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Investigation of Factors Influencing Design and Performance of Soil Cement Pavement Layers

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Investigation of factors influencing design and performance

of soil cement pavement layers

By

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Soil cement has been used as a means of stabilizing highway pavement layers, airport pavement layers, embankments, and foundations for decades. The technology uses a compacted mixture of soil, cement, and water to form a hardened material layer that has specific strength and durability properties. Even after decades of utilization, however, design of soil cement pavement layers has room for enhancement.

This thesis investigates factors that influence the design and performance of cement stabilized pavement layers in Mississippi. A survey was conducted to collect information about soil cement design procedures from across the U.S. The factors examined in the laboratory investigation are strength gain with time, unconfined compressive strength variability, elastic modulus, and wheel tracking. More than 1,100 specimens were tested to determine the influence of these factors on the design and performance of soil cement pavement layers.

DEDICATION

This work is dedicated to my family and friends for all the love and support throughout this process.

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LIST OF SYMBOLS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
APA	Asphalt Pavement Analyzer
ASTM	American Society for Testing and Materials
C_A	*Pit A* Linear Fit Constant
C_B	*Pit B* Linear Fit Constant
CBR	California Bearing Ratio
C_C	*Pit C* Linear Fit Constant
C_F	Linear Fit Constant
C_I	Cement Index According to Current MDOT Protocol (%)
C_i	Equation Constant for *i* Line
C_L	Lower Boundary Constant
CMRC	Construction Materials Research Center
Comp/Ext	Compressometer/Extensometer
COV	Coefficient of Variation (%)
C_U	Upper Boundary Constant
C_w	Cement Content Referencing Dry Soil Mass (%)
D_{AVG}	Average Diameter from Four Measurements (mm)
DOT	Department of Transportation

E	General Elastic Modulus Denotation (ksi or psi)
E_{Comp}	Elastic Modulus Using Strain Measured by Compressometer (GPa)
E_e	Elastic Modulus Taken at 0.33 σ_{max}, Reinhold (1955) (GPa)
E_{fp}	Modulus of Elasticity at a Strength Level of f_p (GPa)
EM	Identifier for Elastic Modulus Testing Category
E_{sc}	Elastic Modulus in Compression, Felt and Abrams (1957) (GPa)
$E_{X\text{-}Head}$	Elastic Modulus Using Strain from Crosshead Displacement (GPa)
FWD	Falling Weight Deflectometer
G	Gradation Modulus
GGBFS	Ground Granulated Blast-Furnace Slag
G_S	Specific Gravity of Soil Solids
H_0	Null Hypothesis
H_a	Alternative Hypothesis
H_{AVG}	Average Height from Four Measurements (mm)
HLWT	Hamburg Loaded Wheel Tester
IQR	Inter Quartile Range ($Q_1 - Q_3$)
LAC	Linear Asphalt Compactor
LB	Lower Boundary Line
LF	Linear Fit Line
LL	Liquid Limit (%)
MDOT	Mississippi Department of Transportation
ME	Margin of error (kPa)
MEPDG	Mechanistic-Empirical Pavement Design Guide

ML	Inorganic Silt
MS	Mississippi
MSU	Mississippi State University
MT-8	Mississippi Test Method 8
MT-9	Mississippi Test Method 9
MT-25	Mississippi Test Method 25
MT-26	Mississippi Test Method 26
NCHRP	National Cooperative Highway Research Program
NP	Non-plastic
OMC	Optimum Moisture Content (%)
PA	Pit Soil A
PB	Pit Soil B
PC	Pit Soil C
PI	Plasticity Index (%)
PM	Plastic Mold Split-Mold Assembly
PM-CF	Plastic Mold Assembly Used in Conjunction with Compactor Frame
PCA	Portland Cement Association
PW	Identifier for PURWheel Testing Category
Q_1	25th Percentile
Q_3	75th Percentile
R^2	Coefficient of Determination
SC	Soil and Cement (Okyay and Dias 2010)
SGC	Superpave Gyratory Compactor

SL	Soil and Lime (Okyay and Dias 2010)
SLC	Soil, Lime, and Cement (Okyay and Dias 2010)
ST	Identifier for Strength vs. Time Testing Category
Stdev	Standard Deviation
SV	Identifier for Strength Variability Testing Category
SVM	Identifier for Strength Variability using MDOT Curing Method Testing Category
UB	Upper Boundary Line
UC	Unconfined Compression
USCS	Unified Soil Classification System
V	Volume (m^3)
WTP	Wheel Tracking Protocol
df	Degrees of Freedom
d_{fr}	Final Rut Depth per Test (mm)
f_p	Uniaxial Compressive Strength (MPa)
h/d	Height to Diameter Ratio
n	Number of Replicates
n_0	Number of Outliers
n_{Comp}	Number of Data Points Used to Find E_{Comp}
n_{reps}	Number of Replications Based on Reliability and Margin of Error from Table 4.2
$n_{X\text{-}Head}$	Number of Data Points Used to Find $E_{X\text{-}Head}$
q_{28}	Unconfined Compressive Strength Value at 28 Days Curing (Okyay and Dias 2010)

