0	56.5
	35.5	42.0	40.0	43.0	44.5	43.0	48.5	53.5	57.5	56.0	55
	38.5	42.0	42.0	43.5	45.5	42.0	52.0	50.0	54.0	53.0	55
	36.5	42.0	48.5	45.0	44.5	46.0	51.5	50.5	52.0	56.0	56
	37.0	47.5	49.0	43.5	47.0	48.0	50.5	51.5	57.5	53.5	54
	38.0	53.5	41.0	47.0	48.0	49.0	50.5	45.0	52.0	54.0	52
	35.5	46.0	41.5	48.0	45.5	44.5	47.5	50.5	56.5	54.5	54.5
	40.0	38.5	45.0	43.5	44.0	50.5	47.5	49.0	53.5	53.0	52
	39.0	40.0	43.5	43.5	45.0	47.0	47.0	52.0	55.5	58.5	52
	34.5	40.0	42.5	45.0	45.5	47.5	48.0	51.0	53.0	57.0	53.5
	39.5	40.0	43.5	46.5	45.0	48.5	47.5	51.5	55.5	53.5	58.5
	36.5	39.5	44.0	45.0	44.0		47.0	55.0	51.5	59.5	59
	38.5	40.5	46.5	42.5	44.0		46.5	55.0	52.5	56.0	53.5
***Average**	37.0	42.9	44.0	44.7	45.3	46.2	49.0	51.1	53.8	55.3	54.7
****Adjusted Average**	30	34	35	36	36	37	39	41	43	44	44

*Average = Rebound Value (Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

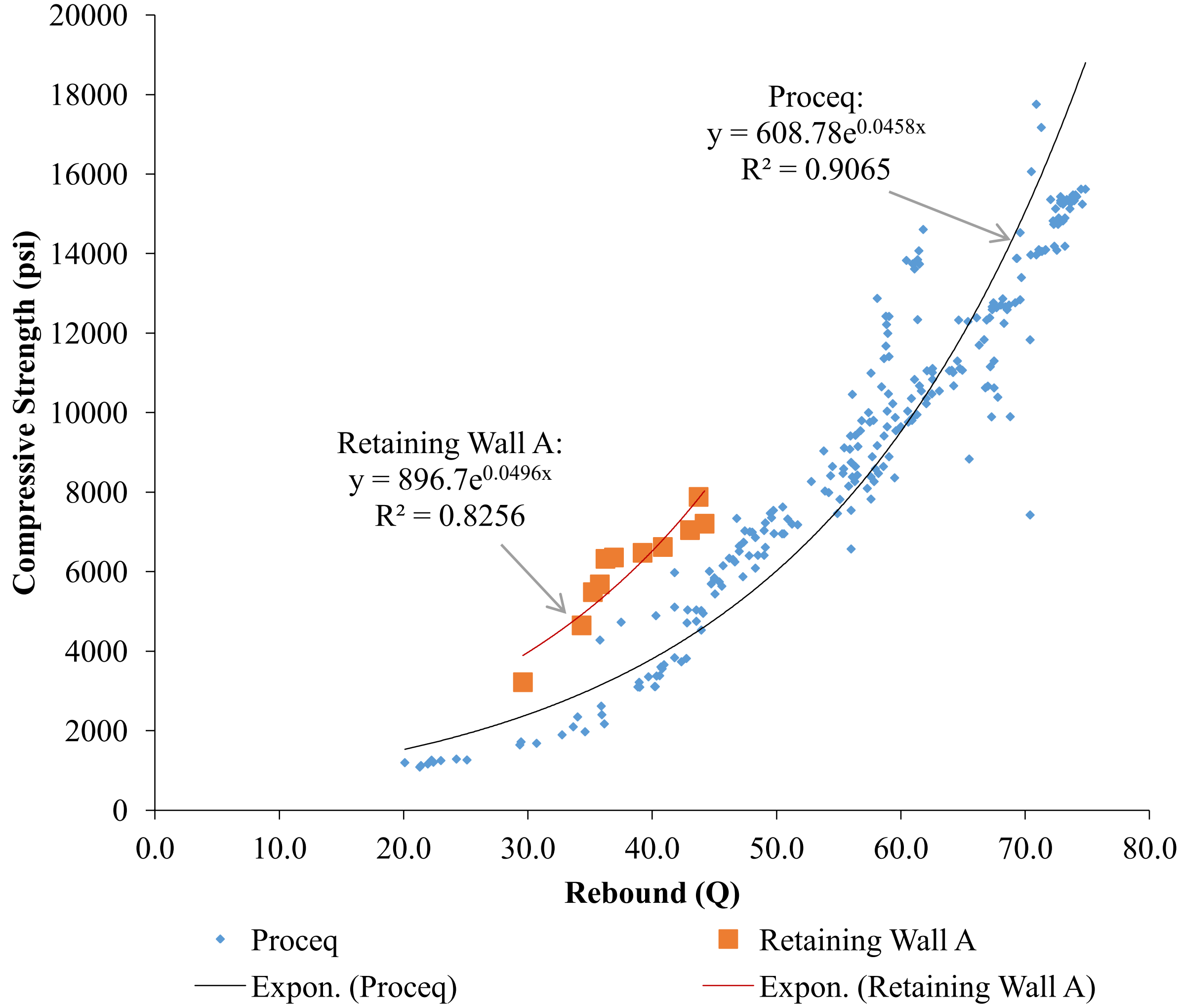


Figure B-3: Rebound Value (Q) vs. Compressive Strength (psi) for Retaining Wall A

Table B-4: Rebound Values for Group B 6x12 in. Cylinders

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str. (psi)	3487	4833	5150	5715	6226	6403	5994	6260	6368	6351	6203	6745	6834	7163	6732	7014	7554	7116	6919	6651	7189	7817	7641	7852
	40.0	47.5	55.5	56.0	54	58.0	58.5	56	60	59.0	60.0	62.0	61.0	63.5	60.0	59.5	66.5	64.0	63.5	66.5	64.5	64.5	65	65
	41.0	46.5	54.0	54.0	59.5	58.0	59	57	61	65.0	59.5	61.5	63.0	58.5	59.5	65.5	65.0	62.5	62.0	63.5	64.0	65	61.5	68
	40.0	44.5	55.0	55.0	54.5	60.0	64.5	62	56.5	61.5	61.5	61.5	61.0	62.5	64.5	64.5	69.5	61.0	60.0	64.0	59.0	64.5	67	63.5
	42.5	44.0	49.0	57.5	53	61.5	61	56.5	60	62.0	60.5	60.5	60.0	64.5	68.0	63.0	62.0	60.0	62.5	61.5	55.5	64.5	62.5	66.5
	47.5	54.0	55.0	55.0	55.5	58.0	63	57.5	60.5	63.5	61.0	61.0	64.0	66.0	64.5	64.0	66.0	64.5	66.0	62.5	61.5	67.5	63.5	61
	47.0	49.0	58.0	60.0	58	60.5	63.5	63	63.5	62.5	59.0	63.5	63.0	64.0	63.5	60.5	65.0	66.5	65.5	59.5	65.0	65	64	67
	41.0	46.0	55.5	60.0	56.5	62.5	61	63	61	61.0	4.0	59.0	63.0	62.5	60.5	61.0	60.0	65.5	63.5	62.0	62.0	69	66	67
	41.0	53.0	52.5	55.0	59.5	58.0	62	60	57.5	60.0	63.5	64.0	62.0	60.0	60.0	61.5	65.0	64.5	64.5	64.0	60.0	64.5	65	63
	43.0	51.5	56.0	58.5	51.5	58.5	62.5	58.5	61.5	63.5	63.0	61.5	59.5	60.0	64.0	63.5	67.0	61.5	61.5	60.0	64.0	65.5	66	67.5
	38.5	52.0	50.5	57.0	57	60.0	58	62	62.5	61.5	62.0	60.0	62.0	64.0	65.0	61.5	69.0	66.0	60.5	62.0	63.5	67	65	69
	43.5	47.5	54.5	58.5	55	58.0	63.5	64	59	62.5	59.5	59.0	63.0	62.5	62.0	62.5	65.0	62.5	64.5	61.5	63.5	65.5	64.5	63
	41.5	51.5	55.0	58.5	55	61.0	61	60	61	64.0	63.5	62.0	63.5	62.0	65.0	65.5	67.0	60.0	61.5	65.0	62.0	69.5	60.5	66.5
	45.5	48.0	52.5	61.0	51.5	59.0	63.5	64	5	59.0	61.5	59.0	60.0	60.5	66.0	60.0	62.0	61.0	61.5	62.5	64.5	69.5	67	63
	41.5	52.5	56.0	56.5	51.5	59.0	59	63	61.5		62.5	61.0	62.5	63.5	63.0	65.5	65.0	66.0	63.0	61.0	63.5	65.5	65.5	65
	45.5	45.0	54.5	56.5	52	59.0	58	61	62.5		63.5	62.0	63.5	66.5	62.5	60.0	66.0	61.5	63.5	60.5	59.5	67	62	67
	40.0	48.5	55.0			61.0	59	61	58						59.0									
	40.5	51.0	54.0			58.0																		
***Average**	42.3	48.9	54.3	57.3	54.9	59.4	61.1	60.5	56.9	61.9	57.6	61.2	62.1	62.7	62.9	62.5	65.3	63.1	62.9	62.4	62.1	66.3	64.3	65.5
****Adjusted Average**	34	39	43	46	44	48	49	48	46	50	46	49	50	50	50	50	52	51	50	50	50	53	51	52

*Average = Rebound Value (Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

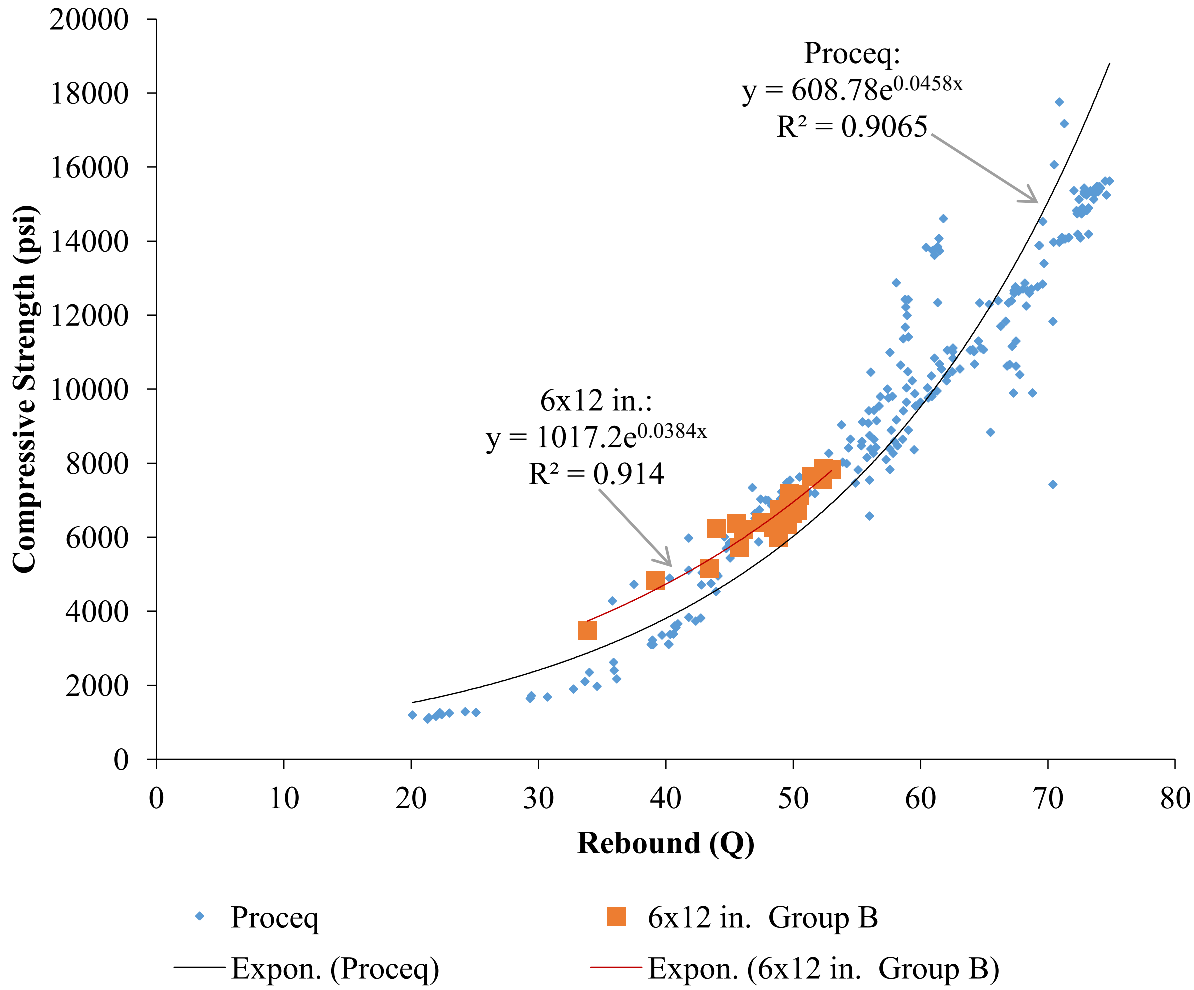


Figure B-4: Rebound Value (Q) vs. Compressive Strength (psi) for Group B 6x12 in. Cylinders

Table B-5: Rebound Values for 24x18x4 in. Slab B

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3487	4833	5150	5715	6226	6403	6459.67	6910	7065	7054	7770
	35.5	37.0	42.0	47.0	45	43.5	48.5	48.0	51	51.0	58
	36.5	38.5	43.5	43.0	45	42.5	53.5	48.0	58.0	55.0	56.5
	38.0	44.0	38.0	41.5	48	49.5	48.5	50.5	53.5	54.0	57.5
	37.5	35.5	42.0	50.5	45	46.5	45.0	52.5	60.5	59.0	63
	36.0	43.0	45.5	42.5	48	46.5	43.0	51.0	54.5	57.5	60
	35.0	34.0	41.5	50.0	44.5	48.5	49.5	54.0	58.0	54.5	52.5
	35.0	38.0	38.0	46.0	45	45.5	54.0	52.5	59.0	57.0	57.5
	36.5	34.0	36.0	49.0	45.5	49.0	50.0	52.5	56.5	61.0	61
	33.5	34.5	46.0	47.5	45.5	46.5	47.5	49.0	55.5	58.0	57.5
	37.5	40.5	45.0	49.0	52.5	48.0	51.0	53.0	60.5	55.5	59
	35.0	42.5	35.5	45.0	46.5	47.5	46.5	51.5	55.0	56.0	56.5
	34.5	35.0	49.0	48.0	45	50.5	47.5	49.0	54.0	63.0	59
	37.5	36.5	42.0	50.5	47	46.0	46.0	53.0	57.0	54.0	60
	34.5	38.5	38.0	53.5	47	48.5	46.5	52.0	56.0	54.5	57.5
	35.5	40.5	42.5	54.0	47	48.0	46.5	54.5	53.5	52.5	59.5
								54.5			
***Average**	35.9	38.1	41.6	47.8	46.4	47.1	48.2	51.6	56.5	56.2	58.3
****Adjusted Average**	29	31	33	38	37	38	39	41	45	45	47

*Average = Rebound Value (Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

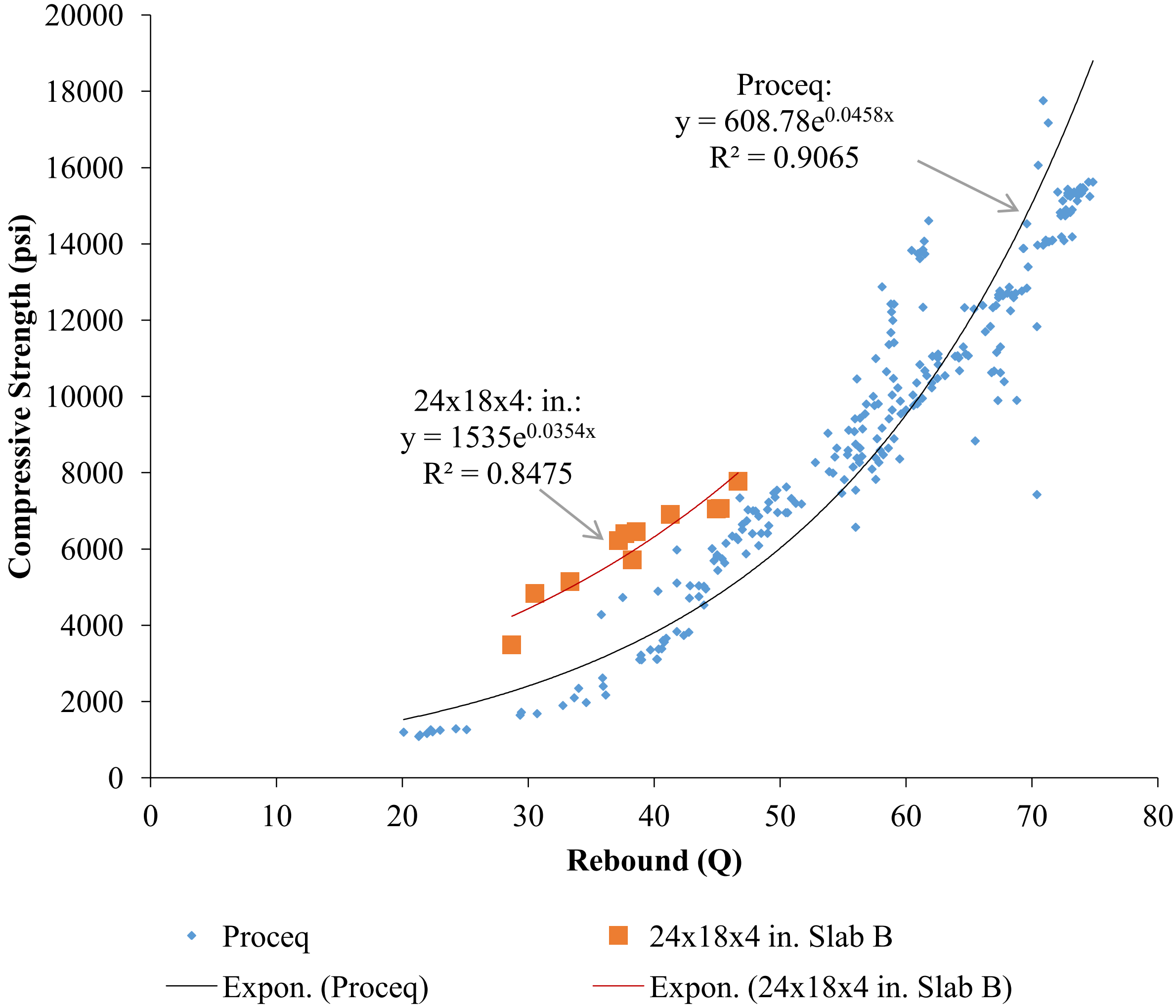


Figure B-5: Rebound Value (Q) vs. Compressive Strength (psi) for 24x18x4 in. Slab B

Table B-6: Rebound Values for Retaining Wall B

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3487	4833	5150	5715	6226	6403	6460	6910	7065	7054	7770
	35.0	39.5	39.5	42.0	45	47.0	50.0	51.0	51.5	51.5	50.5
	34.0	37.5	40.0	42.5	54.5	43.5	50.0	51.0	54.0	49.5	53.5
	35.5	38.5	40.0	44.5	46.5	47.0	49.0	49.5	51.0	51.5	59
	37.5	39.0	40.5	42.0	47.5	47.0	47.5	46.0	52.0	48.5	58.5
	36.5	38.0	39.5	46.0	47	47.5	48.0	56.5	53.0	55.5	53.5
	36.0	38.5	40.5	40.5	45.5	44.0	46.5	47.0	50.5	59.0	56.5
	36.0	37.5	39.5	42.5	46.5	47.5	49.0	46.0	51.0	54.0	56
	35.0	36.5	38.5	40.0	47	44.5	50.5	45.0	52.5	56.5	50
	35.5	36.5	51.0	42.5	46	43.5	46.5	47.5	49.5	53.0	52
	37.0	35.5	40.0	40.0	44.5	45.5	45.5	49.0	52.0	51.5	53
	34.0	35.5	38.5	41.0	46.5	43.0	48.0	48.5	56.5	51.0	54
	38.0	37.5	38.0	41.0	42.5	47.0	45.5	49.0	50.5	56.0	50.5
	33.0	38.5	46.0	41.5	46.5		44.5	48.5	50.0	56.5	56
	32.5	42.0	39.0	42.0	46.5		46.0	49.0	52.5	59.0	55
	34.5	37.5	39.5				47.5	51.5	57.0	52.5	51.5
	36.5	38.5						49.0			
	34.5										
***Average**	35.4	37.9	40.7	42.0	46.6	45.6	47.6	49.0	52.2	53.7	54.0
****Adjusted Average**	28	30	33	34	37	36	38	39	42	43	43

*Average = Rebound Value (Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

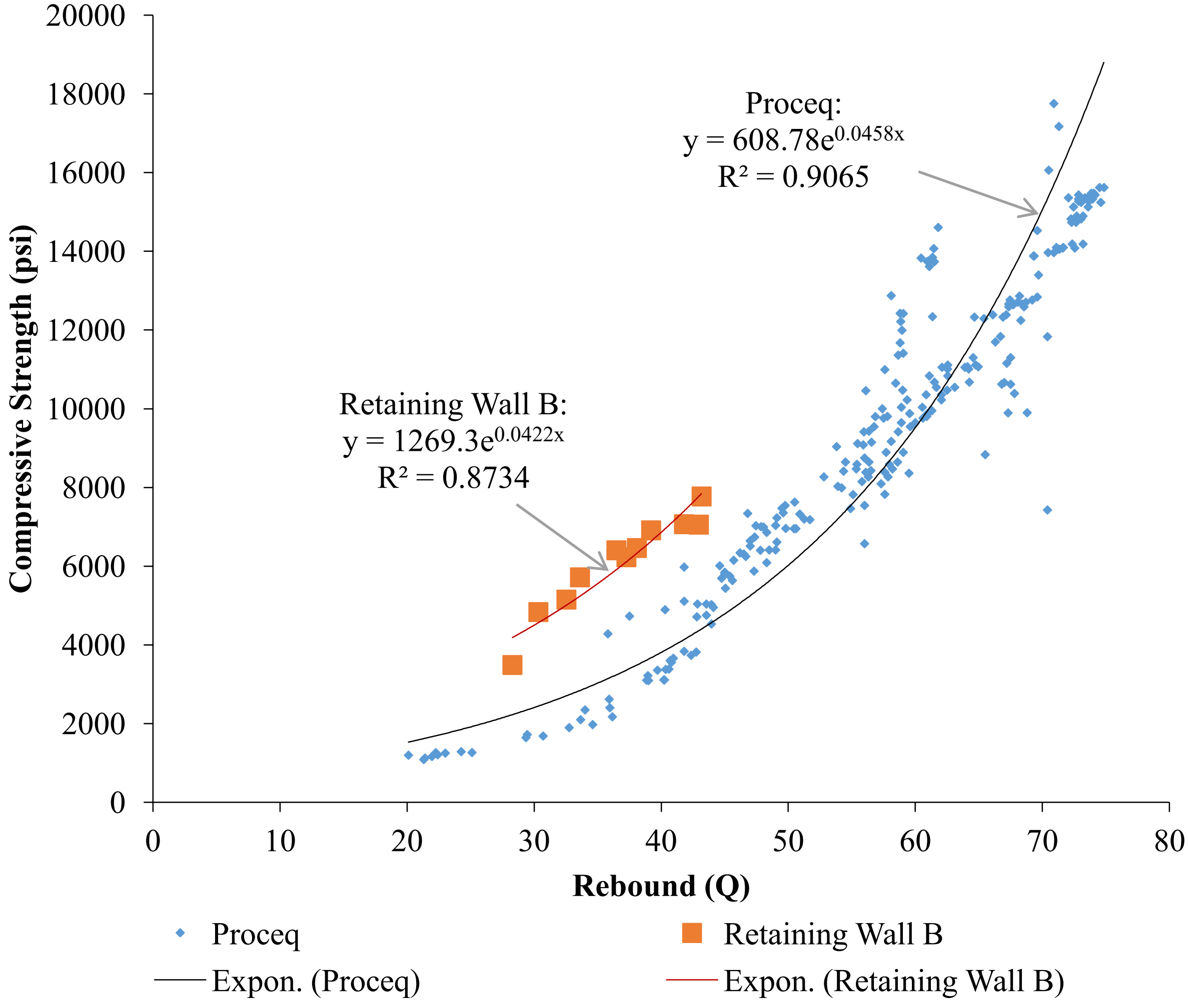


Figure B-6: Rebound Value (Q) vs. Compressive Strength (psi) for Retaining Wall B