q_t	Unconfined Compressive Strength after *t* Days of Curing (Okyay and Dias 2010)
q_u	Unconfined Compressive Strength (psi)
r	Correlation Coefficient
t	Time
t_{crit}	Critical *t-test* Statistic
t_{stat}	Calculated *t-test* Statistic
$\bar{x}$	Mean of Sample Set (kPa)
$z_{\alpha/2}$	Z-score for Alpha Divided by Two
α	Level of Significance
γ	Total Density of Specimen Including Solid and Moisture Mass (g/cm^3)
γ_d	Maximum Dry Density (kg/m^3)
ε_{max}	Strain at Failure from Crosshead Displacement (%)
μ_1	Mean of Term 1
μ_2	Mean of Term 2
σ	Compressive Stress (kPa)
σ_{max}	Unconfined Compressive Strength at Failure (kPa)
$\omega_{measured}$	Moisture Content Measured from Mixed Material (%)
$\omega_{natural}$	Moisture Content at Time of Sampling (%)
9C	Class 9 Group C Material

CHAPTER 1

INTRODUCTION

1.1 Introduction

Soil cement has been a popular soil stabilization technique for roadways, airport pavements, embankments, and foundations for decades. ACI (2009) defines soil cement as “a mixture of soil and measured amounts of portland cement and water, compacted to a high density” and “a material produced by blending, compacting, and curing a mixture of soil/aggregate, portland cement, possibly other cementitious materials, and water to form a hardened material with specific engineering properties.” Engineers have been using soil cement technology since 1915, when a mixture of shells, sand, and portland cement was blended with a plow and compacted (ACI 2009). There have been approximately 200,000 km by 7.3 m wide equivalent of soil cement pavement placed in the United States since then (ACI 2009).

The soil cement design process has evolved over decades. In 1935, the Portland Cement Association (PCA) started the process of developing procedures to produce a uniform and durable soil cement mixture (Scullion et al. 2005). After extensive efforts, the PCA developed the moisture-density test (ASTM D 558), the wet-dry test (ASTM D 559), and the freeze-thaw test (ASTM D 560) in order to determine optimum moisture content, maximum standard proctor dry density, and minimum design cement content (Scullion et al. 2005). ASTM D 559 and ASTM D 560 utilize a method for determining minimum cement content based on the durability of the material. The tests involve 12 cycles of wetting and drying or freezing and thawing, respectively, along with a specified procedure of brushing the specimens to induce mass loss. The percentage of mass lost is compared to standards found from PCA acceptance criteria, and the tests provide a minimum cement content for design.

Over time, many agencies have adapted to only using compressive strength criterion to design soil cement materials. Correlations between durability and compressive strength were used to move away from the wet-dry test and freeze-thaw test. Agencies preferred design based on compressive strength rather than using ASTM D 559 and D560. The reasons include the wet-dry and freeze-thaw tests required a longer test time (one month compared to one week), more lab equipment, and more technician involvement (Scullion et al. 2005). Also, the poor repeatability of the wet-dry and freeze-thaw tests because of brushing inconsistencies between laboratories has contributed to the reduced use of these tests in favor of design using compressive strength (Samson 1986 and Scullion et al. 2005). Unlike the uniform criterion from PCA for the wet-dry and freeze-thaw tests, agencies have adopted their own standards for compressive strength in design.

Design of soil cement in Mississippi is governed by Mississippi Test Method 25 (MT-25). The Mississippi Department of Transportation (MDOT) has set a minimum compressive strength of 2070 kPa for design of base pavement layers. Specimens are made at the estimated design cement index (C_I) as well as plus one and minus one percent of the estimated design cement index. One specimen is tested for compressive strength per cement index per curing time (7 or 14 days). The design cement index is the least amount of cement that produces a compressive strength of 2070 kPa or greater in 7 or 14 days. This procedure specifies the cement index and the curing time required.

The design of soil cement materials has room for enhancements even after decades of use and research. Many factors influence the design and performance of soil cement pavement layers. This thesis will investigate factors that influence the design and performance of soil cement pavement layers in Mississippi. The factors included are strength gain with time, unconfined compressive strength variability, elastic modulus, and wheel tracking.

1.2 Objectives and Scope

This thesis is part of a larger study for the Mississippi Department of Transportation (MDOT), referred to as State Study 206. The primary objectives of this thesis were to 1) obtain information from other agencies pertaining to soil stabilization practices, 2) investigate factors that influence the design and performance of soil cement pavement layers, and 3) make recommendations to better the design of soil cement pavement layers. The following tasks were completed in order to meet the outlined objectives.

- Create, distribute, and compile results from a survey pertaining to soil stabilization practices.
- Conduct a literature review.
- Investigate factors that influence the design of soil cement pavement layers:
  - Strength Gain with Time
  - Unconfined Compressive Strength Variability

- Elastic Modulus
- Wheel Tracking

- Recommend enhancements to design of soil cement pavement layers.

Chapter 2 contains a literature review providing information on the four components investigated: strength gain with time, unconfined compressive strength variability, elastic modulus, and wheel tracking. Also, Chapter 2 provides the summary of surveys collected from agencies that give insight into soil stabilization practices. An experimental program is explained in Chapter 3, including labeling regime, material descriptions, specimen fabrication, test methods, and test matrices. Chapter 4 contains results and discussion from the strength gain with time and unconfined compression strength variability investigations. Chapter 5 contains results and discussion from the elastic modulus and wheel tracking investigations. Conclusions and recommendations for the enhancement of soil cement design are found in Chapter 6, and all raw data collected is provided in four appendices.

CHAPTER 2

LITERATURE AND PRACTICE REVIEW

2.1 Overview of Literature and Practice Review

The literature and practice review was divided into two phases: literature review and practice review. The literature review phase assembled information into the four components listed in Chapter 1: i.e., 1) Strength gain with time, 2) Unconfined compressive strength variability, 3) Elastic modulus, and 4) Wheel tracking. This information was presented by referenced source organized in chronological order. The practice review focused on a survey sent nationwide in the fall of 2012.

2.2 Strength Gain with Time Literature Review

2.2.1 Felt and Abrams (1957)

The authors investigated strength gain over time of four different soil cement materials. In general, strength gain between time periods became smaller as time progressed for the sandy materials. Figure 2.1 plots strength gain versus time of an A-2-4 material (labeled Soil 2 in original document), which is the same classification as the materials in the present study, at different cement contents. The A-2-4 material had the following properties: 42% retained on the No. 40 sieve, 17% passing the No. 200 sieve, liquid limit of 17 and non plastic.

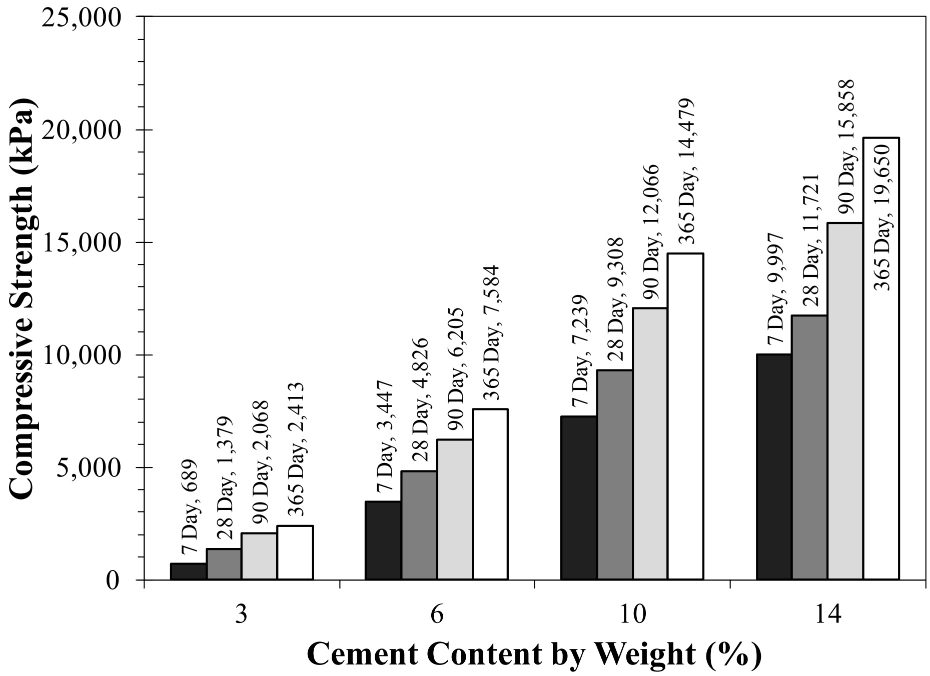


Figure 2.1 Strength vs. Time of A-2-4 Soil from Felt and Abrams (1957)

As curing time increased, there was a less drastic increase in strength. Also, the authors noted specimens that were dried at 54 C for 6 days after a 21 day moist cure before compression testing exhibited approximately twice the compressive strength as those that were completely moist cured. Specimens of different *h/d* ratios (1.15 and 2.00) were tested and compared to ASTM C 42's correction. The correction evaluated was a strength correction factor for conversion between a 2.00 to a 1.15 *h/d* ratio. The correction factor was to multiply a 2 *h/d* ratio strength by 1.1 to obtain an equivalent strength of a 1.15 *h/d* ratio. Results aligned with published corrections in ASTM C 42.