Table B-7: Rebound Values for Group C 6x12 in. Cylinders

	Day1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str. (psi)	3269	4622	5059	5383	5789	6034	5982	6766	6291	6297	5917	6851	7058	7100	6792	6896	7044	6941	7579	7185	7841	7297	7704	7406
	45.5	53.0	53.0	56.0	61	62.0	59	61.5	59	64.0	60.5	61.0	62.5	59.0	55.5	64.0	60.5	63.5	66.5	68.0	61.0	67.5	65.5	63.5
	41.5	51.5	55.0	59.0	60	60.5	61	60.5	58.5	61.0	61.0	61.5	64.5	60.0	61.5	63.5	60.0	67.5	59.5	65.5	64.0	69.5	63.5	65
	43.5	51.5	56.0	57.0	62.5	60.0	61.5	60.5	58.5	63.0	64.5	62.0	61.0	61.5	64.5	64.0	64.0	60.0	61.0	64.5	63.5	65	66	68
	45.5	55.0	55.0	56.0	58.5	61.5	62.5	60.5	62	61.0	64.4	60.5	55.0	66.5	65.5	62.5	65.0	63.5	66.5	64.0	66.5	66	65	67
	40.0	50.5	55.5	59.5	61	61.0	61.5	59.5	60	60.0	61.0	62.0	62.0	56.0	64.5	63.0	62.5	62.5	65.0	64.0	64.0	65.5	64.5	64.5
	41.0	55.0	54.0	57.5	60	58.5	59	60.5	61.5	59.0	64.0	63.0	61.5	64.5	63.0	60.0	63.0	64.0	64.5	63.5	63.0	66.5	65.5	65
	42.0	48.5	50.5	56.0	55.5	58.0	63	61.5	59	60.0	62.0	60.5	63.0	61.5	58.5	60.0	65.0	65.0	61.5	64.5	63.0	64.5	66	66.5
	43.5	50.5	55.5	56.0	57	64.5	61	58	58.5	63.0	63.0	61.5	62.5	59.0	61.5	60.5	63.0	67.0	67.5	66.0	65.0	63.5	61.5	62.5
	43.0	49.0	55.0	56.5	59	60.0	63	62	61.5	58.5	65.0	58.5	63.0	63.5	60.5	62.5	66.0	63.5	64.0	63.0	67.0	64.5	64.5	63
	46.0	51.0	55.0	57.0	60.5	61.0	62.5	59	62	63.0	58.5	63.0	65.0	63.5	66.5	61.0	65.5	63.0	59.5	61.5	65.5	68.5	65.5	66.5
	43.0	48.5	52.5	56.0	56.5	59.5	61	60.5	59.5	59.5	61.0	59.5	66.5	63.0	62.0	59.5	64.5	62.5	64.5	67.0	62.5	64.5	66.5	61.5
	38.5	49.0	54.5	55.5	59.5	60.5				66.0	63.0	62.0	61.5	59.5	64.5	62.5	62.5	67.5	67.5	63.5	65.0	68	64	67.5
	42.0	52.5	51.5	55.5	60	64.0				61.0	63.5	59.0	61.0	62.0	62.0	63.0	65.5	66.0	64.5	65.5	65.0	68	61.5	69.5
	44.0	54.5	54.0	56.5	61	60.5				64.0	60.0	59.0	58.5	65.5	58.5	63.5	63.5	63.0	62.0	64.5	68.5	67.5	67	66.5
	44.0	53.0	55.0	58.5		59.0				62.0	62.0	60.0	60.5	64.0	59.5	61.0	61.5	65.0	64.5	63.5	67.0	63.5	66.5	66
***Average**	42.9	51.5	54.1	56.8	59.4	60.7	61.4	60.4	60.0	61.7	62.2	60.9	61.9	61.9	61.9	62.0	63.5	64.2	63.9	64.6	64.7	66.2	64.9	65.5
****Adjusted Average**	34	41	43	45	48	49	49	48	48	49	50	49	49	50	49	50	51	51	51	52	52	53	52	52

*Average = Rebound Value(Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

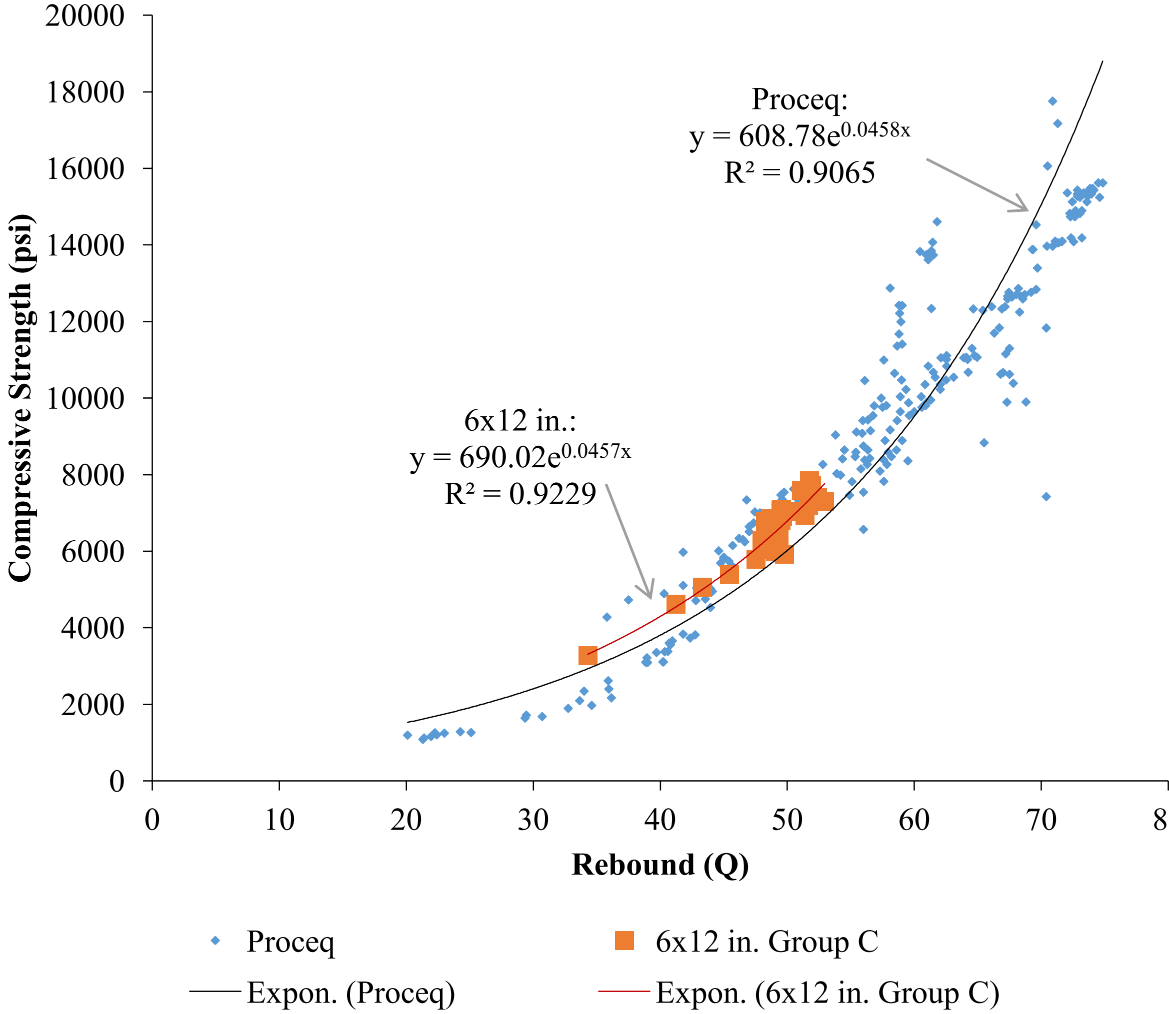


Figure B-7: Rebound Value (Q) vs. Compressive Strength (psi) for Group C 6x12 in. Cylinders

Table B-8: Rebound Values for 24x18x4 in. Slab C

	Day1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3269	4622	5059	5383	5789	6034	6574	6925	6993	7382	7469
Core Str. (psi)				4580	5401			5719	6328	5953	7187
	36.5	46.0	55.5	62.5	60.5	61.5	61.0	64.0	66.5	64.0	59
	34.0	51.5	51.5	57.5	56.5	62.0	58.5	60.0	63.5	61.5	69
	42.5	45.5	54.0	57.0	58.5	57.0	60.0	63.5	66.0	66.5	60.5
	40.5	49.0	52.5	50.0	58	62.0	59.0	62.0	67.0	63.0	58
	37.5	44.5	55.5	51.0	60	56.0	60.0	60.0	63.5	62.5	68.5
	36.5	47.0	53.0	51.0	61	60.0	63.0	59.5	62.0	62.5	69.5
	42.5	55.5	51.5	54.5	60.5	59.5	57.5	62.0	65.0	61.0	67
	42.0	41.0	51.0	55.5	59	59.5	57.0	54.5	61.0	57.5	63
	39.0	41.5	53.5	51.5	60.5	56.0	59.0	59.0	65.5	62.5	67
	39.0	49.0	55.0	50.0	60.5	58.5	61.5	61.5	64.5	63.5	66
	37.0	49.0	55.0	52.0	58	58.5	60.5	63.0	61.5	61.5	67.5
	42.0	48.0	51.5	53.0	60.5	52.0	57.5	63.0	60.5	64.5	63
		51.5	48.5	51.0	60		59.0	59.0	64.5	56.0	59
		47.5	54.5		60.5		60.5	64.0	65.5	61.5	59.5
							57.5	61.0	69.0	57.0	63.5
***Average**	39.1	47.6	53.0	53.6	59.6	58.5	59.4	61.1	64.4	61.7	64.0
****Adjusted Average**	31	38	42	43	48	47	48	49	51	49	51

*Average = Rebound Value (Q)

**Adjusted Average = Average x Form factor of standard cylinders (i.e. 0.8)

**Adjusted Average will be used for the graphs

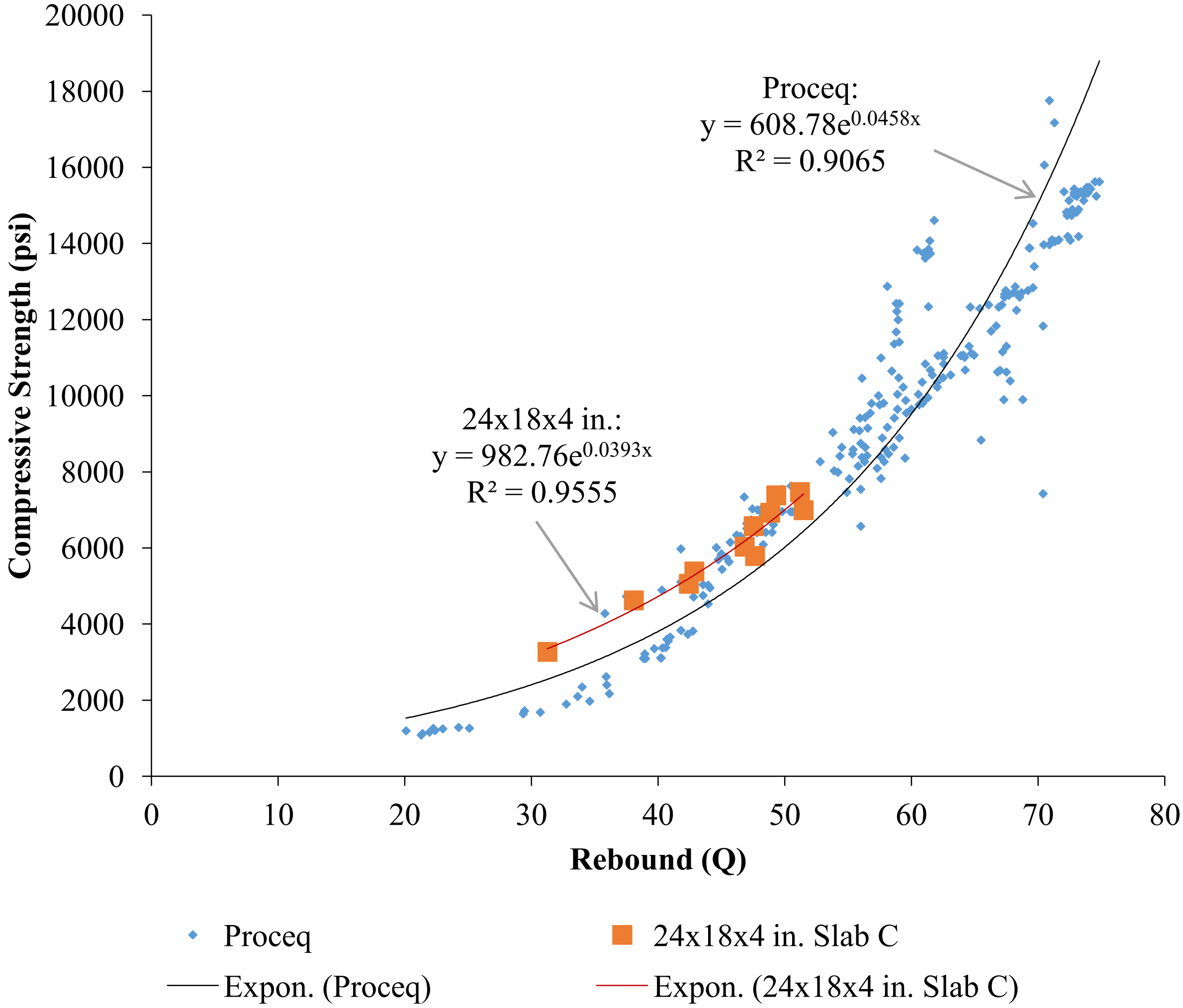


Figure B-8: Rebound Value (Q) vs. Compressive Strength (psi) for 24x18x4 in. Slab C

Appendix C

Ultrasonic Pulse Velocity Test Results for Cylinders, Slabs, and Retaining Walls

Table C-1: Ultrasonic Pulse Velocity (UPV) Test results for Group A 6x12 in. Cylinders (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str. (psi)	3219	4648	5484	5680	6322	6356	6549	6463	6264	6594	6635	6150	7003	6742	6117	7239	6948	6947	7275	7012	7333	7431	8023	8185
	14986	14803	15514	15858	15709	15408	16549	16463	16264	15883	15959	15934	15808	15909	15538	15959	16114	16010	16088	15442	15985	16404	15959	16431
	14265	14847	15490	15883	15758	15504	16098	16252	15880	15883	15959	15883	15985	15934	15883	15883	16114	16010	16114	15371	16088	16271	15883	16404
	14234	14825	15466	15909	15833	15456	16065	16042	15965	15909	15985	15934	16010	15909	15858	15883	16140	16010	16166	15371	15959	16244	15909	16377
	14388	14825	15490	15883	15808	15601	16067	16067	15990	15808	15985	1959	15934	15934	15883	15883	16114	15985	16166	15758	16010	16192	15808	16404
	14451	14847	15442	15883	15808	15674	16042	16067	15864	15858	15959	15959	15909	15909	15858	15858	16140	16062	16114	15684	16062	16010	15783	16244
		14875	15442	15883	15808	15337	16016	16016	15889	15858	15883	15985	15909	15934	15883	15883	16140	16062	16140	15660	16010	16114	15734	16324
		14825	15490	15883	15833	15291	15889	16067	15914	15858	15909	15959	15909	15909	15883	15858	16114	16062	16140	15660	16036	16088		16140
			15418	15783	15858	15798	15914	16016	15965	15909	15959		15833	15883	15883	15808	16088	16114	16140		15883	16062		16166
							16042	16042	15965								15684		16114		15959			
Average	14465	14835	15469	15871	15802	15509	16076	16115	15966	15871	15950	13945	15912	15915	15834	15877	16072	16039	16131	15564	15999	16173	15846	16311

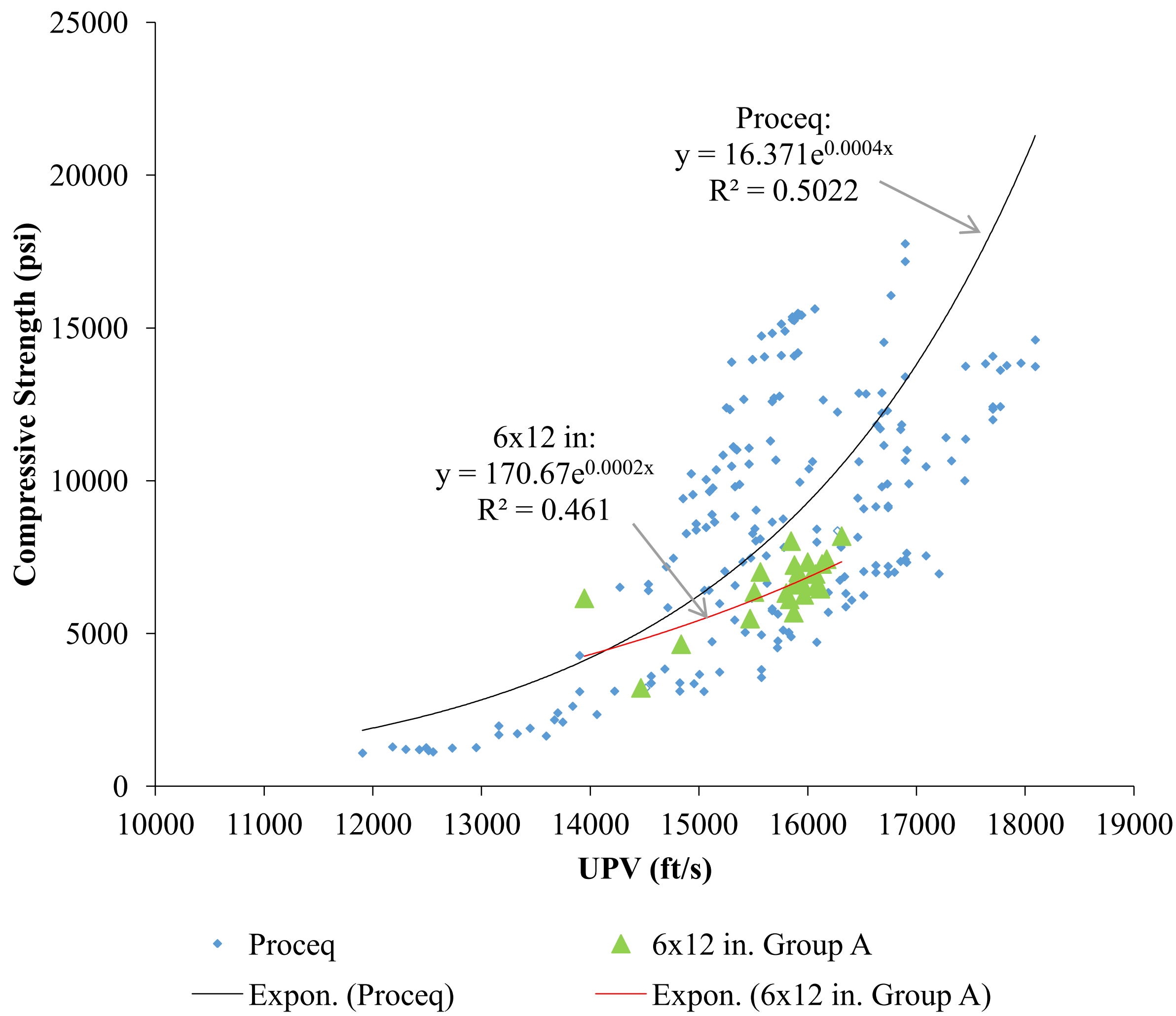


Figure C-1: UPV (ft/s) vs. Compressive Strength (psi) for Group A 6x12 in. Cylinders

Table C-2: UPV Test results for 24x18x4 in. Slab A (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3219	4648	5484	5680	6322	6356	6474	6621	7045	7207	7880
Core Strength (psi)				4487	4740			6303	6865	5791	6624
	14231	13429	15213	15275	15337	15496	15974	15806	15291	15005	15346
	14286	14313	15060	15213	15291	15625	15974	15707	15823	15989	15268
	14437	13405	15136	15198	15182	15528	15974	15658	15856	15917	14860
	14563	13441	15213	15228	15167	15432	15974	15641	15806	15877	14993
	14409	14663	15182	15121	15244	15544	15907	15576	15823	15745	14919
	14606	14881	15322	15030	18091	15658	15924	15560	15823	15714	15160
	14634	14881	15167	15075	15091	15593	15957	15512	15806	15661	15222
	14563	14570	15030		15275	15228	15971	15544		15753	15114
	14620	14695			15030	15432				15707	15206
	14563	14667									
Average	14491	14295	15165	15163	15523	15504	15957	15626	15747	15708	15121

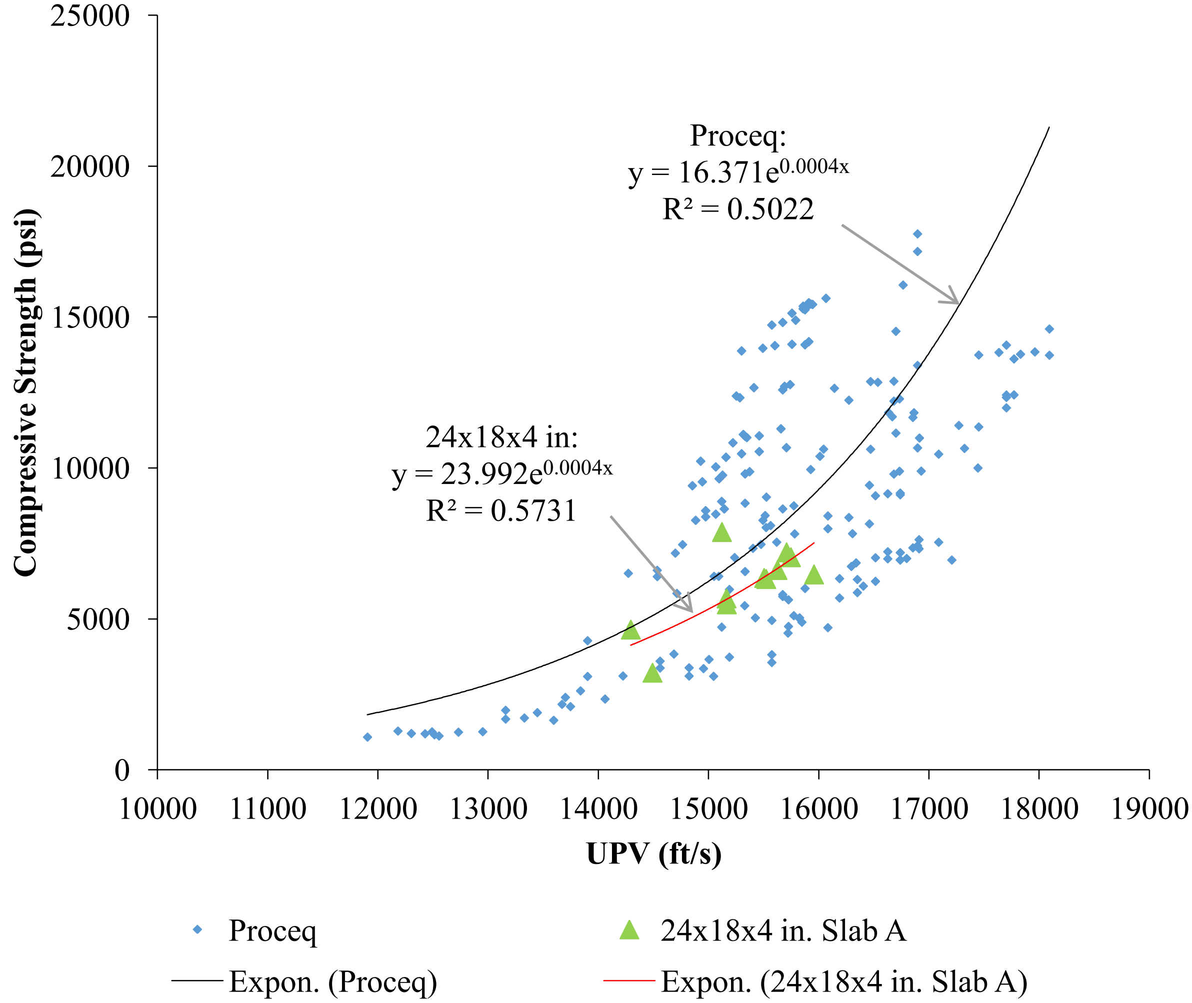


Figure C-2: UPV (ft/s) vs. Compressive Strength (psi) for 24x18x4 in. Slab A

Table C-3: UPV Test Results for Retaining Wall A (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3219	4648	5484	5680	6322	6356	6474	7045	7207	7880
	13130	14080	14444	14045	14460	14447	14004	14269	15187	14231
	13130	14110	14444	14045	14490	14454	14066	14237	14908	14200
	13048	14261	14509	14013	14490	14679	14066	14140	15116	14110
	13186	14261	14509	13982	14490	14747	14128	14077	15012	14261
	13103	13904	14381	13982	14579	14713	14159	14140	15081	14080
	13021	14021	14444	13951	14549	14747	14159	14077	15081	14170
	12913	13992	14444		14459	14815	14066	14045	15116	14080
	13021	14110				14884			15258	
	13075	14080							15258	
		14110								
Average	13070	14093	14454	14003	14502	14686	14093	14141	15113	14162