2.2.2 George (2006)

George (2006) conducted a field trial study in order to find materials, additives, and procedures that would help solve the problems with crack susceptibility in cement-treated materials. Six test sections were designated for the study, including different material/additive/procedure combinations. The study used the falling weight defectometer (FWD) for deflection and modulus testing, cored samples for unconfined compression testing, and dynamic cone penetration for subgrade testing.

Cores were cut from the test sections after specified curing times had been reached. The first cores were cut after 28 days of curing. Core cutting was performed with a typical pavement coring rig. Samples were wiped dry before being brought to a laboratory for testing. Two to three cores were taken from each test section. Compressive strengths were found in accordance with ASTM D 1633. Since *h/d* ratios were different for each core because of sampling variability, all strengths were normalized to an *h/d* ratio of 2:1 and reported. Table 2.1 reports test section description and compressive strengths of sampled cores. Figure 2.2 shows a graphical representation of the Table 2.1 data.

Table 2.1 Field Core Compressive Strengths from George (2006)

			Compressive Strength (kPa)		
Section ID	**Additives/%**	**Procedures**	**28 day**	**440 day**	**1564 day**
1A/3A	Cement/5.5	Control	710	1670	1730
2	Cement/5.5	Precracked	880	2370	3370
1B/3B	Cement/5.5	Precut	1070	1910	2630
4	Cement/3.5 Fly Ash/8	---	910	2470	3270
5	Lime/2 GGBFS/6	---	1390	3720	5730
6	Lime/3 Fly Ash/12	---	240	910	1280

Note: All material stabilized was an MDOT Class 9c material.
Additive/% - Denotes additives used in section/Percent by mass of additives

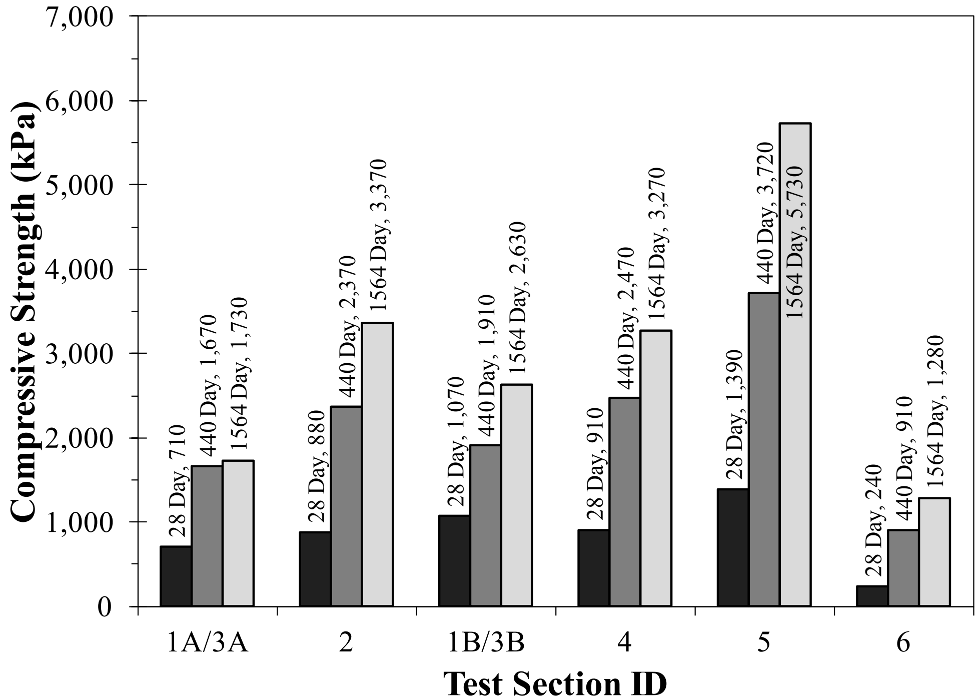


Figure 2.2 Field Core Compressive Strength from George (2006) from Table 2.1

The author notes that all the compressive strengths increase during both time intervals: 28 to 440 days and 440 to 1564 days. However, the amount of increase between additives and procedures was different. It was seen that the conventional approach to constructing cement treated layers (1A/3A) yielded lower compressive strengths than the procedures including precutting and precracking. The highest increases in strength occurred with the use of lime and GGBFS.

2.2.3 Okyay and Dias (2010)

Okyay and Dias (2010) conducted an experimental study that investigated the mechanical properties of cement and lime stabilized soils for pile supported load transfer platforms. A portion of the study included obtaining the behavior with regard to compressive strength of these materials over time. The authors tested compressive strength of specimens at 7, 28, 90, and 350 days.

The material used in the study was classified as inorganic silt with low plasticity, ML, according to the unified soil classification system and an A-4 according to the AASHTO classification system. The liquid limit of the A-4 material was 30 with a plasticity index of 10. Cylindrical specimen dimensions were 100 mm tall by 50 mm diameter. Specimens were compacted to standard proctor maximum dry density and optimum moisture content by means of static compaction pressure (2200 kPa) at a rate of 1 mm/min. Curing took place in plastic bags at 20 C for the assigned curing duration. Compression tests were conducted at a constant loading rate of 0.1 mm/min. Table 2.2 shows the notation, additive concentrations, and the number of replicates of each for compression strength tests. Figure 2.3 shows the strength gain with time for each of the combinations given in Table 2.2.

Table 2.2 Compressive Strength Information from Okyay and Dias (2010)

	Treatment	**Additive Concentration by Wt.**		
Materials	**Notation**	**Lime (%)**	**Cement (%)**	***n***
Soil + Lime	SL	3	---	12
Soil + Cement	SC	---	6	12
Soil + Lime +Cement	SLC1	2	3	12
	SLC2	2	5	12

Values taken from Figure 6 in Okyay and Dias (2010)

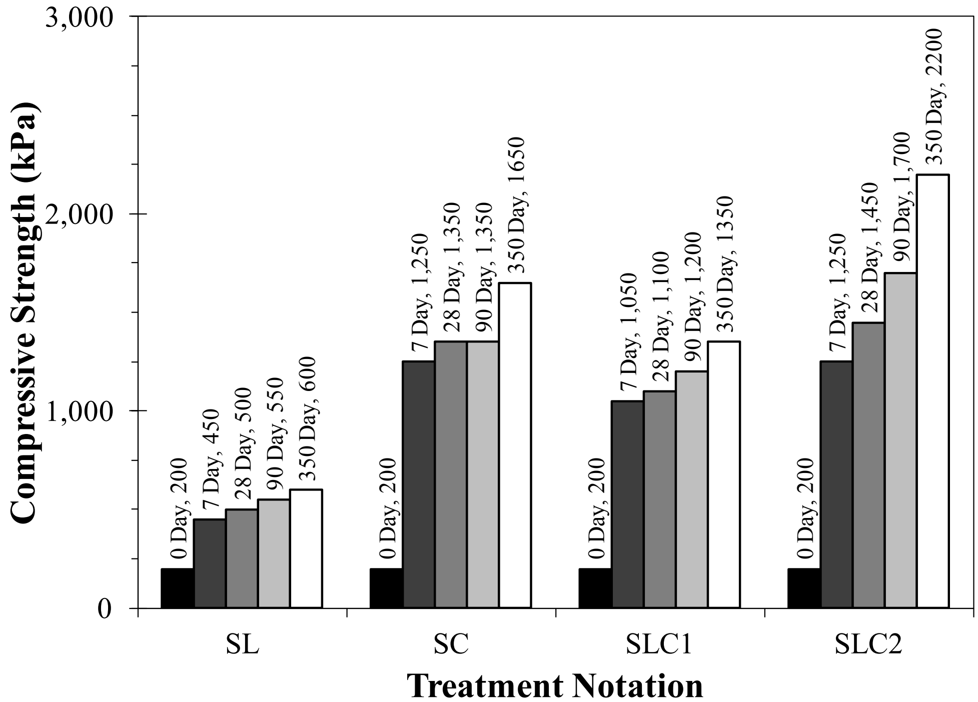


Figure 2.3 Strength Gain with Time from Okyay and Dias (2010)

The authors noted that the compressive strength of the specimens increased with time. However at some point, the strengths seemed to plateau. Material treated with only cement achieved more than 80% of 350 day compressive strength in the first 90 days. The authors found that SC, SL, and SLC1 exhibited the same strength behavior over time. Behavior over time of the SC, SL, and SLC1 treatments can be represented by a linear logarithmic function shown in Equation 2.1.

$$q_t \;/\; q_{28} = 0.81 + 0.058\ ln(t) \qquad \text{(Eq. 2.1)}$$

Where:

q_t = strength after t days of curing

q_{28} = strength value at 28 days after curing

t = curing time in days

2.3 Unconfined Compression Strength Variability Literature Review

2.3.1 Felt and Abrams (1957)

Felt and Abrams (1957) conducted a variability study on twenty-four 7.1 cm diameter by 14.2 cm tall cylinders, at 6% and 14% cement contents by mass. Material used for this study was an AASHTO classified A-4. Specimens were cured in a moist room for 28 days. Results can be found in Table 2.3. The authors concluded the variability results were good to excellent in the case of compressive strength (σ_{max}) of the soil cement mixture.