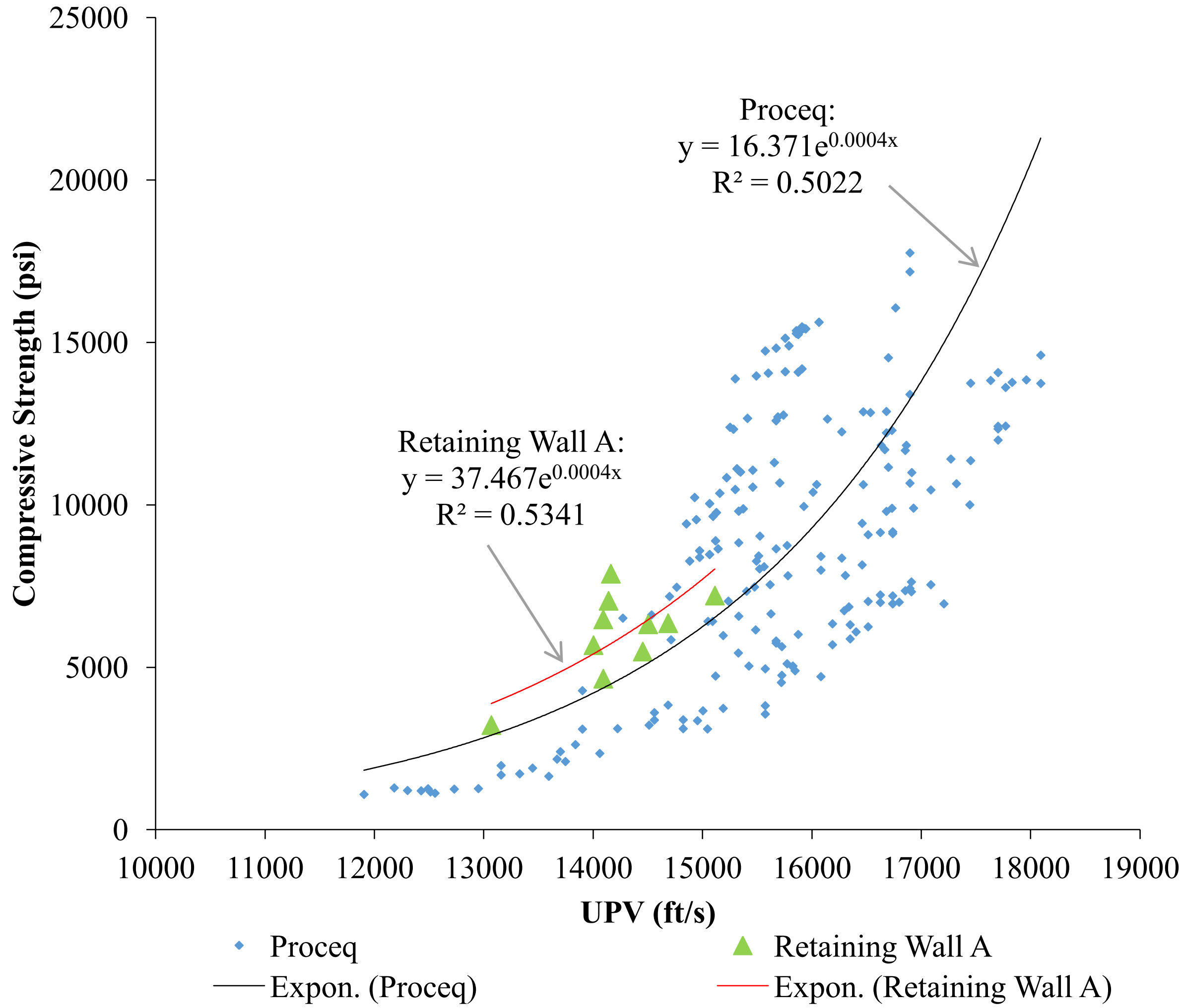


Figure C-3: UPV (ft/s) vs. Compressive Strength (psi) for Retaining Wall A

Table C-4: UPV Test Results for Group B 6x12 in. Cylinders (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str. (psi)	3487	4833	5150	5715	6226	6403	5994	6260	6368	6351	6203	6745	6834	7163	6732	7014	7116	7554	6919	6651	7189	7817	7641	7852
	13898	15093	15684	15783	15635	15823	15994	16088	16368	16035	15985	15758	15909	16062	15783	16192	16271	16114	16271	16324	16218	16088	16036	16351
	13956	15002	15684	15758	15611	15873	16068	16088	16088	16010	15883	15709	15883	16010	15758	16218	16271	16114	16192	16324	16218	16192	16114	16431
	14015	14980	15684	15709	15635	15898	15985	16036	16088	15959	15883	15883	16088	16062	15562	16192	16297	16114	16114	16324	16166	16114	16062	16271
	13995	15093	15635	15758	15562	15873	16010	15934	16036	15959	15934	15934	16140	16036	15758	16244	16297	16114	16088	16244	16192	16218	16036	16192
	14074	15093	15635	15709	15635	15898	16010	15959	16088	15985	15883	15959	16114	15985	15783	16244	16297	16140	16088	16192	16114	16297	16166	16324
	13802	15070	15684	15684	15611	15898	15985	15934	16036	16010	15909	15909	16140	16036	15808	16192	16271	16114	16062	16244	16062	16351	16140	16377
	13898		15564	15635	15635	15848	16010	15934	16036	15959		15959	16114	16010	15783	16218	16297	16140	16062	16244	16062	16377	16192	16540
			15684	15611	15611		15959		16036				16062	15934	15758	16218	16324	16114	16010	16271	16062	16377	16218	16458
			15635				15909						16088			16271	16297		16010	16218	15985		16218	16458
Average	13948	15055	15654	15706	15617	15873	15992	15996	16097	15988	15913	15873	16060	16017	15749	16221	16291	16121	16100	16265	16120	16252	16131	16378

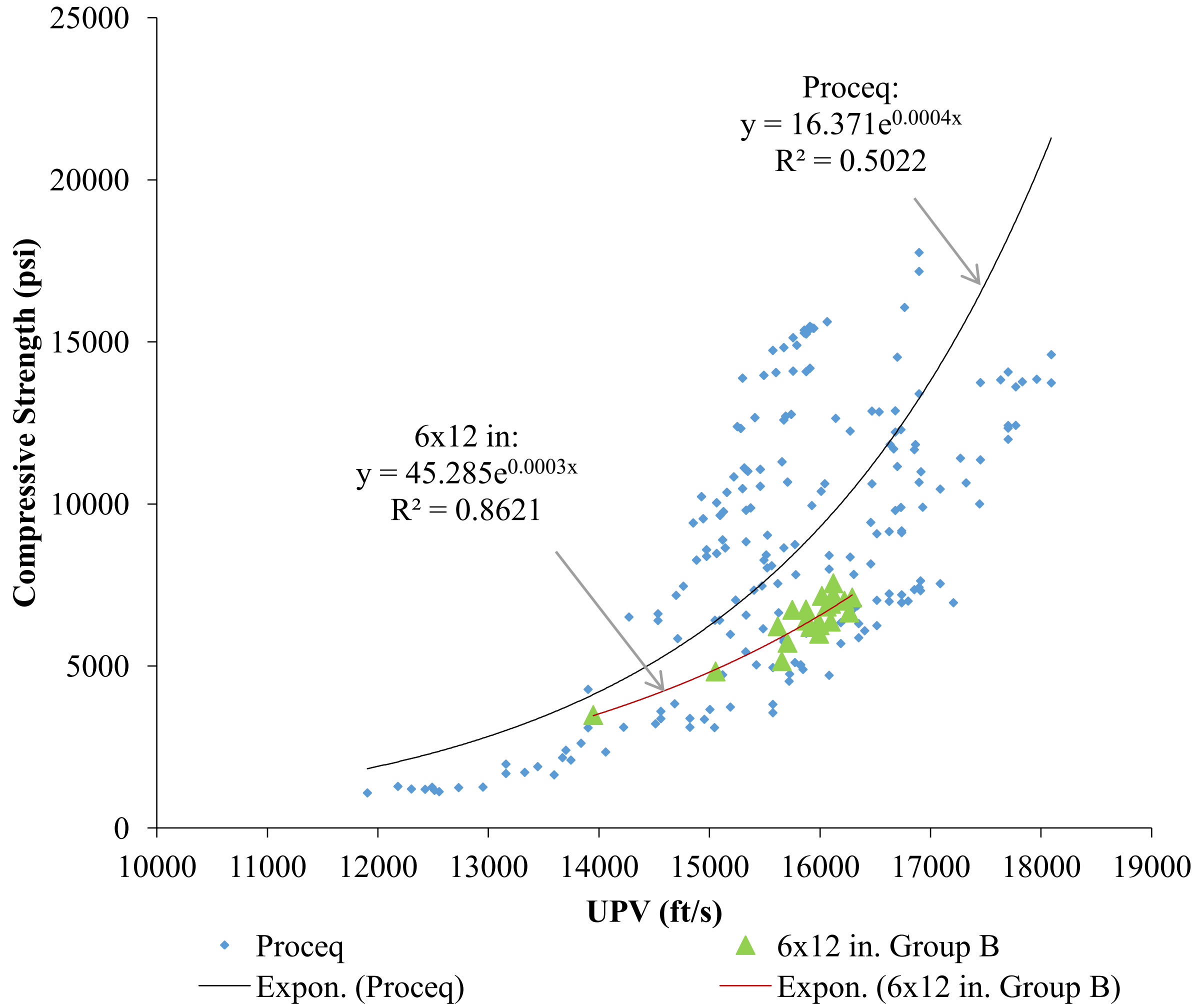


Figure C-4: UPV (ft/s) vs. Compressive Strength (psi) for Group B 6x12 in. Cylinders

Table C-5: UPV Test Results for 24x18x4 in. Slab B (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3487	4833	5150	5715	6226	6403	6460	6910	7065	7054	7770
	13991	14822	15835	16484	16224	16566	16434	16785	16998	15228	15075
	13830	14111	15973	16208	16353	16600	16550	16717	16464	15337	15091
	14208	14995	15865	15988	16304	16583	6684	16717	16497	15213	15121
	14143	14937	14719	15911	16337	16566	16208	16717	16398	15228	15091
	14169	14951	15850	16098	16418	16550	16717	16684	16414	15244	15121
	14118	14981	15988	15957	16353	16550	16684	16700	16365	15198	15152
	14067	14951	16004	15881	16467	16517	16633	16768	16332	15198	15152
			16145					16684	16266	15198	
			16161						16283	15167	
Average	14075	14821	15838	16075	16351	16562	15130	16722	16446	15223	15115

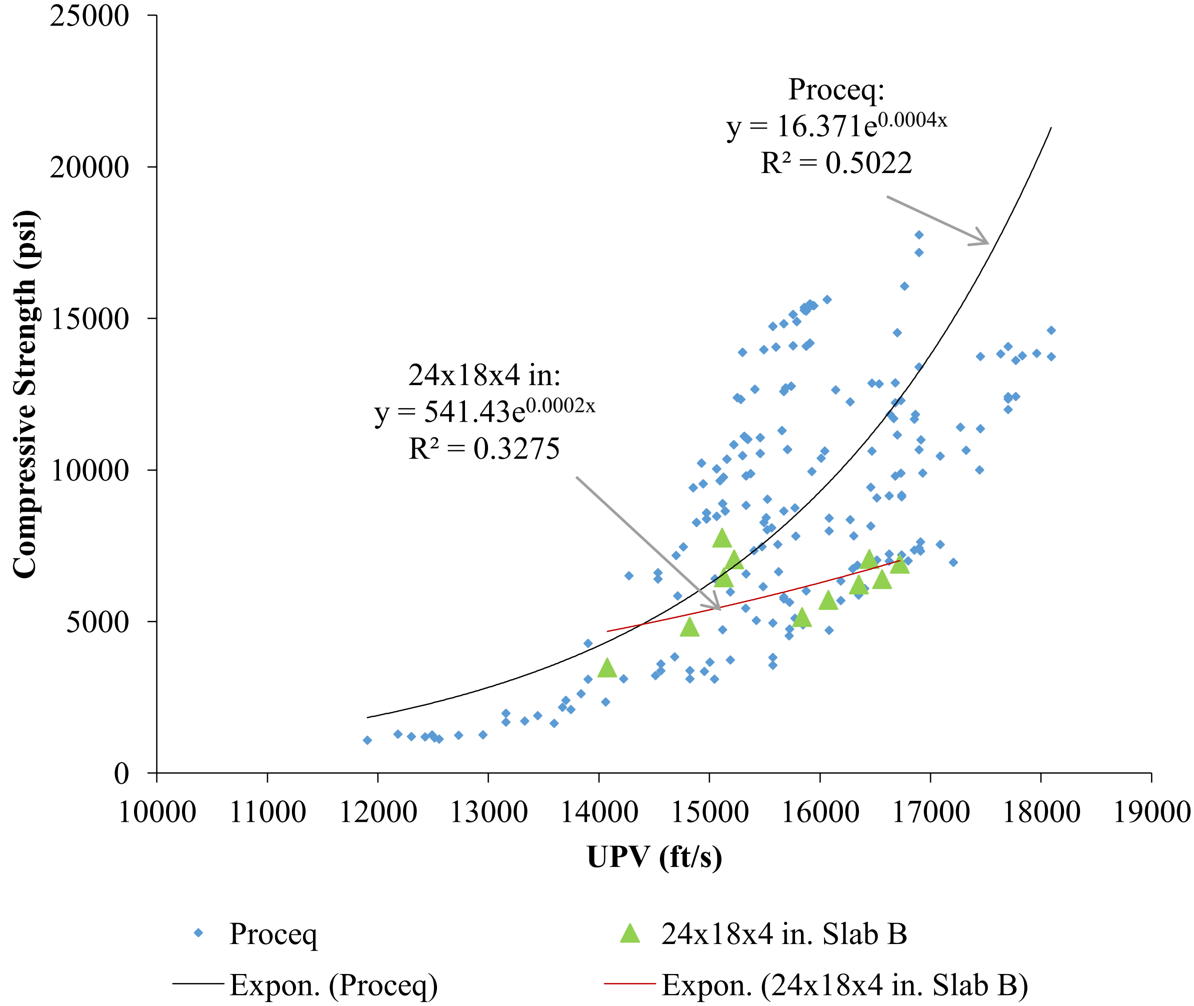


Figure C-5: UPV (ft/s) vs. Compressive Strength (psi) for 24x18x4 in. Slab B

Table C-6: UPV Test Results for Retaining Wall B (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3487	4833	5150	5715	6226	6403	6460	6910	7065	7054	7770
	12399	13550	14245	14345	14345	14141	14874	14303	14658	14568	14555
	12399	13524	14303	14286	14028	14028	14968	14332	14598	14598	14253
	12249	13418	14332	14315	14028	14028	14719	14390	14568	14598	14078
	12509	13444	14332	14286	14266	14028	14843	14361	14449	14568	14049
	12553	13471	14390	14286	14285	14141	14781	14303	14568	14598	14224
	12443	13471	14132	14286	14317	14217	14781	14390	14449	14479	14020
	12421	13471	14188	14345		14285	14925	14303	14449	14508	14224
	12487	14170	14217	14256		14137	14937	14245		14449	
	12421			14227						14508	
Average	12431	13565	14267	14292	14212	14126	14854	14328	14534	14542	14200

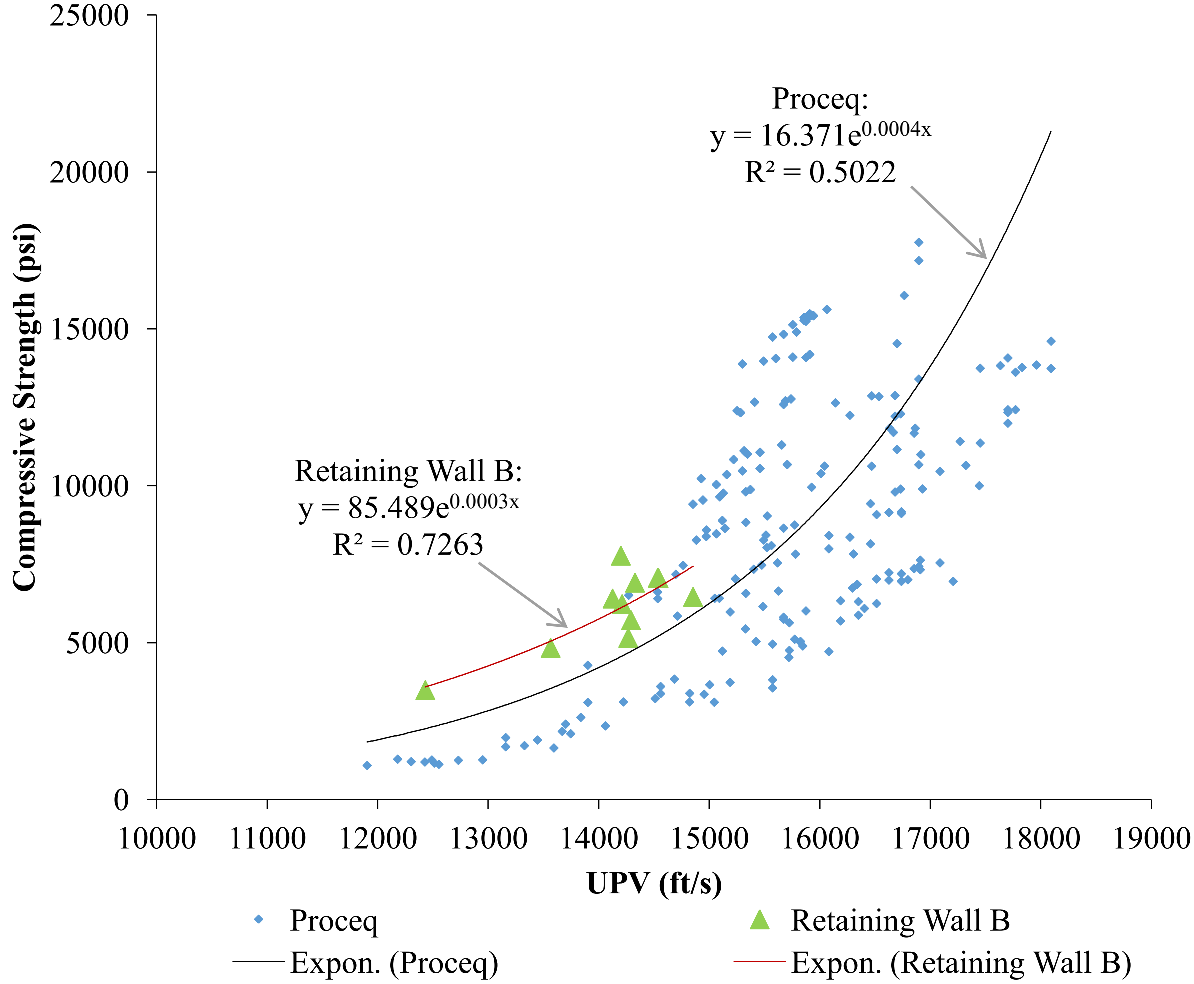


Figure C-6: UPV (ft/s) vs. Compressive Strength (psi) for Retaining Wall B

Table C-7: UPV Test Results for Group C 6x12 in. Cylinders (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180	
6x12 in. Str. (psi)	3269	4622	5059	5383	5789	6034	5982	6766	6291	6297	5917	6851	7058	7100	6792	6896	7044	6941	7579	7185	7841	7297	7704
	14094	14970	15674	15704	15699	16026	15873	16155	16000	16088	15959	16010	16234	16313	16207	16129	16367	16340	16026	16026	15823	16502	16420
	13995	15015	15647	15552	15699	16051	15873	16181	16051	16088	15985	16010	16234	16287	16181	16129	16313	16367	16051	15773	16026	16529	16529
	13917	15993	15699	15601	15699	16077	15898	16207	16000	16088	15959	15985	16260	16287	16340	16155	16260	16393	16026	15974	16207	16502	16340
	13898	15015	15674	15752	15699	15949	15873	16207	16000	16088	15959	15985	16260	16287	16367	16181	16234	16367	15848	15873	16207	16393	16447
	13898	14993	15674	15552	15773	16000	15848	16207	16000	16114	15909	16010	16287	16260	16367	16181	16181	16367	16051	16026	16000	16103	16340
	13907	15015	15699	15625	15773	16051	15870	16207	16000	16114	15959	15985	16287	16313	16393	16103	16260	16393	16077	15848	15723	16722	16287
	13897	15015	15576	15601	15773	16103	15823	16207	16000	16100	15959	16010	16234	16313	16393	16207	16234	16313	16181	16181	15601	16393	16077
					15823				15924	16144	15959	16010	16234	16313	16367		16260	16313	16026	16103	15748	16234	16207
											15985			16260	16340						15552	16393	16129
																						16287	16260
Average	13944	15145	15663	15627	15742	16037	15865	16196	15997	16103	15959	16001	16254	16293	16328	16155	16264	16357	16036	15976	15876	16406	16304