Table 2.3 Felt and Abrams (1957) Compressive Strength Variability

Test	C_w (%)	n	Mean	Stdev	COV (%)
σ_{max} (kPa)	6	6	3378	241	7.1
	14	6	6426	172	2.7

2.3.2 Kasama et al. (2007)

Kasama et al. (2007) experimented with the high strengthening of cement treated clay by mechanical dehydration in order to produce material with comparable strength to concrete. The authors conducted a literature review on the compressive strength of cement treated soils. A comparison of cemented material types was created within the findings of the literature review. The compressive strengths literature investigation included proceedings from the 26th to the 34th (in 1999) Japan National Conference on Geotechnical Engineering. The author acknowledged several factors (i.e. cement content, cure time, moisture content, curing environment) influence compressive strength. The statistics gave a general reference for the mean unconfined compressive strength, coefficients of variation, and maximum unconfined compressive strengths for the values found in the proceedings. A wide range of materials was included in the literature findings with mean compressive strengths from 260 to 10,740 kPa. Authors suggested that more variation in compressive strength was found with decreasing grain size.

2.3.3 Varner (2011)

Varner (2011) conducted a variability study on in place cement treated pavement layers within MDOT highway projects. Design requirements for cement treated pavement layers changed in 2004 and the study was to investigate the variability of the new design standards. The variables that were considered in the study were layer thickness, unit weight, cement content, and unconfined compressive strength. Two highways were included in the study: a section of Highway 84 in Jefferson Davis county and a section of Highway 25 in Winston County. Twenty cores were taken from each location, along with unstabilized base material from the shoulder of the roadway.

The material from Highway 84 classified as an A-2-6 with a design cement content by weight of 3.8%; the material from Highway 25 classified as an A-2-4 with a design cement content by weight of 3.1%. Unconfined compression strengths were corrected for different *h/d* ratios because cores were not the same length after coring and trimming. The design requirement for UC strength was 2068 kPa. Table 2.4 shows the adjusted unconfined compression strength statistics obtained for each tested highway.

Table 2.4 Hwy 84 and 25 Compressive Strength Variability

Highway	**n**	**Mean (kPa)**	**Stdev (kPa)**	**COV (%)**	**% Meeting σ Req'd**
84	17	4579	1251	27.3	100
25	19	2437	844	34.7	63

Specimens adjusted based on lab produced correlation to h/d ratio of 1.15:1.

The author notes that the higher COV values for the compressive strength of the field cores indicate the presence of poor construction methods and poor quality control methods. The author recommended the following with regard to the study: cement content be prescribed as a percent by mass and that unconfined compression strength should be included in the quality control program for cement-treated pavement layers.

2.4 Modulus Literature Review

2.4.1 Reinhold (1955)

Reinhold (1955) investigated the elastic behavior of four blended materials (Table 2.5), made from fine material with Heppenheim clay. The author references Siebel (1940), indicating there should be a 3 to 1 height to width ratio in specimens where strain measurements are taken, therefore, rectangular specimens were 7.07 by 7.07 by 23.21 cm. Compression testing was performed with a 500 ton hydraulic testing machine. Strain measurements were taken on the middle 10 cm of each specimen by a mirror apparatus. This was performed to avoid the friction influence of the shear cone and only investigate the mono-axial specimen stress condition. Specimens were made at optimum moisture content. The cement content was prescribed as a ratio of cement to dry soil. For example, the 1:6 cement to soil ratio denoted one part cement to six parts dry soil by weight. Table 2.5 provides average test results. σ_{MAX} was defined as the maximum compressive stress and E_e was defined as the real elastic modulus up to 0.33 σ_{MAX}.

Reinhold (1955) noted the stress strain diagrams indicated the materials behaved almost perfectly elastically up to approximately 0.33 σ_{MAX}. Thus, E_e in Table 2.5 shows the average elastic modulus of each material and cement content in the region up to 0.33 σ_{MAX}. The author stated the elastic behavior of soil cement is generally a function of its strength. The data suggests that higher cement contents within a mixture produce higher elastic modulus values. The research concluded that (1) compressive strength is the determinant for soil cement elastic behavior, (2) density, cement content, moisture content, and clay content influence elastic behavior of soil cement, (3) and a linear stress-strain relationship can be assumed up to one third of a specimen's compressive strength.

Table 2.5 Average Elastic Properties, Reinhold (1955)

Soil	Sand (%)	Clay (%)	LL (%)	PI (%)	Cement:Soil Ratio	σ_{MAX} (kPa)	E_e (GPa)
					1:6	8766	13.6
A	100	0	---	NP	1:8	5796	11.0
					1:10	4179	8.9
					1:6	11769	14.0
C	75	25	17	NP	1:8	7854	11.2
					1:10	5649	9.1
					1:6	7119	9.1
D	50	50	25	9	1:8	4914	8.1
					1:10	3972	6.5
					1:6	5250	4.5
F	0	100	39	18	1:8	3825	3.8
					1:10	2943	2.9

2.4.2 Felt and Abrams (1957)

Felt and Abrams (1957) provided a range of strength and elastic properties in soil cement mixtures with different soils, described relationships between these properties, and showed new methods to develop and perform the tests. Also provided was a brief variability study on elastic modulus. The paper was part of a comprehensive study of soil cement mixture physical characteristics. Four different soils from Illinois were tested; in particular Soil 2, an A-2-4 soil based on the U.S. Bureau of Public Roads classification, which is the type of material used in the present study. Specimens used for determining modulus of rupture, static modulus of elasticity in flexure, dynamic resonance modulus, dynamic Poisson's ratio, and modified cube compressive strength tests were 7.6 by 7.6 by 28.6 cm beams. Specimens used for compressive strength, static elastic modulus in compression, and static Poisson's ratio were 7.1 cm diameter by 14.2 cm tall cylinders. Specimens used only for compressive strength were 5.1 cm diameter by 5.1 cm tall cylinders. Also, 10.2 cm diameter by 11.7 cm tall cylinders were used for compressive strength. Specimens were compacted to ASTM D 558-44 (standard proctor) optimum moisture and maximum density.

The author utilized a compressometer outfitted with an SR-4 clip gage to measure displacements in the middle 7.6 cm of each specimen. Specimens were capped with gypsum plaster before testing. Elastic modulus in compression as well as compressive strength specimens were aged in a moist environment for 7, 28, and 90 days. 365 day tests were also cured for compressive strength tests. The elastic modulus in compression was taken as the secant modulus at approximately 33% of the ultimate load. For the A-2-4 soil, the elastic modulus in compression ranged from 2.1 GPa to 19.3 GPa at cement contents ranging from 3 to 14% by weight. The author compared elastic modulus in compression values with the work of Reinhold (1955), finding similar results for similar materials. It was also found that dried specimens (at 54 C for 6 days after 21 day moist cure) have higher compressive strengths, they usually exhibit a lower modulus of elasticity in compression.

This work concluded that modulus of rupture, compressive strength, and modulus of elasticity depend on soil type, cement content, curing time, and curing method. It was also noted that all parameters increased as the cement content and moist curing time increased. The study also shows that the elastic modulus in compression at 33% of ultimate load is approximately 60 to 75% of the resonance (dynamic) modulus, calculated from the fundamental transverse frequency, weight, and dimensions of the prism.

The authors conducted a variability study on twenty-four 7.1 cm diameter by 14.2 cm tall cylinders, at 6% and 14% cement contents by mass. Material used for this study was an AASHTO classified A-4. Specimens were cured in a moist room for 28 days. Results can be found in Table 2.6. The authors concluded the variability results were good to excellent in the case of elastic modulus in compression (E_{sc}) of the soil cement mixture.

Table 2.6 Felt and Abrams (1957) Elastic Modulus Variability

Test	**C_w (%)**	**n**	**Mean**	**Stdev**	**COV (%)**
E_{sc} (GPa)	6	6	3.5	0.26	7.3
	14	6	4.6	0.36	7.8

2.4.3 Thompson (1966)

A study was performed to investigate the shear strength and elastic properties of typical lime and soil mixtures and to determine any relationship between the elastic properties and the unconfined compressive strength of these mixes. Four typical soils in Illinois were classified as an A-7-6 (18), A-6 (6), A-6 (8), and A-4 (8). The lime used was a commercially produced high-calcium hydrated lime. Specimens dimensions were 50.8 mm tall by 101.6 mm diameter compacted in three lifts, with a compaction effort of 20 blows per layer with a 1.8 kg hammer dropped from a height of 305 mm. Specimens were compacted to maximum dry density and optimum moisture content. Curing took place in a sealed container at 49 C for 0, 1, 2, 4, and 6 days. Compression testing was at a rate of 1.27 mm/min and was conducted with confining pressures from 0 to 241 kPa. Readings of load and total deformation were recorded during testing.

The confining pressures were found to have little effect on the calculated elastic modulus values. Elastic modulus values were noted to be much higher after the addition of lime. These elastic modulus values for the lime-soil mixtures ranged from 0.14 GPa to 1.10 GPa. A linear regression analysis (Equation 2.2) was conducted between the unconfined strength and elastic modulus of the specimens that were tested at a confining pressure of 103 kPa. Analysis found a highly significant regression at an $\alpha = 0.01$.

$$E = 9.98 + 0.124q_u \qquad \text{(Eq. 2.2)}$$

Where:

E = Elastic Modulus (ksi)

q_u = unconfined compression strength (psi)

2.4.4 Kolias and Williams (1984)

Kolias and Williams (1984) derived a relationship between a term referred to as gradation modulus (defined in the next paragraph), uniaxial compressive strength, and the modulus of elasticity of typical materials used in cement stabilization. The method proposed gives a rapid approximation of the modulus of elasticity without laboratory testing, which could be used for pavement analysis. The authors used data from a previous study, as well as data from Reinhold (1955). Materials ranged from a flint gravel aggregate to a fine grained silty material. Specimens used for the procedure included prismatic (101.6 by 101.6 by 254 mm) and cylindrical (101.6 mm diameter by 254 mm tall) types compacted to refusal according to British Standard Methods for Stabilized Soils (BS 1924:1967). Reinhold (1955) compacted specimens to maximum standard proctor density. Gradation modulus correlation to elastic modulus was stronger than that of mean aggregate size. Gradation modulus was therefore used for estimating elastic modulus. Trends were further strengthened through data obtained from other literature, including Williams and Patankar (1968), Fossberg et al. (1972), Felton (1975, unpublished), Felt and Abrams (1957), and Toklu (1976).