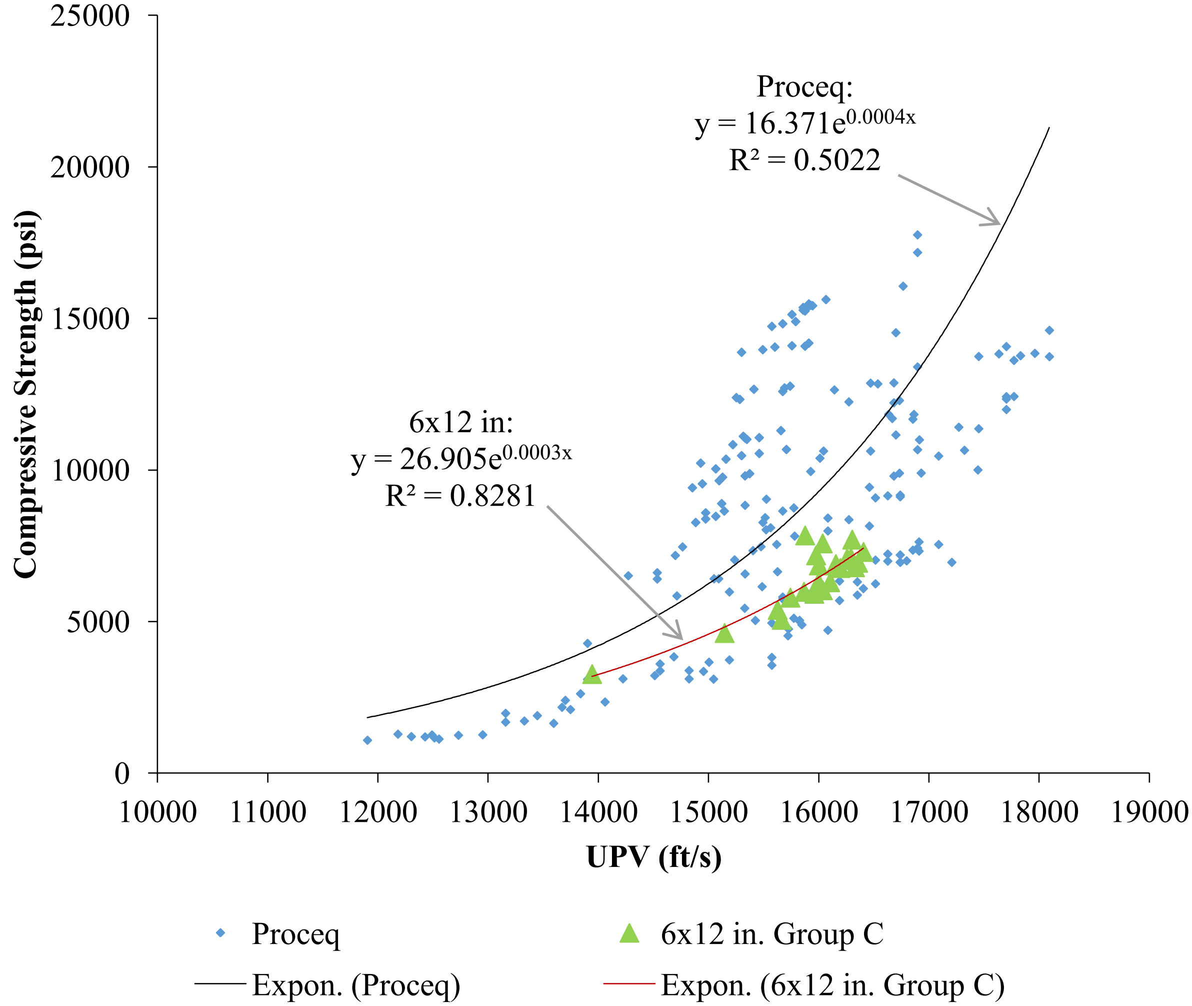


Figure C-7: UPV (ft/s) vs. Compressive Strength (psi) for Group C 6x12 in. Cylinders

Table C-8: UPV Test Results for 24x18x4 in. Slab C (ft/s)

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 90	Day 120	Day 180
6x12 in. Str. (psi)	3269	4622	5059	5383	5789	6034	6574	6925	6993	7382	7469
Core Strength (psi)				4580	5401			5719	6328	5953	7187
	13953	15121	15448	15690	15789	15690	16112	15823	16465	15560	15991
	13979	15152	15448	15658	15789	15690	16146	15806	16287	15740	16199
	14218	15000	15464	15740	15823	15213	16164	15707	16304	16026	15873
	14286	15136	15512	15823	15823	15244	15890	15512	16216	15873	16112
	14272	15060	15464	15773	15839	15259	16077	15560	16322	15806	16112
	14245	15121	15496	15806	15873	15353	16094	15641	16287	15690	16199
	14245	15045	15448		15890	15890	16199	15609	16216	15723	16322
	14231	15015			15890			15432	16164	15625	
	14231	15045									
		15212									
Average	14184	15091	15469	15748	15840	15477	16097	15636	16283	15755	16115

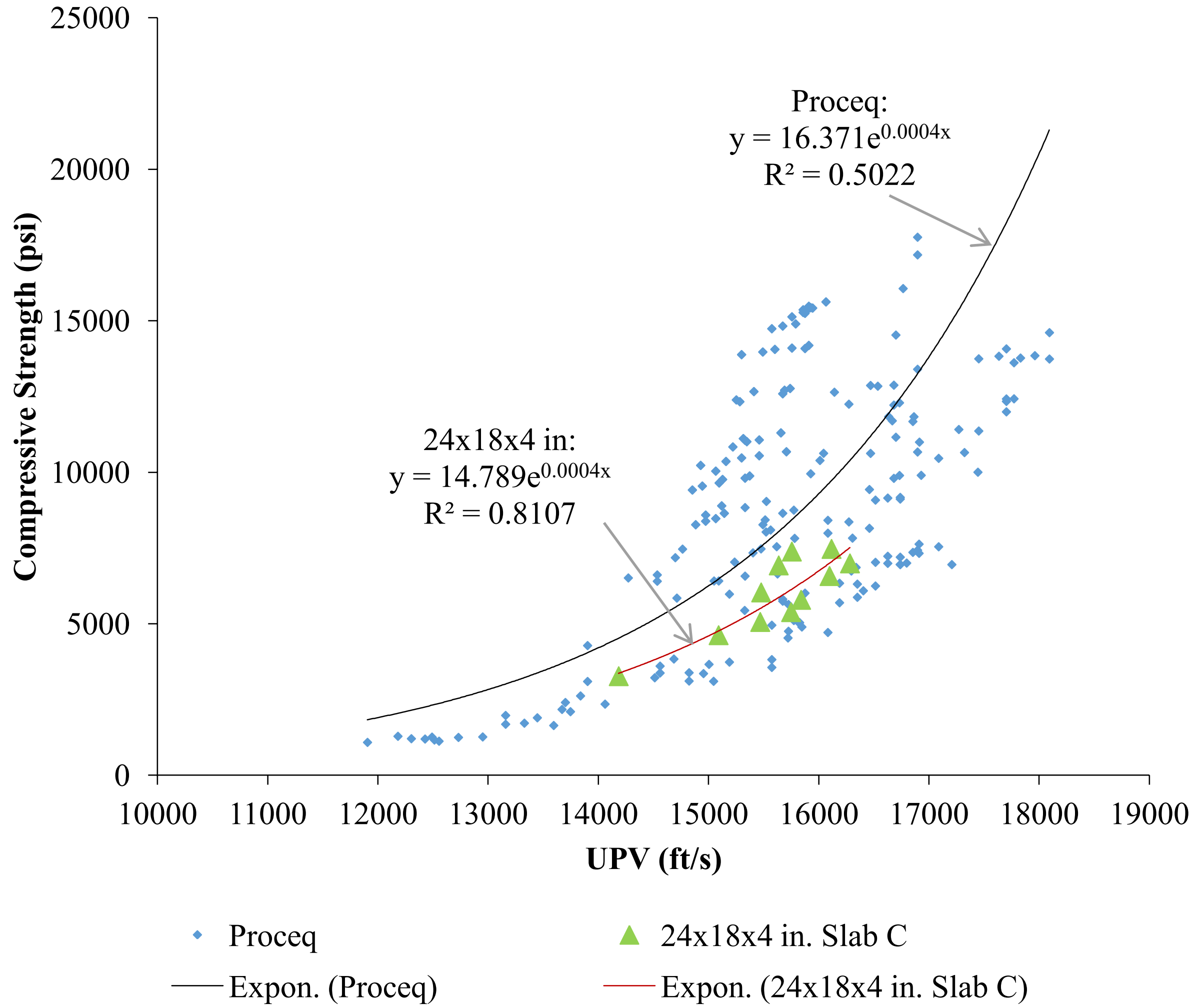


Figure C-8: UPV (ft/s) vs. Compressive Strength (psi) for 24x18x4 in. Slab C

Appendix D

Windsor Pin Penetration Test Results for Cylinders, Slabs, and Retaining Walls

Table D-1: Pin Penetration Test Results for Group A 6x12 in. Cylinders (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180	
6x12 in. Str (psi)	3219	4648	5484	5680	6322	6356	6549	6463	6264	6594	6635	6150	7003	6742	6117	7239	6948	6947	7275	7012	7333	7431	8023
	757	771	809	819	814	864	834	849	863	802	849	856	824	861	806	814	832	841	834	850	834	857	851
	776	809	798	849	854	836	854	824	860	804	829	869	831	804	814	899	875	838	880	827	835	874	876
	822	787	858	824	842	848	856	847	864	809	812	820	851	851	810	816	868	855	850	863	860	837	810
	839	834	812	814	820	826	835	821	750	814	837	831		841	827	839	841		826	807	828	831	867
	813	811	811	824	818	878				803					819					832			
	817	788	801	837	816	840				846													
	771	770	803		818	842																	
	818	777	801		840																		
	824	798																					
Average	804	794	812	828	828	848	845	835	834	813	832	844	835	839	815	842	854	845	848	836	839	850	851

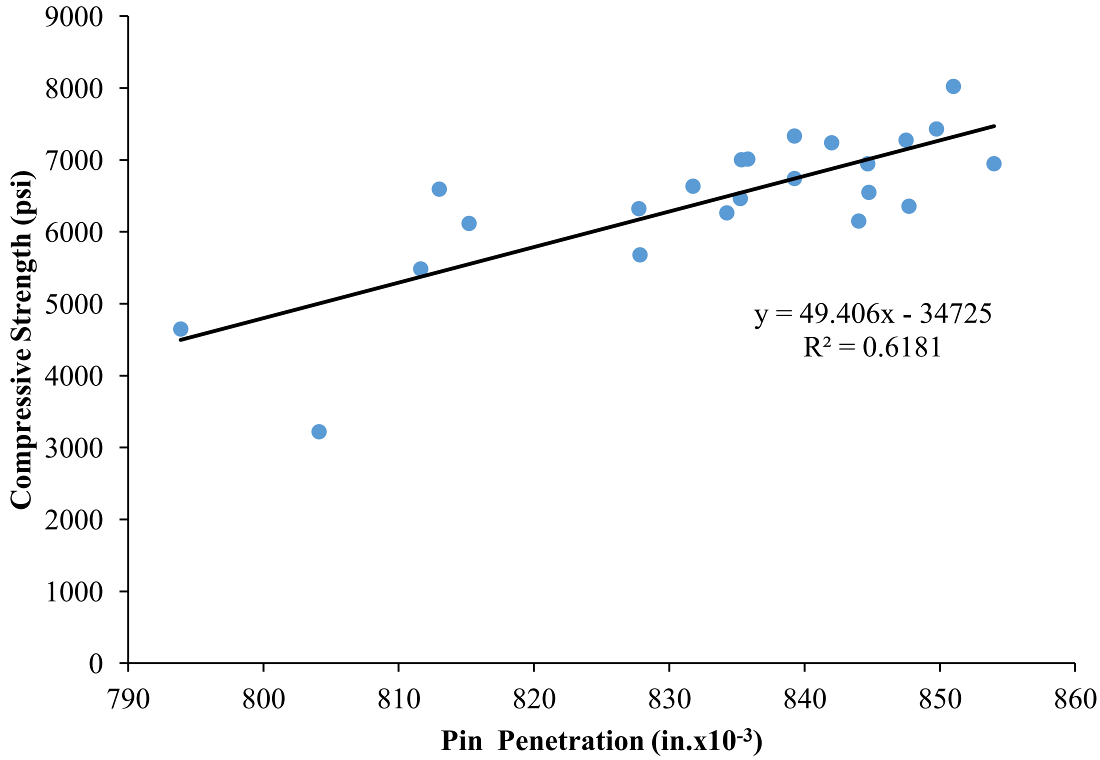


Figure D-1: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for Group A 6x12 in. Cylinders

Table D-2: Pin Penetration Test Results for 24x18x4 in. Slab A (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 120	Day 180
6x12 in. Str (psi)	3219	4648	5484	5680	6322	6356	6474	6621	7207	7880
Core Strength (psi)				4487	4740			6303	5791	6624
	773	824	829	834	829	821	834	832	834	824
	778	805	818	809	856	835	804	852	819	848
	749	814	816	797	842	867	807	859	828	835
	767	807	819	831	829	824	826	837	829	839
	754	768	807	839	843	824	809	824	814	856
	764	785	823	826			812	867		833
							834			
							829			
							851			
Average	764	801	819	823	840	834	823	845	825	839

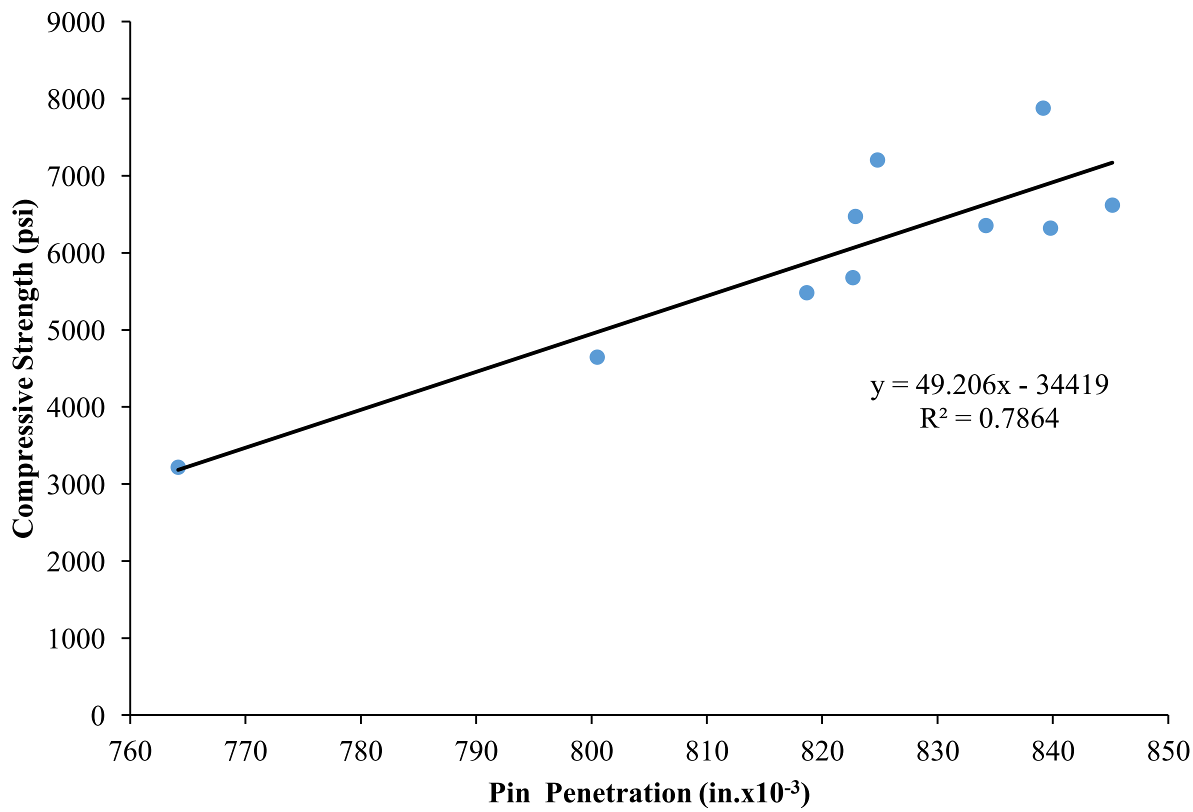


Figure D-2: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for 24x18x4 in. Slab A

Table D-3: Pin Penetration Test Results for Retaining Wall A (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 28	Day 42	Day 56	Day 120	Day 180
6x12 in. Str (psi)	3219	4648	5484	5680	6356	6474	6621	7207	7880
	792	798	812	819	830	801	852	846	824
	803	820	803	836	821	829	849	834	836
	757	793	831	825	888	846	841	835	829
	767	821	814	806	838	821	829	800	827
	734	779	798	834	834	834	830	826	807
	786	871	827	830	813	813	835		829
	783	797	814			812			
	776		807						
	776								
	777								
Average	775	811	813	825	837	822	839	828	825

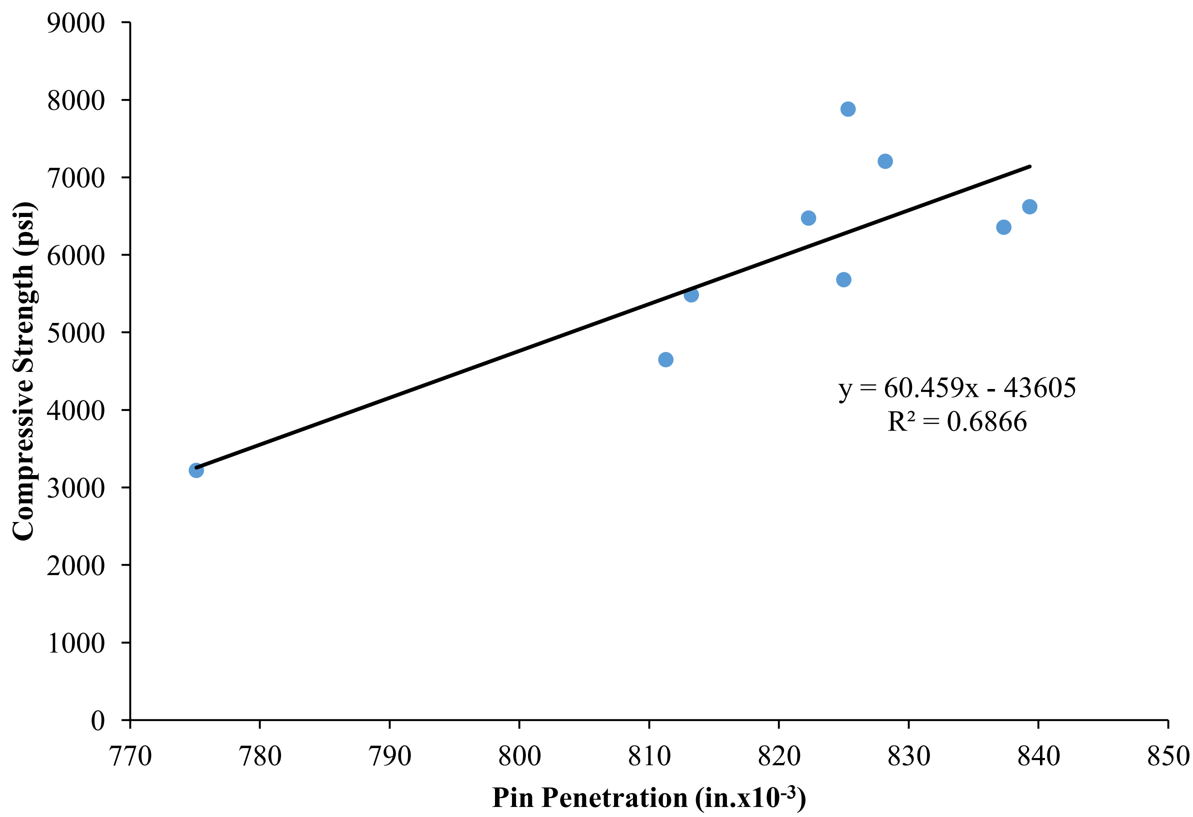


Figure D-3: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for Retaining Wall A

Table D-4: Pin Penetration Test Results for Group B 6x12 in. Cylinders (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str (psi)	3487	4833	5150	5715	6226	6403	5994	6260	6368	6351	6203	6745	6834	7163	6732	7014	7116	7554	6919	6651	7189	7817	7641	7852
	774	831	829	813	825	831	829	823	811	819	814	861	841	835	834	842	839	820	842	866	859	867	811	832
	754	806	803	815	839	869	852	822	813	809	837	812	831	838	852	854	813	856	828	846	871	849	827	839
	781	829	809	816	840	844	839	841	823	829	834	820	840	801	853	848	854	847	831	852	877	854	834	849
	776	804	814	817	825	822		862	824	824	809	857		815			846						845	
	784	798	802	839	859	847		817	851		833			836									837	
	741	814	852	843		846			860															
	779		807	844																				
			804	847																				
				874																				
				877																				
				881																				
Average	770	814	815	842	838	843	840	833	830	820	825	838	837	825	846	848	838	841	834	855	869	857	831	840

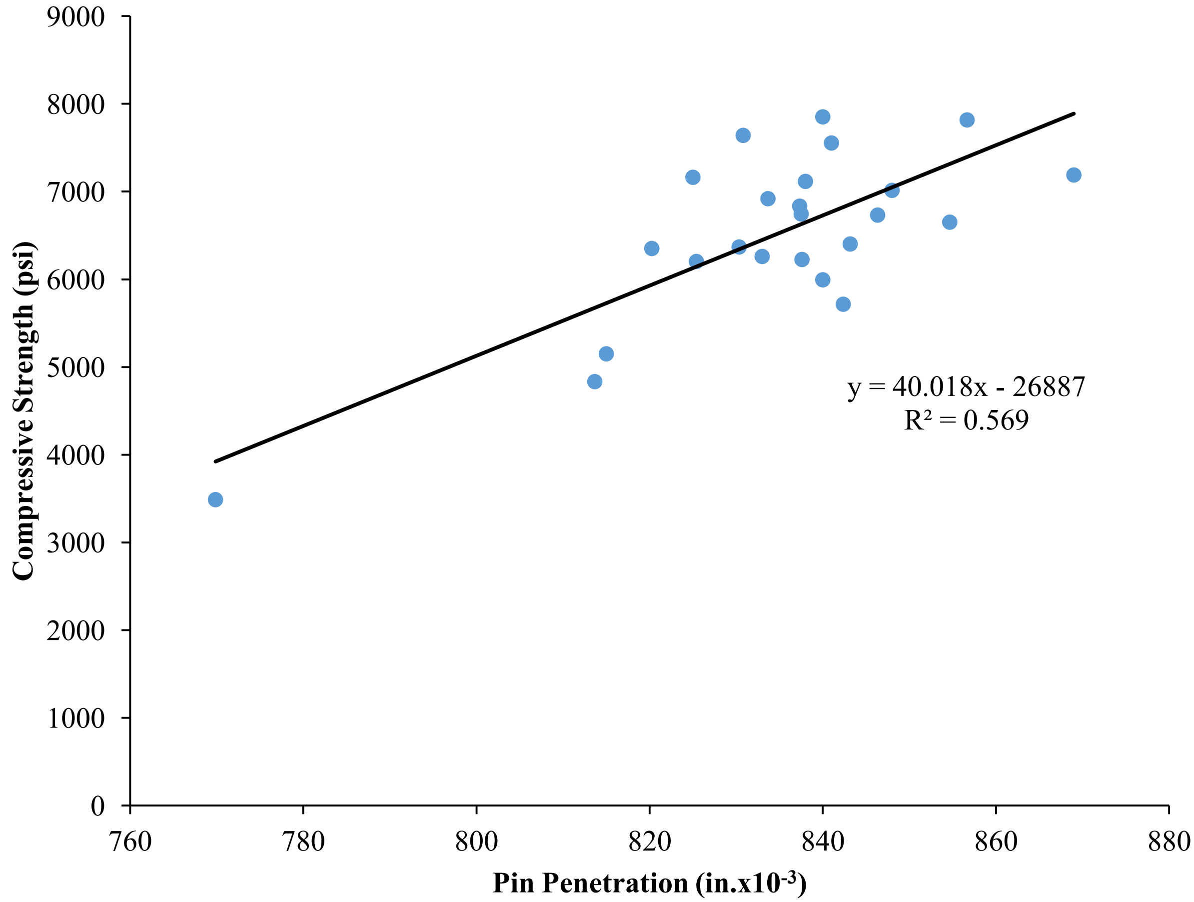


Figure D-4: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for Group B 6x12 in. Cylinders

Table D-5: Pin Penetration Test Results for 24x18x4 in. Slab B (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 120	Day 180
6x12 in. Str (psi)	3487	4833	5150	5715	6226	6403	6460	6910	7054	7770
	781	754	756	806	837	845	797	820	823	827
	786	747	750	827	825	831	860	838	820	832
	751	766	749	834	817	865	829	819	868	837
	783	726	746	804	833	823	810	812	830	858
	749	759	729	824	825	821	805	795	854	829
	722		732	799	829	826	838	834		818
							851	804		836
							807	832		
Average	762	750	744	816	828	835	825	819	839	834

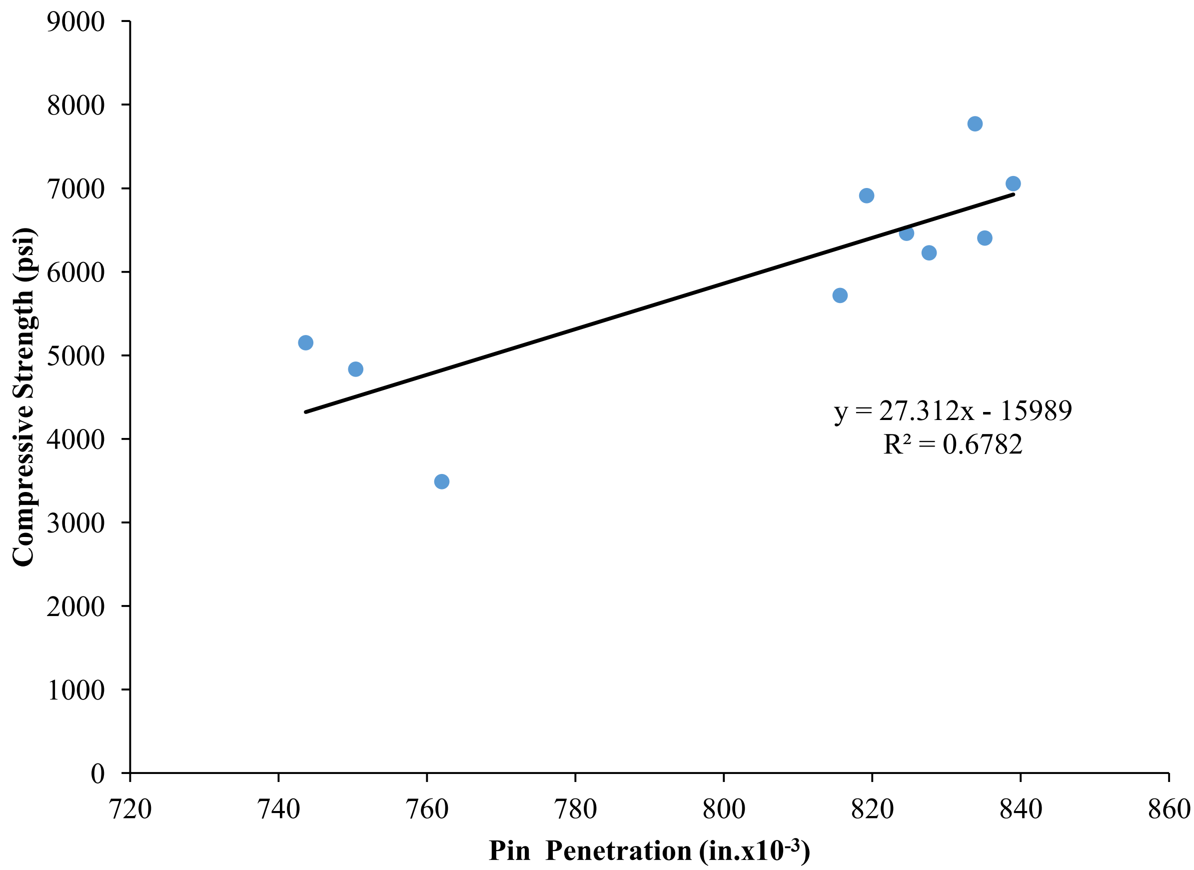


Figure D-5: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for 24x18x4 in. Slab B

Table D-6: Pin Penetration Test Results for Retaining Wall B (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 120	Day 180
6x12 in. Str (psi)	3487	4833	5150	5715	6226	6403	6460	6910	7054	7770
	712	761	749	801	836	859	813	850	835	860
	707	776	771	787	841	826	810	818	808	830
	703	782	768	793	804	819	811	815	854	811
	732	738	774	778	831	837	826	819	864	823
	698	742	756	784	829	829	799	815	845	822
	702	757	753	781	837		793	814		845
	691	768								
Average	706	761	762	787	830	834	809	822	841	832

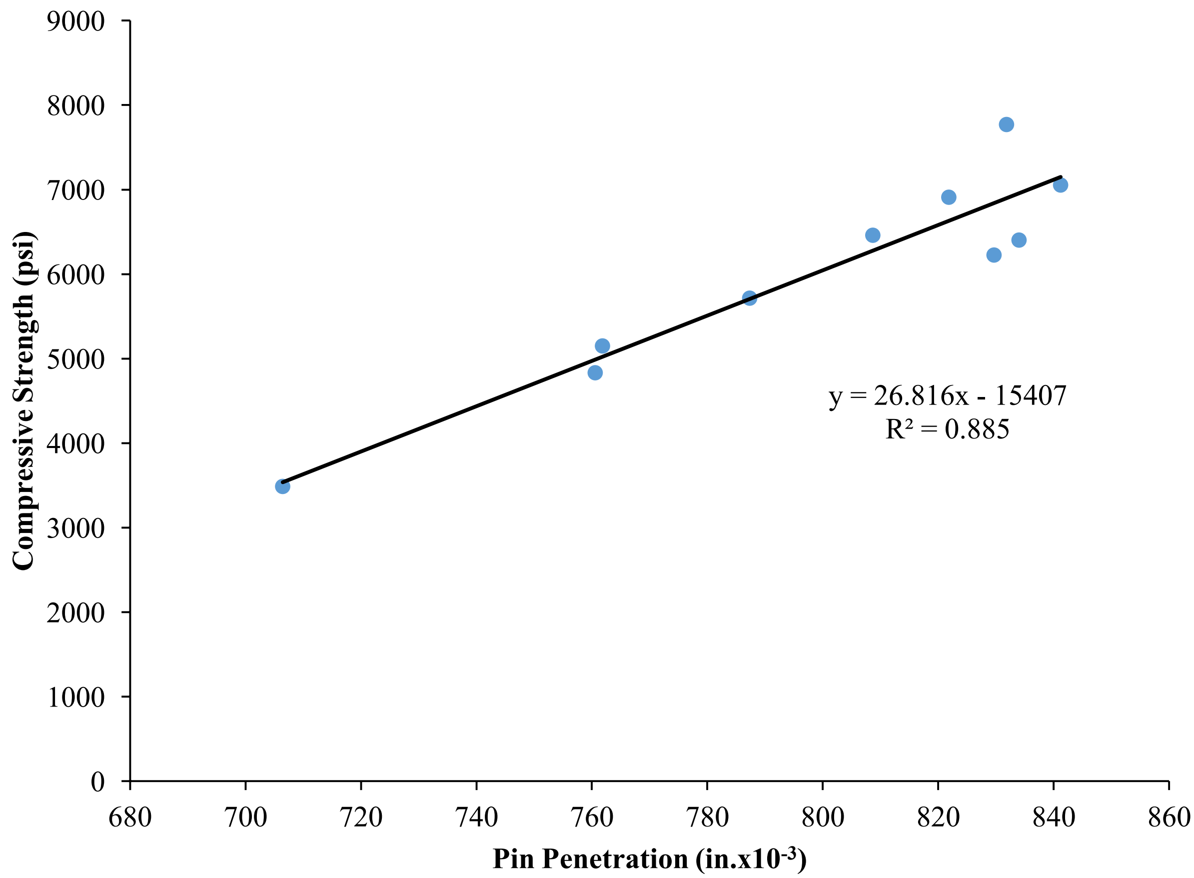


Figure D-6: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for Retaining Wall B

Table D-7: Pin Penetration Test Results for Group C 6x12 in. Cylinders (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 35			Day 42			Day 56			Day 90			Day 120			Day 180		
6x12 in. Str (psi)	3269	4622	5059	5383	5789	6034	5982	6766	6291	6297	5917	6851	7058	7100	6792	6896	7044	6941	7579	7185	7841	7297	7704	7406
	771	815	831	819	873	878	810	829	852	881	831	858	834	834	854	820	849	837	834	854	875	839	860	861
	820	842	815	826	867	845	837	824	826	815	816	854	773	836	834	815	844	836	837	824	831	821	826	863
	833	823	804	824	831	844	845	821	839	812	876	861	839	831	804	856	837	829	844	821	875	804	846	847
	832	821	832	821	839	848	848			809	822	832	846		827							836	842	
	807	809	798	829	837	834	875			857	849	815										843		
	809	829	854		824																			
	856	823	824		875																			
	758	798	823																					
	834																							
	817																							
Average	814	820	823	824	849	850	843	825	839	835	839	844	823	834	830	830	843	834	838	833	860	829	844	857

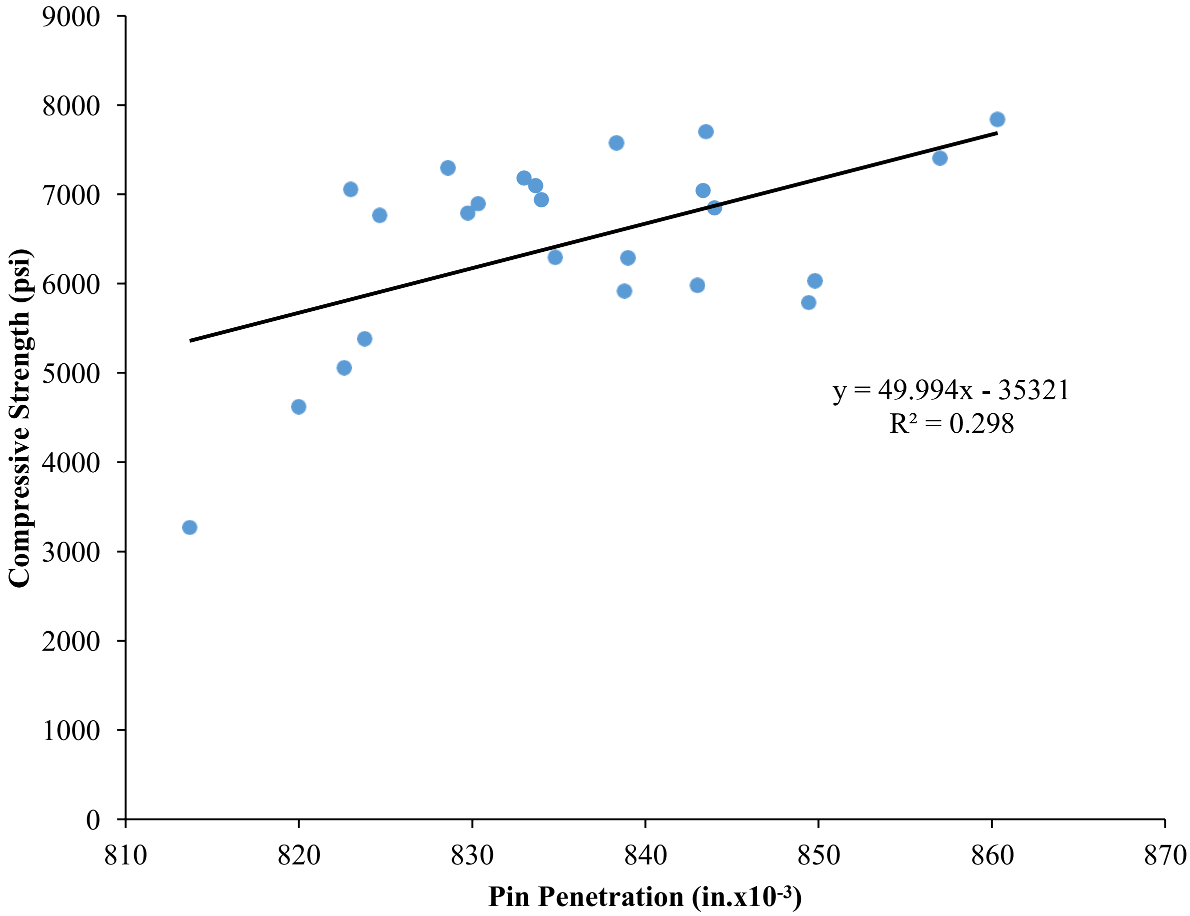


Figure D-7: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for Group C 6x12 in. Cylinders

Table D-8: Pin Penetration Test Results for 24x18x4 in. Slab C (in.x10^{-3})

	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28	Day 42	Day 56	Day 120	Day 180
6x12 in. Str (psi)	3269	4622	5059	5383	5789	6034	6574	6925	7382	7469
Core Strength (psi)				4580	5401			5719	5953	7187
	781	773	801	837	804	879	876	812	835	841
	786	776	807	834	819	806	828	809	814	801
	751	759	826	831	833	848	839	862	834	827
	783	778	807	839	812	834	834	822	811	821
	749	767	824	826	854	832	846	865	891	831
	722	751	806	809	831		838	831	859	818
								832		
Average	762	767	812	829	826	840	844	833	841	823

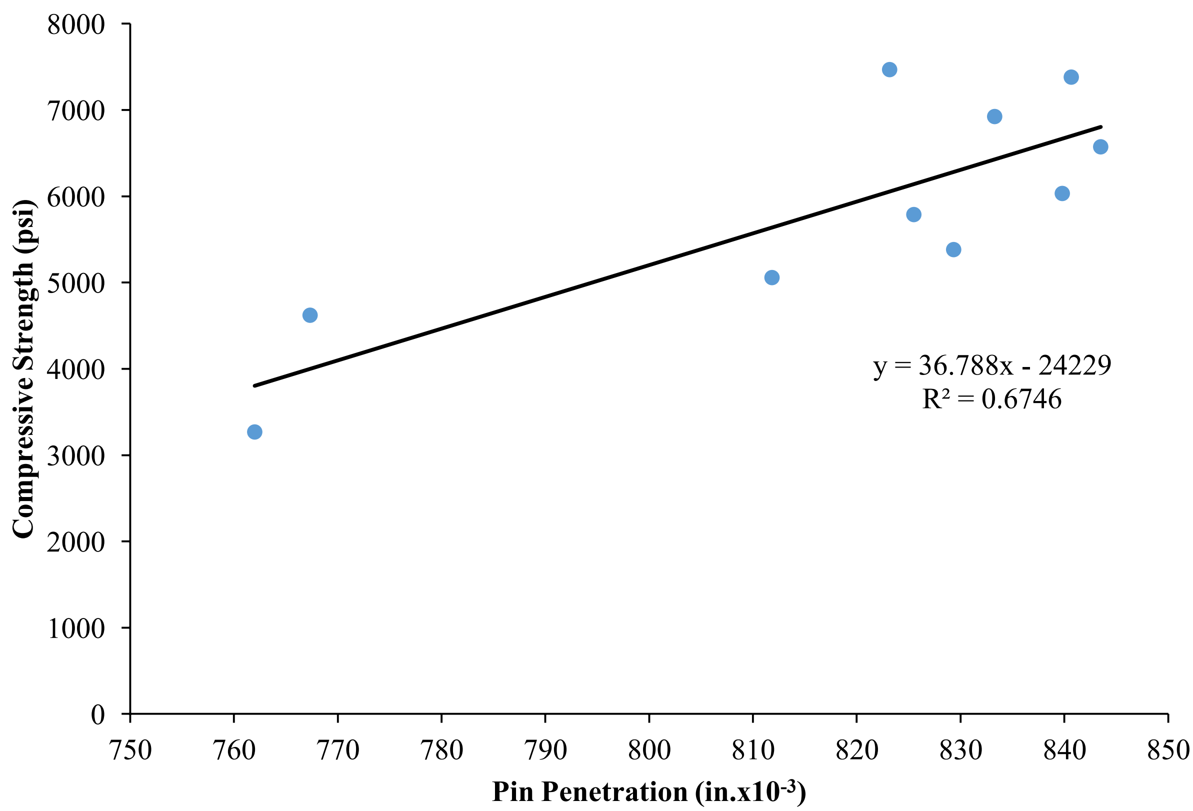


Figure D-8: Pin Penetration (in.x10^{-3}) vs. Compressive Strength (psi) for 24x18x4 in. Slab C

Appendix E

Windsor Probe Penetration Results for Retaining Walls

Table E-1: Windsor Probe Test Results for Retaining Wall A

Age (Days)	Exposed Probe	Average Exposed Probe (in.)	Str. (psi)	Average Str. (psi)	Std. Dev
7	1.71	1.78	2256	2890	0.07
	1.72		2336		
	1.86		3524		
	1.86		3524		
	1.77		2812		
14	2.07*	1.92	5425*	4119	0.10
	1.88		3762		
	1.96		4475		
21	1.81*	1.93	3128*	4159	0.08
	1.96		4475		
	1.89		3842		
28	1.91	1.95	4000	4343	0.03
	1.96		4475		
	1.97		4555		
42	2.05	2.01	5189	4845	0.04
	1.97		4555		
	2.00		4792		
56	2.08	2.09	5505	5611	0.02
	2.09		5585		
	2.11		5743		
90	2.14	2.12	6059	5822	0.03
	2.08		5505		
	2.13		5901		
120	2.28	2.15	7248	6007	0.11
	2.08		5189		
	2.09		5585		
180	2.09	2.18	5585	6403	0.08
	2.24		6931		
	2.22		6693		

*Data not used

Table E-2: Windsor Probe Test Results for Retaining Wall B

Age (Days)	Exposed Probe	Average Exposed Probe (in.)	Str. (psi)	Average Str. (psi)	Std. Dev
7	1.56	1.62	910	1465	0.10
	1.53		672		
	1.76		2654		
	1.57		1069		
	1.68		2020		
14	1.76*	1.92	2654*	4045	0.01
	1.93		4169		
	1.91		3921		
21	2.04	2.05	5109	5109	0.02
	2.08		5505*		
	2.04		5109		
28	2.14*	1.96	5981*	4476	0.01
	1.97		4555		
	1.95		4396		
42	1.93	2.00	4258	4605	0.06
	2.05		5267*		
	2.02		4951		
56	1.87	1.92	5505	5545	0.05
	1.96		5585		
	1.92		5743*		
90	2.07	2.06	5425	5399	0.02
	2.06		5347		
	2.04		5425		
120	2	2.02	4792*	5109	0.03
	2.06		5347		
	2.01		4871		
180	2.21	2.16	6615	5981	0.05
	2.15		6139		
	2.12		5823		

*Data not used

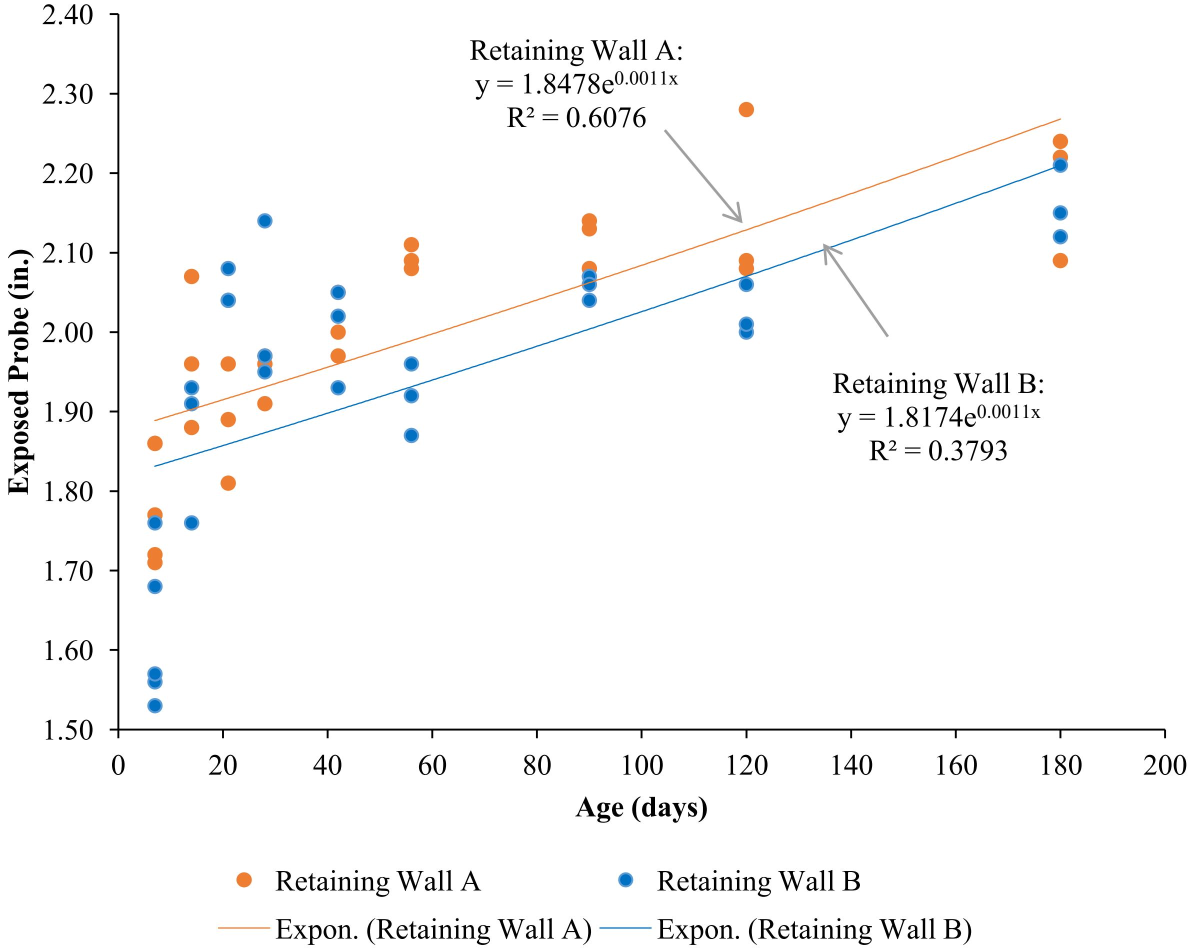


Figure E-1: Length of Exposed Probe (in.) vs. Age (days) for Retaining Walls A&B

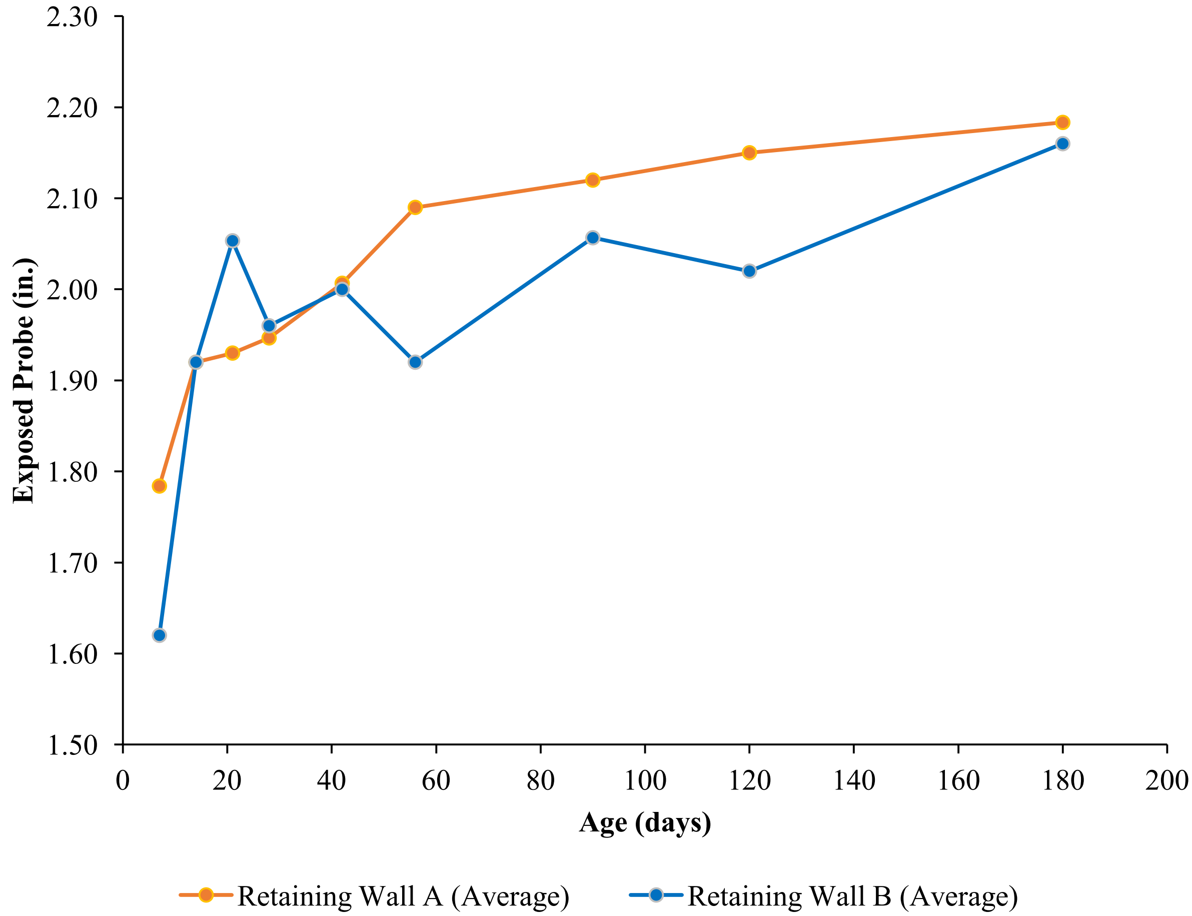


Figure E-2: Average Length of Exposed Probe (in.) vs. Age (days) for Retaining Walls A&B

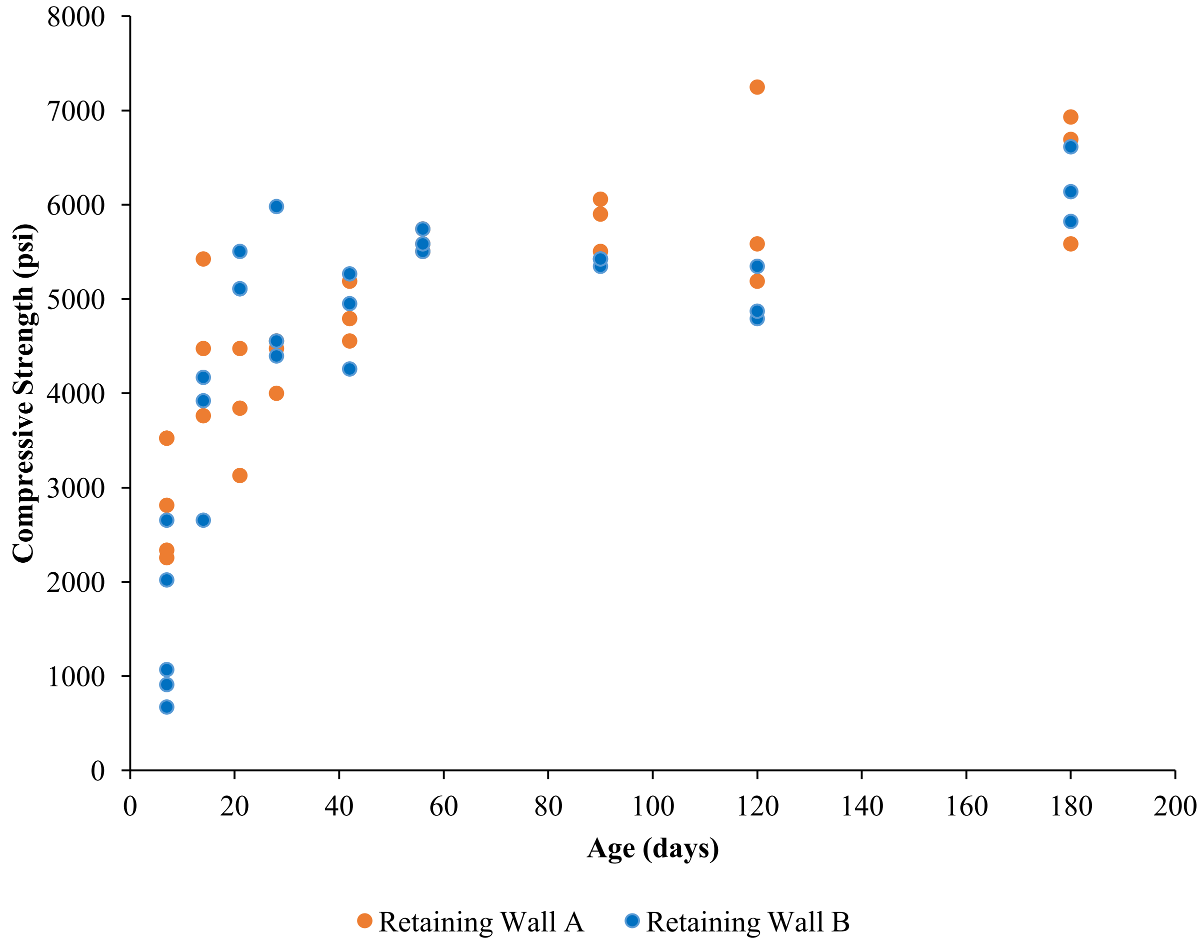


Figure E-3: Compressive Strength (psi) vs. Age (days) for Retaining Walls A&B

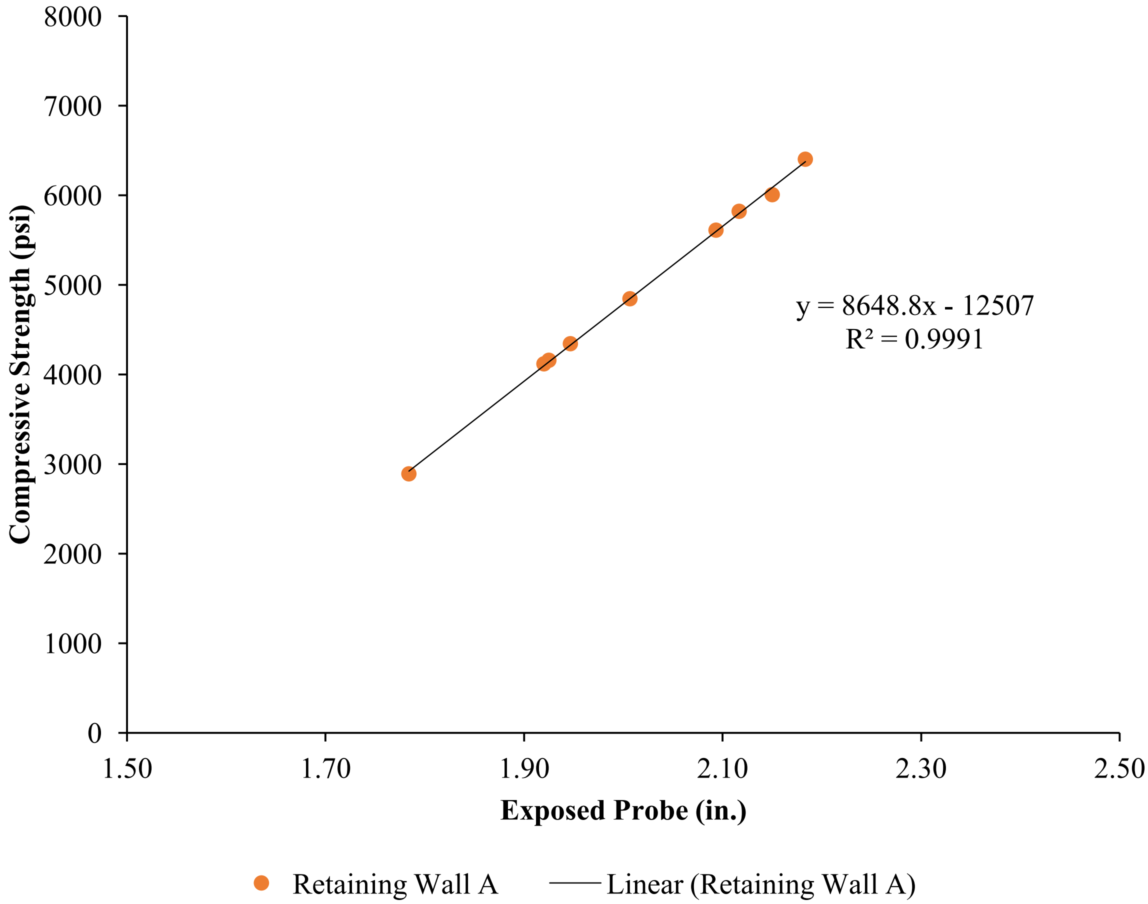


Figure E-4: Average Exposed Probe (in.) vs. Average Compressive Strength (psi) for Retaining Wall A

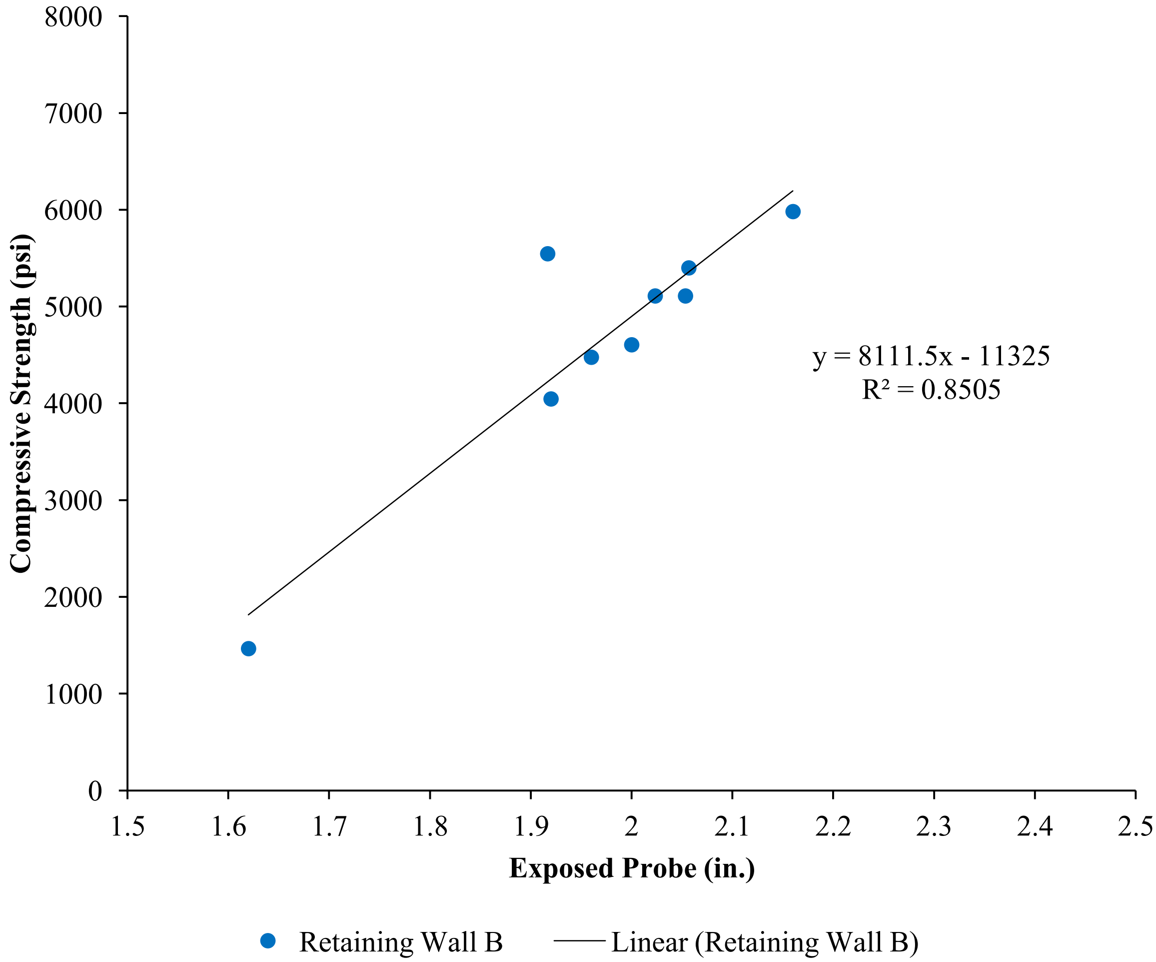


Figure E-5: Average Exposed Probe (in.) vs. Average Compressive Strength (psi) for Retaining Wall B

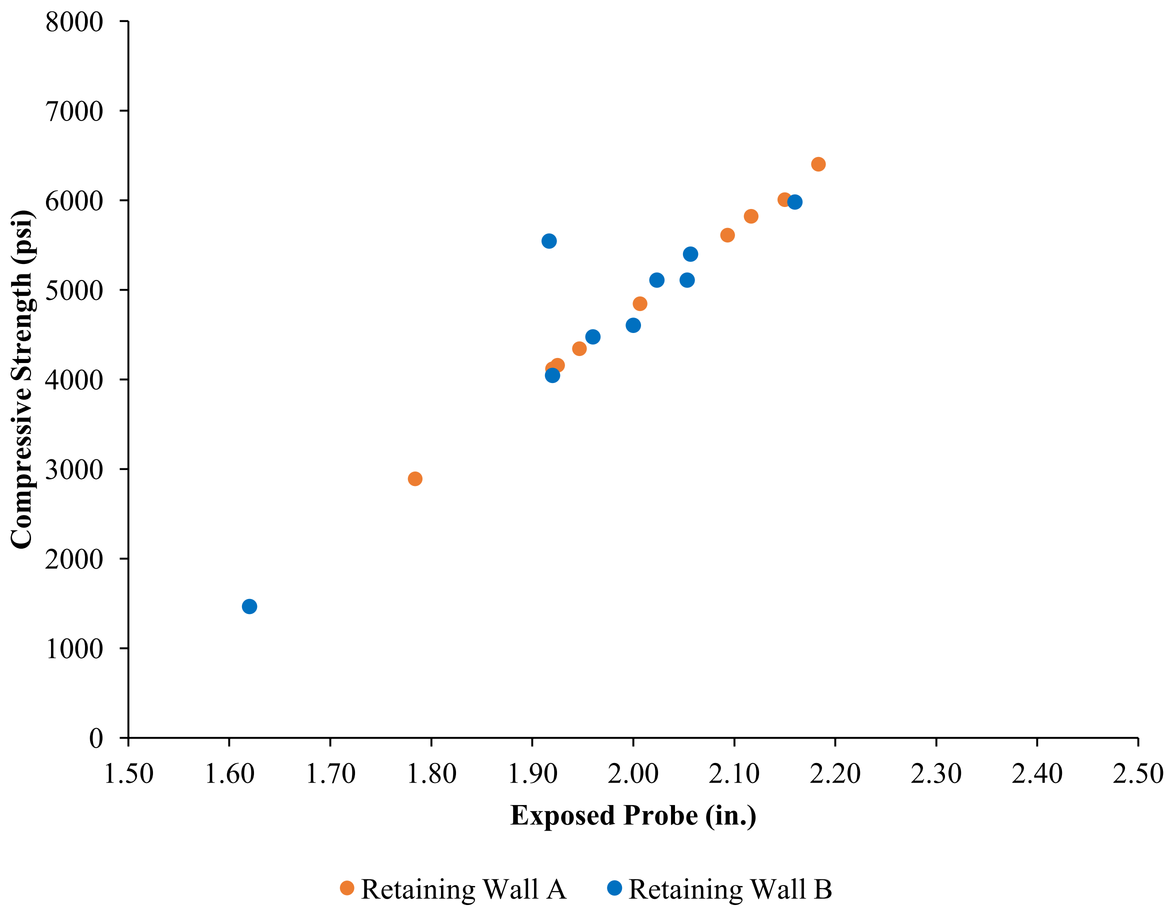


Figure E-6: Exposed Probe (in.) vs. Average Compressive Strength (psi) for Retaining Walls A&B

Appendix F

Strength Prediction Charts for the Rebound Hammer, UPV, Windsor Pin, and Windsor Probe systems and tables for all seven counties

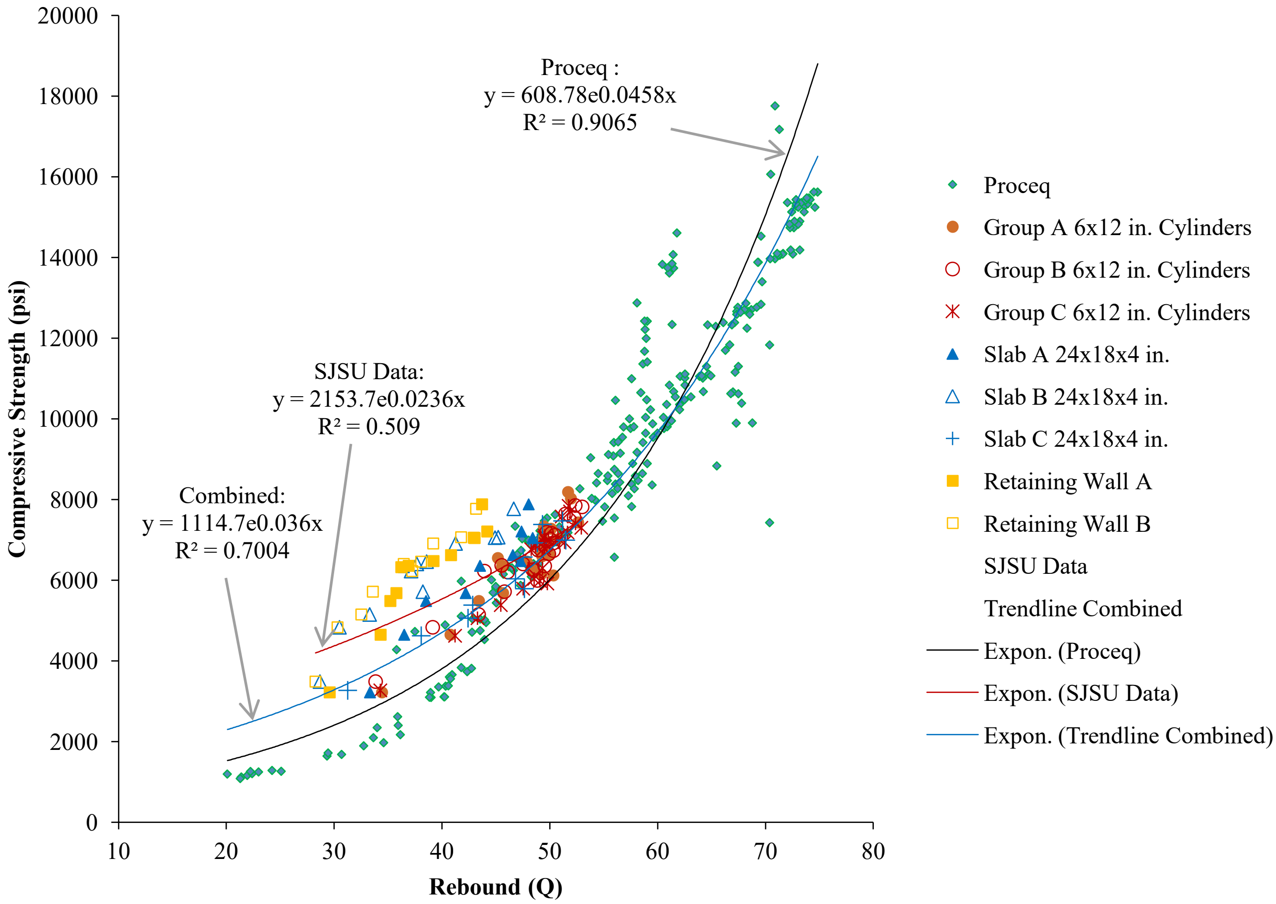


Figure F-1: Strength Prediction Chart for the Silver Schmidt Rebound Hammer

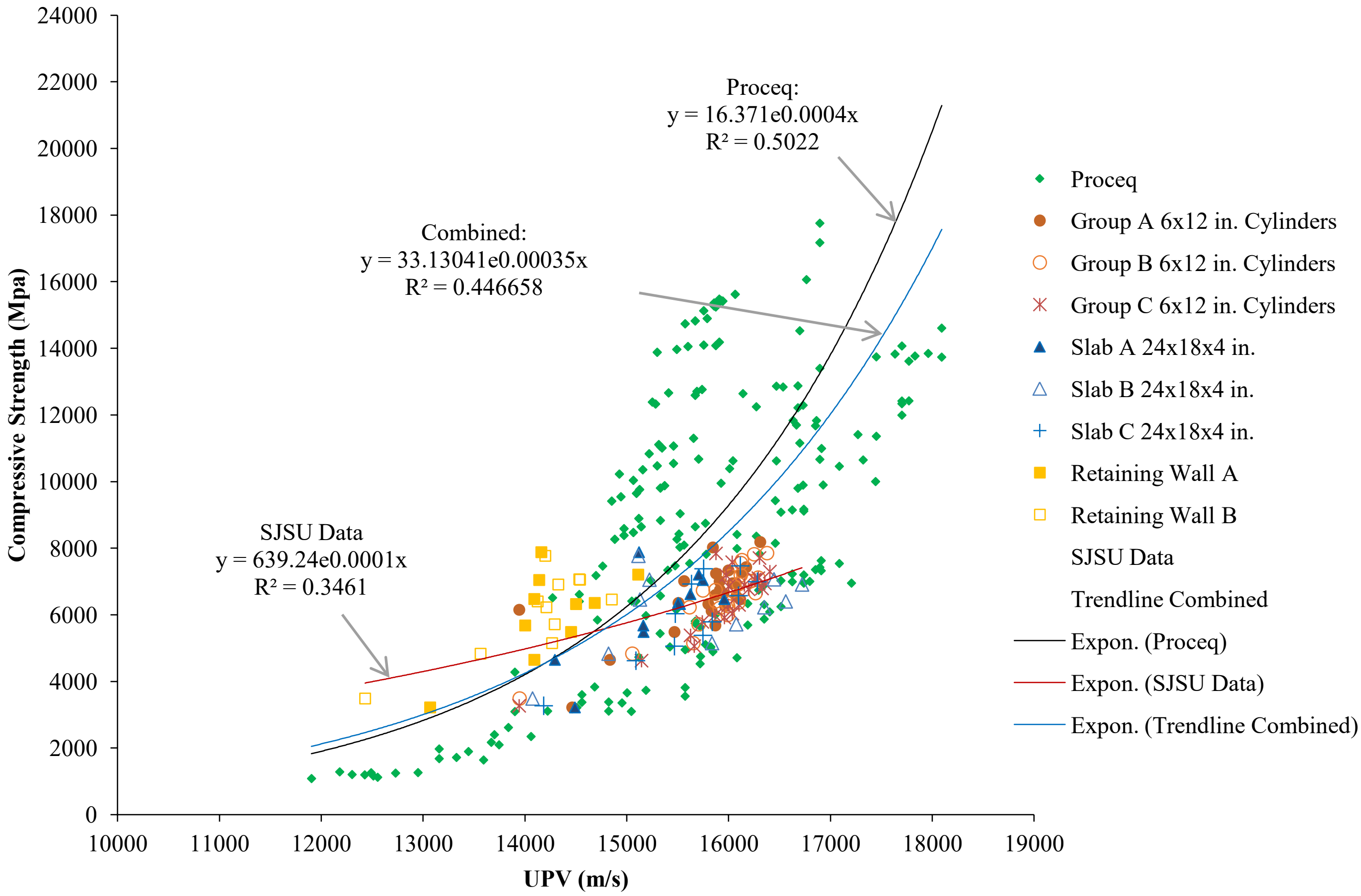


Figure F-2: Strength Prediction Chart for the Ultrasonic Pulse Velocity (UPV)

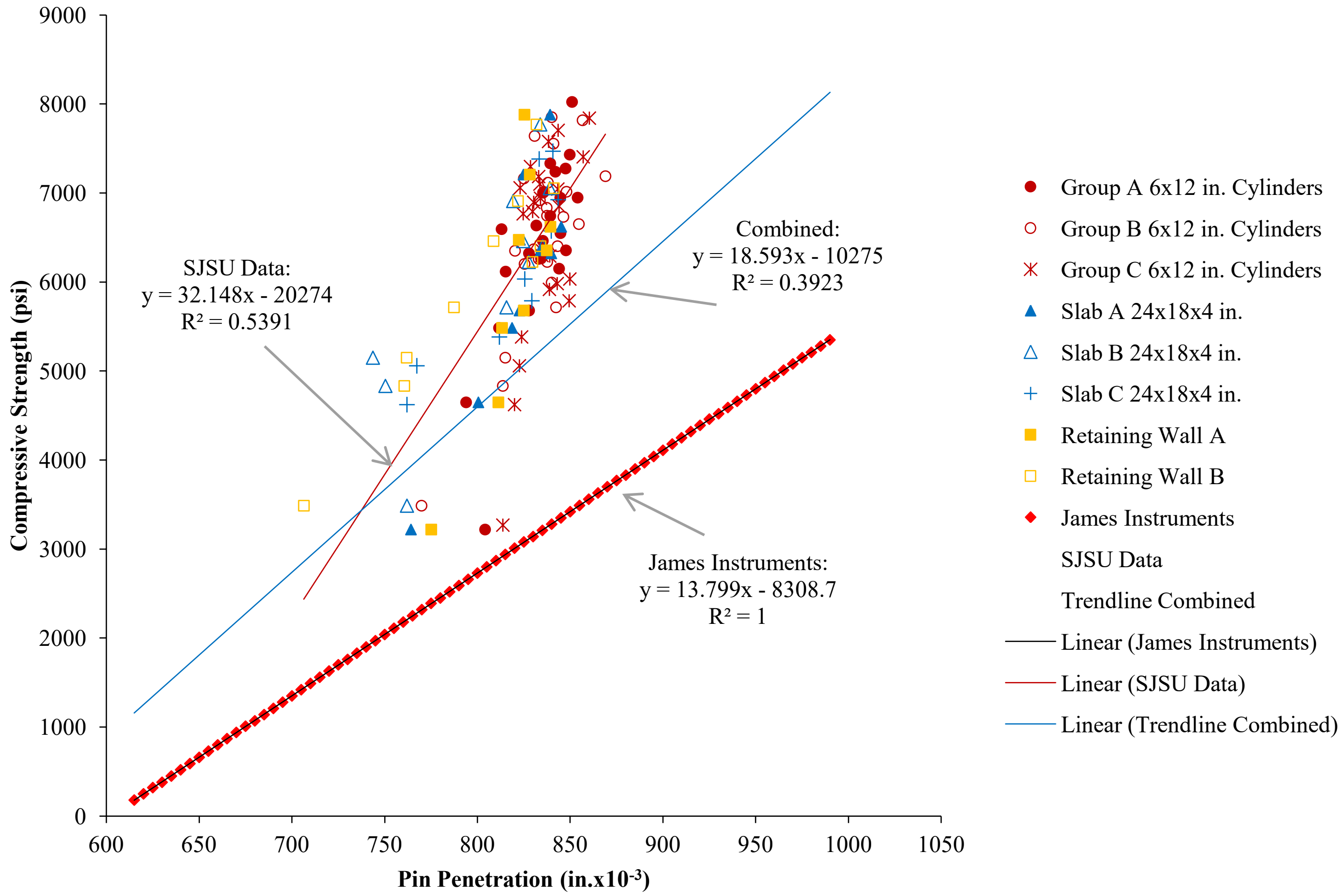


Figure F-3: Strength Prediction Chart for the Windsor Pin Penetration System

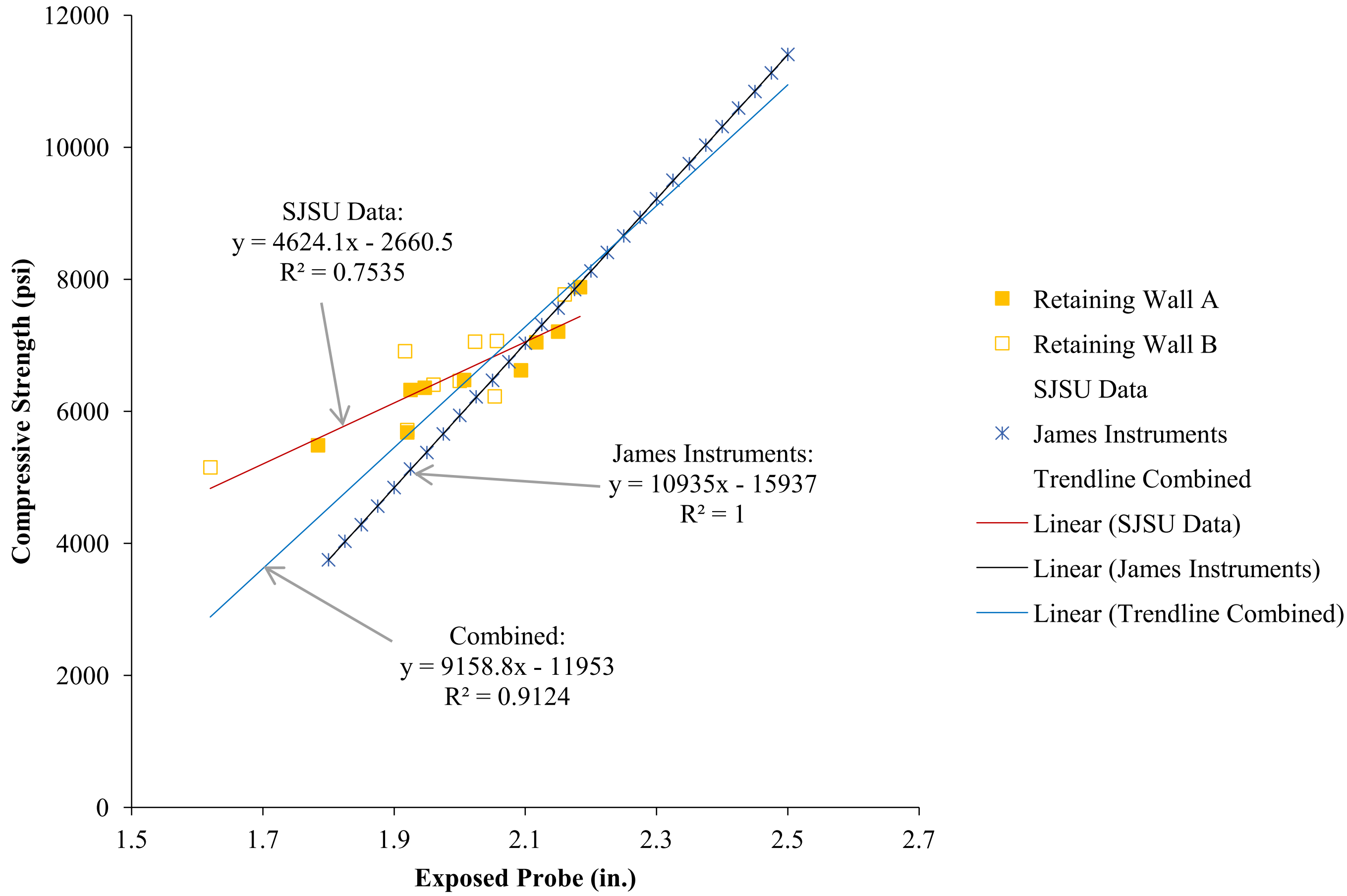


Figure F-4: Strength Prediction Chart for the Windsor Probe System

Table F-1: Contra Costa County Strength Predictions

Bridge No. (Date Built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	**Mean (σ)	Min	Max	% Increase (Mean σ)	σĀ 2StDev	σĀ 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
28C0189R (1966)	5500	8760	6634	8471	5539	7955	6634	8760	45	5649	6802	9108	10261	1153
28C0189L (1966)	5500	8255	7289	8105	3613*	7883	7289	8255	43	6843	7363	8403	8923	520
28C0087 (1965)	5800	8614	7148	8960	3457*	8241	7148	8960	42	6317	7279	9202	10164	962
28C0094 (1965)	4500	7915	7084	9906	2500*	8302	7084	9906	84	5401	6852	9752	11202	1450
28C0091L (1964)	4700	8289	6891	9326	3272*	8169	6891	9326	74	5725	6947	9391	10613	1222
28C0167 (1980)	5000	6664	6377	9631	3444*	7557	6377	9631	51	3954	5756	9359	11161	1802
28C0085 (1975)	4000	8411	7052	8815	4705	8093	7052	8815	102	6245	7169	9016	9940	924
Average	5000	8130	6925	9030	3790	8028	6925	9093	63	5733	6881	9176	10323	1147

Table F-2: Fresno County Strength Predictions

Bridge No. (Date Built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	**Mean (σ)	Min	Max	% Increase (Mean σ)	σĀ 2StDev	σĀ 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
42C0136 (1963)	6000	8301	7373	9685	4633*	8453	7373	9685	41	6127	7290	9616	10779	1163
42 0355 (1966)	6000	8263	7180	8807	4081*	8084	7180	8807	35	6427	7256	8912	9740	828
42 0272 (1967)	6000	7796	6891	9227	3725*	7971	6891	9227	33	5616	6794	9149	10327	1178
42 0270 (1967)	6000	8082	6827	9181	6605	8030	6827	9181	34	5674	6852	9208	10386	1178
42C0649 (2006)	6000	6264	6827	7670	4125*	6920	6264	7670	15	5505	6212	7628	8335	708
42C0009 (1975)	4000	7879	6827	9094	3655*	7933	6827	9094	98	5664	6799	9068	10202	1135
Average	5667	7764	6988	8944	4471	7898	6894	8944	43	5836	6867	8930	9961	1031

Table F-3: Los Angeles County Strength Predictions

Bridge No. (Date built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	**Mean (σ)	Min	Max	% Increase (Mean σ)	σ- 2StDev	σ- 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
53C1457 (1961)	5000	8166	7245	9845	3862*	8418	7245	9845	68	5782	7100	9737	11055	1318
53 0851 (1969)	4000	8401	7052	9692	4135	8382	7052	9692	110	5741	7061	9702	11022	1320
53 2032R (1970)	4000	7241	7438	9295	4540	7991	7241	9295	100	5725	6858	9125	10258	1133
53 2032L (1970)	4000	7521	7438	9967	3472*	8309	7438	9967	108	5435	6872	9745	11182	1437
53 1681 (1965)	4500	7558	7502	9601	1962*	8220	7502	9601	83	5829	7024	9416	10612	1196
53C1261 (1964)	4000	8872	7438	10181	3708*	8830	7438	10181	121	6086	7458	10202	11574	1372
53 2030R (1970)	5000	8322	7663	10547	3508*	8844	7663	10547	77	5821	7332	10355	11867	1511
53 2030L (1970)	4500	8086	7470	10120	3821*	8558	7470	10120	90	5785	7172	9945	11332	1387
Average	4375	8021	7405	9906	3626	8444	7381	9906	94	5775	7110	9779	11113	1334

Table F-4: Placer County Strength Predictions

Bridge No. (Date built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	**Mean (σ)	Min	Max	% Increase (MeanĀσ)Ā	σĀ 2StDev	σĀ 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
19 0128 (1973)	4000	7692	7373	9601	3703*	8222	7373	9601	106	5813	7018	9427	10631	1204
19 0130 (1973)	4000	9070	7084	9295	4510	8483	7084	9295	112	6049	7266	9700	10917	1217
19 0062 (1967)	4300	8455	7502	8960	5592	8306	7502	8960	93	6825	7565	9046	9786	740
19 0131 (1966)	4300	8967	7566	9906	5310	8813	7566	9906	105	6458	7636	9991	11168	1177
19 0085 (1966)	4300	8507	7598	9601	5577	8569	7598	9601	99	6563	7566	9571	10574	1003
19 0040 (1961)	4000	8363	7405	11127	2549*	8965	7405	11127	124	5100	7033	10898	12830	1933
19C0047 (1966)	4000	8455	7470	9906	6986	8610	7470	9906	115	6159	7385	9836	11061	1226
Average	4129	8501	7428	9771	4889	8567	7428	9771	108	6138	7353	9781	10995	1214

Table F-5: San Bernardino County Strength Predictions

Bridge No. (Date built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	**Mean (σ)	Min	Max	% Increase (Mean σ)	σ- 2StDev	σ- 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
54C0157 (1978)	4500	8075	7084	9570	3838*	8243	7084	9570	83	5740	6991	9495	10746	1252
54C0101 (1967)	4850	6287	6795	9845	2115*	7642	6287	9845	58	3793	5718	9567	11491	1925
54C0067 (1961)	5700	7260	7341	9692	2679*	8098	7260	9692	42	5335	6716	9479	10861	1382
54 0769R (1968)	4300	8173	7341	9753	2676*	8423	7341	9753	96	5972	7197	9648	10873	1225
54 1277R (2007)	6000	8005	7433	9790	3958*	7627	6188	9022	27	4629	6128	9126	10625	1499
54 1278L (2007)	6000	7732	7245	8929	5753*	7969	7245	8929	33	6235	7102	8835	9702	867
54 1278R (2007)	5000	7722	7018	9039	4538*	7034	6143	8028	41	4772	5903	8165	9297	1132
54 1277L (2007)	6000	7850	7470	9243	5026*	8188	7470	9243	36	6320	7254	9121	10055	934
Average	5294	7679	7218	9439	3916	7788	6735	9113	48	5220	6504	9073	10357	1285

Table F-6: Santa Clara County Strength Predictions

Bridge No. (Date built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	Mean (σ)	Min	Max	% Increase (Mean σ)	σĀ 2StDev	σĀ 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
37C0031 (1972)	3500	8299	6791	10143	5311	8411	6791	10143	140	5054	6733	10090	11768	1678
37 0247 (1966)	4000	8165	7116	8135	3372*	7805	7116	8165	95	6611	7208	8402	9000	597
37 0246 (1966)	4000	7797	7245	9295	3316*	8112	7245	9295	103	5990	7051	9174	10235	1061
37 0253 (1966)	4000	7513	6409	9173	6974	7698	6409	9173	92	4915	6307	9090	10481	1392
37 0218 (1965)	4000	8394	7653	9860	4911	8636	7653	9860	132	6367	7502	9770	10905	1135
37 0217 (1965)	4500	8393	7180	9433	7733	8335	7180	9433	85	6081	7208	9463	10590	1127
37C0082 (1961)	5000	8721	7245	9356	1644*	8441	7245	9356	69	6274	7357	9524	10608	1083
37C0074 (1964)	4500	9094	7277	9570	3569*	8647	7277	9570	92	6226	7437	9857	11068	1210
37 0149 (1965)	4000	8402	7493	4869	5481	6921	4869	8402	73	3252	5086	8756	10590	1835
Average	4167	8317	7252	8969	5887	8164	6944	9326	101	5714	6939	9390	10615	1225

Table F-7: Ventura County Strength Predictions

Bridge No. (Date built)	Design Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	Windsor Probe (psi)	UPV (psi)	Mean (σ)	Min	Max	% Increase (Mean σ)	σĀ 2StDev	σĀ 1StDev	σ+ 1StDev	σ+ 2StDev	StDev (psi)
52 0280L (1966)	4750	7308	7213	9845	3356*	8122	7213	9845	71	5135	6629	9615	11108	1493
52 0280R (1966)	4750	7355	6923	9845	1291*	8041	6923	9845	69	4887	6464	9618	11195	1577
52 0270 (1964)	4500	6012	7116	9418	1639*	7515	6012	9418	67	4040	5778	9253	10990	1737
52 C0043 (1990)	4100	7720	7116	8807	3913*	7881	7116	8807	92	6168	7024	8738	9595	857
52 0239 (1963)	5000	7576	7084	7647	3469*	7435	7084	7647	49	6822	7129	7742	8048	306
52C0051 (1960)	5500	7782	7180	9326	3851*	8096	7180	9326	47	5883	6989	9203	10310	1107
52 0049 (1994)	6000	7624	7116	9112	3125*	7951	7116	9112	33	5876	6914	8988	10026	1037
Average	4943	7340	7107	9143	2949	7863	6949	9143	61	5545	6704	9022	10182	1159

Table F-8: Santa Clara County Bridge 37C0031 Core Specimen Results

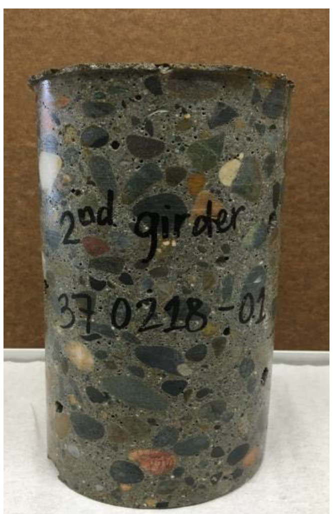
	Design Strength (psi)	Core Compressive Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	UPV (psi)	Windsor Probe (psi)	Mean (σ) of Silver Schmidt and Windsor Pin (psi)
Bridge	3500	-	8299	6791	5311	10143	7545**
Core 1		6865	6994 (-16%)* (2%)***	6819 (0.4%)* (-1%)***	6198 (17%)* (-10%)***	-	6906 (-8.5%)** (1%)***
Core 2		8008	6622 (-20%)* (-17%)***	-	7903 (49%)* (-1%)***	-	6622 (-12.2%)** (-17%)***
Average of Cores		7437	6808 (-18%)* (-8%)***	6819 (0.41%)* (-1%)***	7051 (33%)* (-6%)***		6764 (-10.4%)** (-8%)***

*The percentage between parenthesis represents the percentage increase/decrease of the core from the bridge NDT prediction
**Silver Schmidt + Windsor Pin
***The percentage at bottom represents the percent increase/decrease of the core from the individual equipment prediction

Table F-9: Santa Clara County Bridge 37 0218 Core Specimen Results

	Design Strength (psi)	Core Compressive Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	UPV (psi)	Windsor Probe (psi)	Mean (σ) of Silver Schmidt and Windsor Pin (psi)
Bridge	4000	-	8369	7373	3880	9509	7871
Core 1		5870	7153 (-15%)* (22%)***	7657 (4%)* (30%)***	7109 (83%)* (21%)***	-	7405 (-6%)** (26%)***
Core 2		6020	7150 (-15%)* (18%)***	7745 (5%)* (29%)***	7932 (104%)* (32%)***	-	7448 (-6%)** (23%)***
Average of Cores		5945	7152 (-15%)* (20%)***	7701 (4%)* (30%)***	7520 (94%)* (26%)***		7426 (-6%)** (25%)***

*The percentage between parenthesis represents the percentage increase/decrease of the core from the bridge NDT prediction
**Silver Schmidt + Windsor Pin
***The percentage at bottom represents the percent increase/decrease of the core from the individual equipment prediction



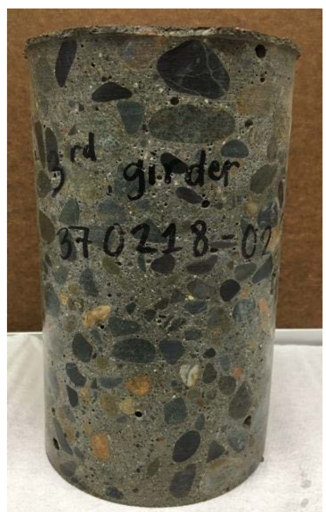



Table F-10: Santa Clara County Bridge 37 0149 Core Specimen Results

	Design Strength (psi)	Core Compressive Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	UPV (psi)	Windsor Probe (psi)	Mean (σ) of Silver Schmidt and Windsor Pin (psi)
Bridge	4000	-	8402	7493	5481	4869	7948**
Core 1		8236	6888 (-18%)* (-16%)***	7377 (-2%)* (-10%)***	5705 (4%)* (-31%)***	-	7132 (-10%)** (-13%)***
Core 2		8353	6446 (-23%)* (-23%)***	7079 (-6%)* (-15%)***	6232 (14%)* (-25%)***	-	6762 (-15%)** (-19%)***
Average of Cores		8295	6667 (-21%)* (-20%)***	7228 (-4%)* (-13%)***	5968 (9%)* (-28%)***	-	6947 (-13%)** (-16%)***

*The percentage between parenthesis represents the percentage increase/decrease of the core from the bridge NDT prediction
**Silver Schmidt + Windsor Pin
***The percentage at bottom represents the percent increase/decrease of the core from the individual equipment prediction

Table F-11: San Bernardino County Bridge 54 1277R Core Specimen Results

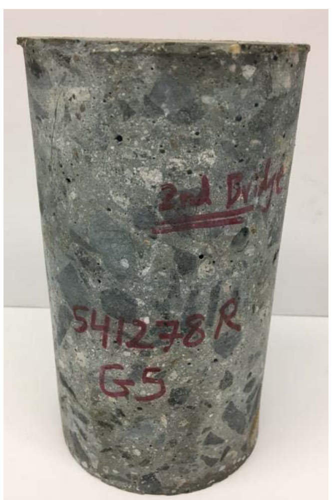
	Design Strength (psi)	Core Compressive Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	UPV (psi)	Windsor Probe (psi)	Mean (σ) of Silver Schmidt and Windsor Pin (psi)
Bridge	6000	-	7756	7277	3898	9790	7517**
Core 1		7599	6390 (-18%)* (-16%)***	7255 (-0.3%)* (-5%)***	6609 (70%)* (-13%)	-	6823 (-9%)** (-10%)***
Core 2		7787	6588 (-15%)* (-15%)***	6969 (-4%)* (-11%)***	6735 (73%)* (-14%)***	-	6801 (-10%)** (-13%)***
Average of Cores		7693	6489 (-16%)* (-16%)***	6672 (-2%)* (-8%)***	7112 (71%)* (-13%)***	-	6801 (-10%)** (-12%)***

*The percentage between parenthesis represents the percentage increase/decrease of the core from the bridge NDT prediction
**Silver Schmidt + Windsor Pin
***The percentage at bottom represents the percent increase/decrease of the core from the individual equipment prediction


Table F-12: San Bernardino County Bridge 54 1278R Core Specimen Results

	Design Strength (psi)	Core Compressive Strength (psi)	Silver Schmidt (psi)	Windsor Pin (psi)	UPV (psi)	Windsor Probe (psi)	Mean (σ) of Silver Schmidt and Windsor Pin (psi)
Bridge	5000	-	7722	7020	3608	9039	7371**
Core 1		7998	5782 (-25%)* (-28%)***	6850 (-2%)* (-14%)***	7718 (114%)* (-3%)***	-	6316 (-14%)** (-21%)***
Core 2		7611	6181 (-20%)* (-19%)***	7237 (3%)* (-5%)***	8395 (133%)* (10%)***	-	6709 (-9%)** (-12%)***
Average of Cores		7805	5981 (-23%)* (-23%)***	7043 (0.3%)* (-10%)***	8057 (123%)* (3%)***	-	6512 (-12%)** (-16%)***

*The percentage between parenthesis represents the percentage increase/decrease of the core from the bridge NDT prediction
**Silver Schmidt + Windsor Pin
***The percentage at bottom represents the percent increase/decrease of the core from the individual equipment prediction



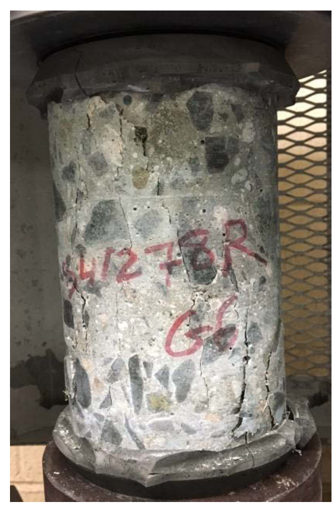


Table F-13: Summary of Core Specimen Results

Bridge No.	Design Strength (psi)	Average Core Compressive Strength (psi)	Predicted Bridge NDT Strength (psi)	Bridge σ-2StDev (psi)	Bridge σ-1StDev (psi)	Bridge σ+1StDev (psi)	Bridge σ+2StDev (psi)	% Increase Core & Design Strength	% Increase Bridge NDT & Design Strength	% Increase Bridge / % Increase Core	70% Predicted Bridge NDT Strength (psi)
37C0031	3500	6966	8411	5054	6733	10090	11768	99	140	1.41	5888
37 0218	4000	5945	8636	6367	7502	9770	10905	49	132	2.69	6045
37 0149	4000	8295	6921	3252	5086	8756	10590	107	73	0.68	4845
54 1277R	6000	7693	7627	4629	6128	9126	10625	28	27	0.96	5339
54 1278R	5000	7805	7034	4772	5903	8165	9297	56	41	0.73	4924
Average										1.30	

Table F-14: Summary of Core Specimen Results

Bridge No.	Bridge Age (years)	Design Strength (psi)	Average Core Compressive Strength (psi)	Predicted Bridge NDT Strength (psi)	Bridge NDT σĀ 2StDev (psi)	Bridge NDT σĀ1StDev (psi)	Bridge NDT σ+1StDev (psi)	Bridge NDT σ+2StDev (psi)
37C0031 (1972)	**45**	**3500**	**6966**	**8411**	**5054**	**6733**	**10090**	**11768**
37 0218 (1965)	**52**	**4000**	**5945**	**8636**	**6367**	**7502**	**9770**	**10905**
37 0149 (1965)	**52**	**4000**	**8295**	**6921**	**3252**	**5086**	**8756**	**10590**
54 1277R (2007)	**10**	**6000**	**7693**	**7627**	**4629**	**6128**	**9126**	**10625**
54 1278R (2007)	**10**	**5000**	**7805**	**7034**	**4772**	**5903**	**8165**	**9297**

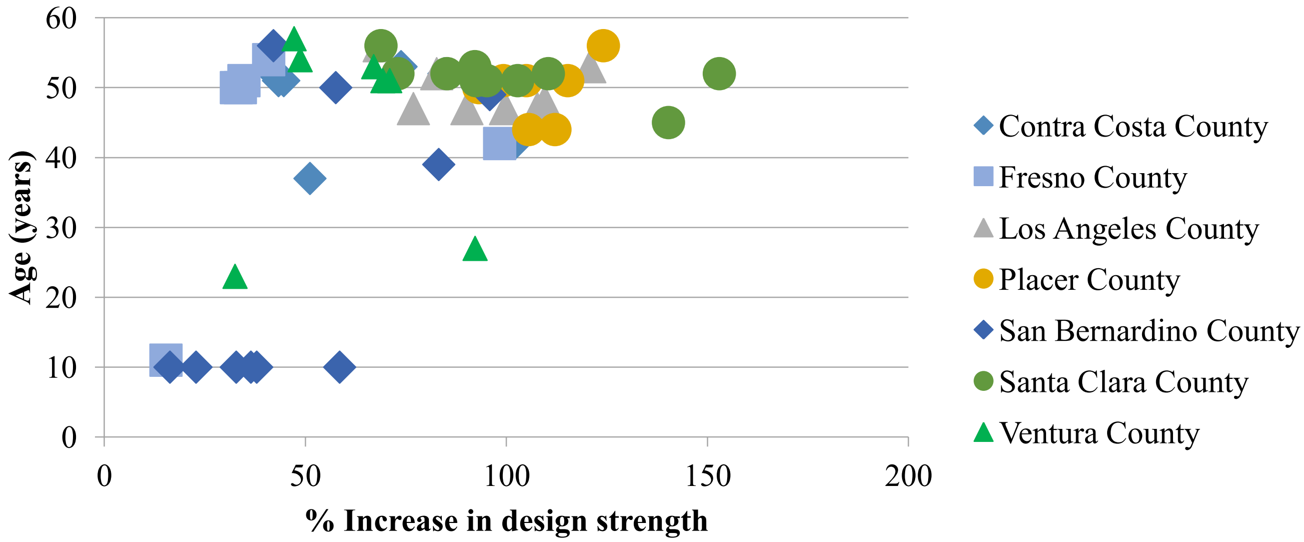


Figure F-5: Age vs. %Increase from Design Strength As Predicted By NDT Predictions

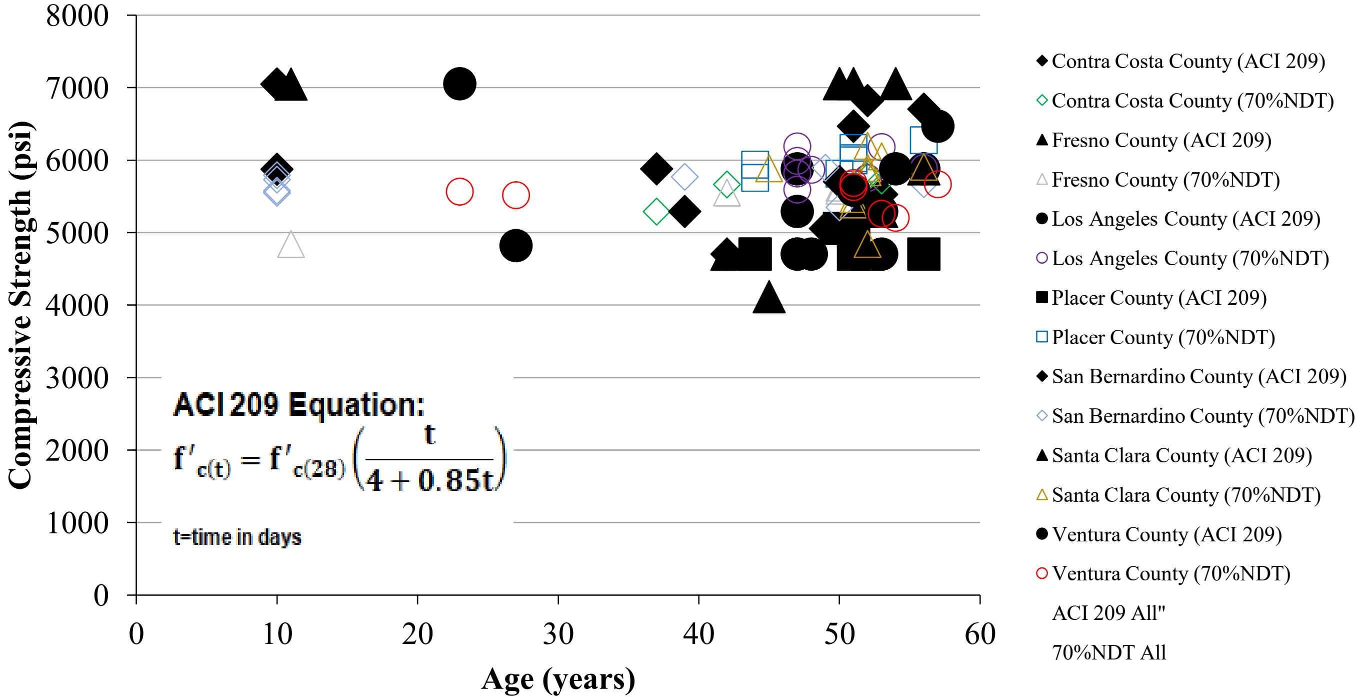


Figure F-6: Comparison of Strength Prediction vs. Age Between 70%NDT and ACI 209 Equation

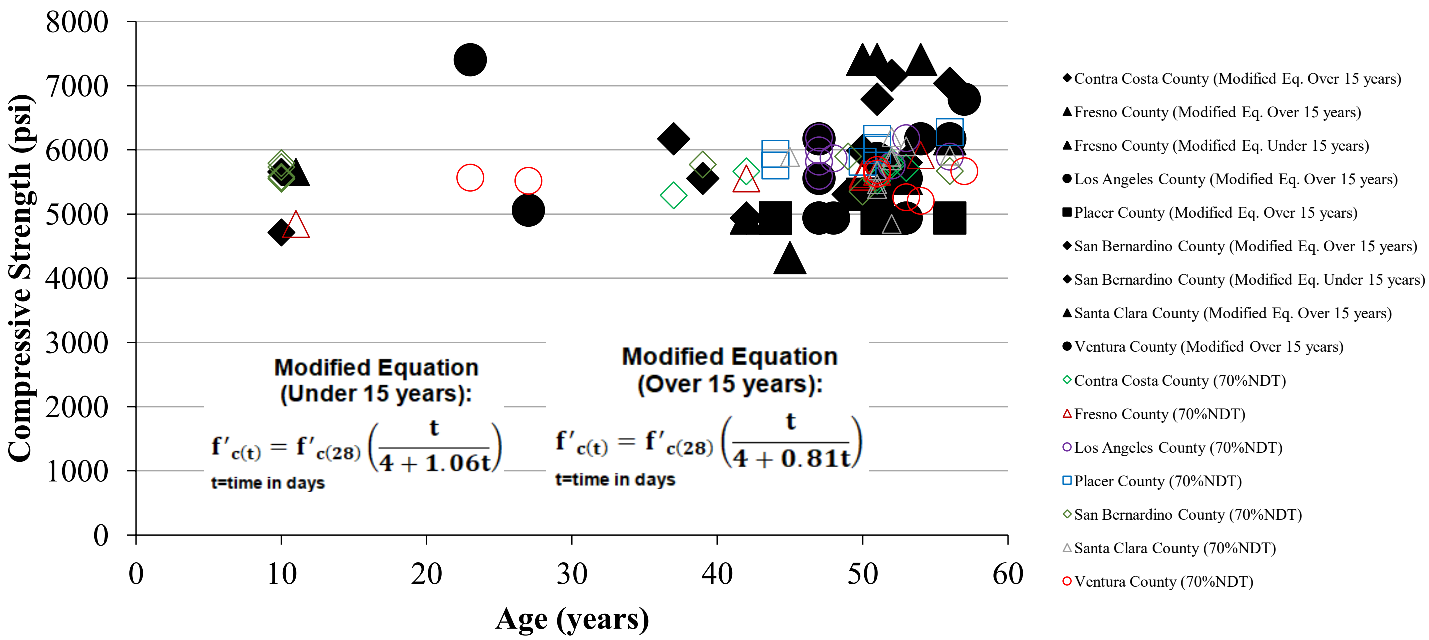


Figure F-7: Comparison of Strength Prediction vs. Age of Modified Equation Predictions

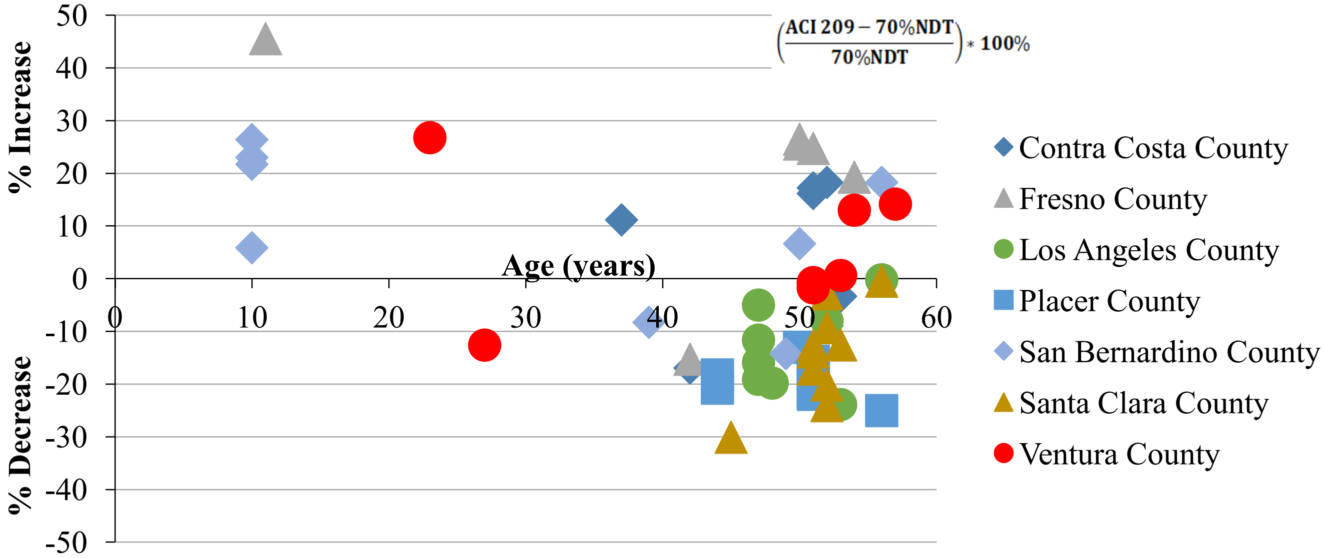


Figure F-8: %Increase or Decrease of ACI 209 Equation from 70%NDT Strength Predictions

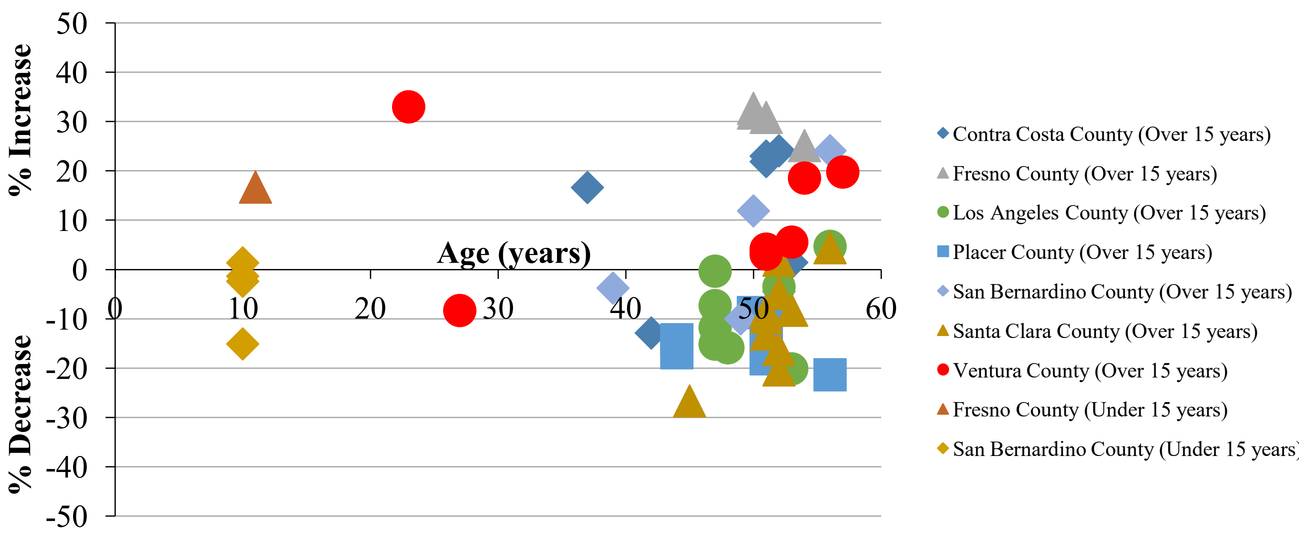


Figure F-9: %Increase or Decrease of Modified Equations from 70%NDT Strength Predictions

Table F-15: Percent Increase or Decrease of ACI 209 Equation From 70%NDT Compressive Strength Predictions

County	Contra Costa	Fresno	Los Angeles	Placer	San Bernardino	Santa Clara	Ventura
	16% (51) (28C0189R)	**19% (54)** (42C0136)	**0.2% (56)** (53C1457)	**-18% (44)** (19 0128)	**-8% (39)** (54C0157)	**-30% (45)** (37C0031)	**-2% (51)** (52 0280L)
	17% (51) (28C0189L)	**25% (51)** (42 0355)	**-20% (48)** (53 0851)	**-21% (44)** (19 0130)	**7% (50)** (54C0101)	**-14% (51)** (37 0247)	**-1% (51)** (52 0280R)
	18% (52) (28C0087)	**26% (50)** (42 0272)	**-16% (47)** (53 2032R)	**-13% (50)** (19 0062)	**18% (56)** (54C0067)	**-17% (51)** (37 0246)	**1% (53)** (52 0270)
	-9% (52) (28C0094)	**26% (50)** (42 0270)	**-19% (47)** (53 2032L)	**-18% (51)** (19 0131)	**-14% (49)** (54 0769R)	**-13% (51)** (37 0253)	**-13% (27)** (52 C0043)
	-3% (53) (28C0091L)	**46% (11)** (42C0649)	**-8% (52)** (53 1681)	**-16% (51)** (19 0085)	**22% (10)** (54 1277R)	**-22% (52)** (37 0218)	**13% (54)** (52 0239)
	11% (37) (28C0167)	**-15% (42)** (42C0009)	**-24% (53)** (53C1261)	**-25% (56)** (19 0040)	**26% (10)** (54 1278L)	**-9% (52)** (37 0217)	**14% (57)** (52C0051)
	-17% (42) (28C0085)		**-5% (47)** (53 2030R)	**-22% (51)** (19C0047)	**6% (10)** (54 1278R)	**-0.5% (56)** (37C0082)	**27% (23)** (52 0049)
			-12% (47) (53 2030L)		**23% (10)** (54 1277L)	**-13% (53)** (37C0074)	
						-3% (52) (37 0149)	
ACI 209 Average	**5%**	**21%**	**-13%**	**-19%**	**10%**	**-14%**	**6%**
	-1%						
Under 15 years	**-**	**46%**	**-**	**-**	**19%**	**-**	**-**
Average	**32%**						
Over 15 years	**5%**	**16%**	**-13%**	**-19%**	**1%**	**-14%**	**6%**
Average	**-3%**						
Over 50 years	**8%**	**24%**	**-11%**	**-19%**	**12%**	**-13%**	**5%**
Average	**1%**						

ACI 209 Equation:

$$f'_{c(t)} = f'_{c(28)}\left(\frac{t}{4+0.85t}\right)$$

t=time in days

+Over estimation
-Under estimation

Table F-16: Percent Increase or Decrease of Modified ACI 209 Equations From 70%NDT Compressive Strength Predictions

County	Contra Costa	Fresno	Los Angeles	Placer	San Bernardino	Santa Clara	Ventura
	22% (51) (28C0189R)	**25% (54)** (42C0136)	**5% (56)** (53C1457)	**-14% (44)** (19 0128)	**-4% (39)** (54C0157)	**-27% (45)** (37C0031)	**3% (51)** (52 0280L)
	23% (51) (28C0189L)	**31% (51)** (42 0355)	**-16% (48)** (53 0851)	**-17% (44)** (19 0130)	**12% (50)** (54C0101)	**-10% (51)** (37 0247)	**4% (51)** (52 0280R)
	24% (52) (28C0087)	**33% (50)** (42 0272)	**-12% (47)** (53 2032R)	**-9% (50)** (19 0062)	**24% (56)** (54C0067)	**-13% (51)** (37 0246)	**6% (53)** (52 0270)
	-4% (52) (28C0094)	**32% (50)** (42 0270)	**-15% (47)** (53 2032L)	**-14% (51)** (19 0131)	**-10% (49)** (54 0769R)	**-8% (51)** (37 0253)	**-8% (27)** (52 C0043)
	1% (53) (28C0091L)	**17% (11)** (42C0649)	**-3% (52)** (53 1681)	**-12% (51)** (19 0085)	**-2% (10)** (54 1277R)	**-18% (52)** (37 0218)	**19% (54)** (52 0239)
	17% (37) (28C0167)	**-11% (42)** (42C0009)	**-20% (53)** (53C1261)	**-21% (56)** (19 0040)	**1% (10)** (54 1278L)	**-20% (52)** (37 0217)	**20% (57)** (52C0051)
	-13% (42) (28C0085)		**-0.3% (47)** (53 2030R)	**-18% (51)** (19C0047)	**-15% (10)** (54 1278R)	**-5% (56)** (37C0082)	**33% (23)** (52 0049)
			-7% (47) (53 2030L)		**-1% (10)** (54 1277L)	**4% (53)** (37C0074)	
						-8% (52) (37 0149)	
ACI 209 (Modified) Average	**10%**	**21%**	**-9%**	**-15%**	**1%**	**-10%**	**11%**
	1%						
Under 15 years	**-**	**17%**	**-**	**-**	**-4%**	**-**	**-**
Average	**6%**						
Over 15 years	**10%**	**22%**	**-9%**	**-15%**	**6%**	**-10%**	**11%**
Average	**2%**						
Over 50 years	**13%**	**30%**	**-6%**	**-15%**	**18%**	**-8%**	**10%**
Average	**6%**						

Modified Eq. <15 years:

$$f'_{c(t)} = f'_{c(28)}\left(\frac{t}{4 + 1.06t}\right)$$

t=time in days

Modified Eq. >15 years:

$$f'_{c(t)} = f'_{c(28)}\left(\frac{t}{4 + 0.81t}\right)$$

t=time in days

+Over estimation
-Under estimation

Table F-17: Average Percent Increase or Decrease of ACI 209 Equation and Modified ACI 209 Equations From 70%NDT Compressive Strength Prediction Comparison

	Under 15 years	Over 15 years	Over 50 years	All Ages
ACI 209	32%	-3%	1%	-1%
Modified Equations	6%	2%	6%	1%

ACI 209 Equation:

$$f'_{c(t)} = f'_{c(28)}\left(\frac{t}{4+0.85t}\right)$$

t=time in days

Modified Equation (Under 15 years):

$$f'_{c(t)} = f'_{c(28)}\left(\frac{t}{4+1.06t}\right)$$

t=time in days

Modified Equation (Over 15 years):

$$f'_{c(t)} = f'_{c(28)}\left(\frac{t}{4+0.81t}\right)$$

t=time in days

References

[1] Unruh, III, R. C., "The Use of Nondestructive Testing Methods for the Condition Assessment of Concrete Bridge Girders," *Massachusetts Institute of Technology, 72 p.,* June 2004.

[2] Lorenzi, A., Filho, L. C., and Campagnolo, J., "Development of Artificial Neural Networks for Interpreting Ultrasonic Pulse Velocity Tests in Concrete," *IBRACON,* Vol. 4(5), pp. 814-828, 2011.

[3] Trtnik, G., Kavcic, F., and Turk, G., "Prediction of Concrete Strength Using Ultrasonic Pulse Velocity and Artificial Neural Networks," *US National Library of Medicine National Institutes of Health*, May 2008.

[4] Promboon, Y., Olsen, L.D., and Lund, J., "Nondestructive Evaluation (NDE) Methods for Quality Assurance of Epoxy Injection Crack Repairs," pp. 1-15. *olsoninstruments.com,* (n.d.).

[5] Government of India: Ministry of Railways. "Guidelines on Non-destructive Testing of Bridges," Aug. 2009, *rdso.indianrailways.gov.in*.

[6] Huang, Q., Gardoni, P., and Hurlebaus, S., "Predicting Concrete Compressive Strength Using Ultrasonic Pulse Velocity and Rebound Number," *ACI Materials Journal*, Vol. 108(4), pp. 403-412, 2011.

[7] Lin, Y., Kuo, S., Hsiao, C., and Lai, C., "Investigation of Pulse Velocity-Strength Relationship of Hardened Concrete," *ACI Materials Journal,* Vol. 104(4), pp. 344-350, 2007.

[8] Bickley, J., "A Brief History of Pullout Testing with Particular Reference to Canada - A Personal Journey," *ACI SP Vol. 261*, pp. 277-286, 2009.

[9] Yun, C., Choi, K., Kim, S., and Song, Y., "Comparative Evaluation of Nondestructive Test Methods for In-Place Strength Determination," *ACI SP Vol. 112*, pp. 111-136, 1989.

[10] Bishr, H., "Pullout Test for Concrete Strength," *Journal of Science and Technology*, Vol. 8(2), 2003.

[11] Samarin, A., and Dhir, R. K., "Determination of In Situ Concrete Strength: Rapidly and Confidently by Nondestructive Testing," *ACI SP Vol. 82*, pp. 77-94, 1984.

[12] Jaggerwal, H., and Bajpai, Y., "Assessment of Characteristic Compressive Strength in Concrete Bridge Girders Using Rebound Hammer Test," *International Journal of Computational Engineering Research (IJCER)*, Vol. 4(4), pp. 1-6, 2014.

[13] Henao, L. R., Gomez, J. F., and Lopez-Agul, J. C., "Rebound Hammer, Pulse Velocity, and Core Tests in Self-Consolidating Concrete," *ACI Materials Journal,* Vol. 109(2), pp. 235-243, 2012.

[14] Al-Manaseer, A.A., Aquino, E.B., "Windsor Probe Test for Nondestructive Evaluation of Normal and High-Strength Concrete," *ACI Materials Journal,* Vol. 96(4), pp. 440-447, 1999.

[15] Masoumi, F., Akgül, F., and Mehrabzadeh, A., "Condition Assessment of Reinforced Concrete Bridges by Combined Nondestructive Test Techniques," *International Journal of Engineering and Technology (IACSIT)*, Vol. 5(6), 2013.

[16] Selcuk, L., Gokce, S., Kayabali, K., and Simsek, O., "A Nondestructive Testing Technique: Nail Penetration Test," *ACI Structural Journal,* Vol. 109(2), pp. 245-252, 2012.

[17] Al-Manaseer, A. A., and Nasser, K.W., "Laboratory and field tests with a new nondestructive apparatus," *Canadian Journal of Civil Engineering Can. J. Civ. Eng.,* Vol. *17*(6), pp. 904-910, 1990.

[18] Pessiki, S. and Johnson, M., "In-Place Evaluation of Concrete Strength Using the Impact-Echo Method," *ACI SP Vol. 143*, pp. 275-296, 1994.

[19] Limaye, H. S. and Meinheit, D. F., "Experience with the Impact-Echo Technique," *ACI SP Vol. 128*, pp. 101-114, Hong Kong, 1991.

[20] Tinkey, B., Fowler, T., and Klingner, R., "Nondestructive Testing of Prestressed Bridge Girders with Distributed Damage," Report FHWA/TX-03/1857-2, *Texas DOT*, 106 p., 2000.

[21] ACI Committee 209. "209R-92: Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures (Reapproved 2008)," 47 p., 2002.