Gradation modulus (G) is found by adding the percentages passing the standard ASTM 37.5 mm, 19.0 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm, 150 µm, and 75 µm sieves and dividing by 100. Equation 2.3 is used to determine an approximate modulus of elasticity for cement stabilized materials. The authors noted that good agreement was found between data collected for prediction of elastic modulus and data used from other publications as verification of the method.

$$E_{fp} = (15.5-1.3G)(f_p)^{1/2} \quad \text{(Eq. 2.3)}$$

Where:

E_{fp} = modulus of elasticity at a strength level of f_p (GPa)

f_p = uniaxial compressive strength (MPa)

G = Gradation modulus

2.4.5 James et al. (2009)

James et al. (2009) conducted a study on the effects of compaction and moisture content on the strength of soils that are chemically stabilized and used in Mississippi pavement construction. Seven soils typically found in Mississippi were tested ranging from silty clays to clayey sand. Three of the soils were similar to those evaluated in this thesis. Specimens were prepared with different standard proctor compaction efforts at OMC and +3% over OMC, using three equal lifts per specimen. Phase one utilized the

CBR (ASTM D 1883) and UC test (MT-26) to relate behaviors to the presently used pavement structural design procedures used by MDOT. Phase two utilized the resilient modulus test (per NCHRP 1-28A document) for lime stabilized materials and UC tests for cement stabilized and lime/fly ash stabilized materials. The study used Equation 2.4 to calculate elastic modulus. A sample of elastic modulus values from materials similar to ones used in the present study are provided in Table 2.7.

$$E = 1200 * q_u \quad \text{(Eq. 2.4)}$$

Where:

E = Elastic Modulus (psi)

q_u = unconfined compression strength (psi)

The study found that, although a smaller density range was observed for cement stabilized materials compared to other stabilizing methods investigated, there was an increase in compressive strength and elastic modulus with an increase in density. In some cases, increasing the amount of blows per layer from ten to forty doubled the elastic modulus, while in other cases only increased it by approximately 50%. Also, it was found OMC +3% generally produced lower elastic modulus compared to specimens made at OMC.

Table 2.7 Cement Stabilized Elastic Modulus (James et al. 2009)

Mat. ID	USCS Mat. Type	C_w (%)	Blows per Lift	% Proctor γ		Elastic Modulus (GPa)			
						@ OMC		@ OMC + 3%	
				OMC	+3% OMC	7 Day	14 Day	7 Day	14 Day
5	SM	5	10	92.1	94.0	0.4	0.6	0.5	0.6
			25	98.2	97.8	0.7	0.9	0.5	0.9
			40	100.8	97.8	0.9	1.2	0.5	0.7
6	SM	5	10	91.4	95.1	1.4	1.7	1.1	1.4
			25	98.6	96.8	2.6	2.5	1.3	1.6
			40	101.3	97.2	2.3	2.9	1.4	1.7
6R	SM	4	10	92.7	94.6	2.1	2.4	1.7	2.0
			25	99.7	96.3	2.9	3.4	1.4	1.7
			40	101.2	96.9	2.9	3.4	1.3	1.5
7	SC	5	10	88.0	92.0	1.1	1.4	1.7	2.0
			25	97.7	96.7	2.4	2.7	1.9	2.5
			40	101.1	97.1	3.0	4.0	2.0	2.5

Note: Materials shown are A-2-4 according to AASHTO classification.
C_w represents portland cement content based on weight of dry soil.
All elastic modulus values calculated from Equation 2.4.
Percent of density calculated from 7 and 14 day average.

2.5 Wheel Tracking Literature Review

2.5.1 Scullion et al. (2005)

Scullion et al. (2005) performed extensive laboratory testing in order to improve the performance of soil cement base layers as well as cement-modified soils. One of the methods utilized to improve the performance of these materials from a design perspective was to investigate the effectiveness of a wheel tracking durability test. Durability tests were once part of the design process (i.e. AASTHO T135 and T136). However, many agencies now only use the unconfined compression test for design. The authors used the South African Wheel Tracking Test to evaluate durability.

The South African Wheel Tracking Test is an erosion durability test that measures the rutting of prismatic specimens under a loaded wheel. The prismatic specimens are submerged in water, covered with a rough neoprene membrane, and tracked with a 17.78 kg beveled rim wheel. The depth of erosion is measured at 15 points along the specimen after 5000 passes. Averaging these depths yields the erosion index for the test. Specimens were cured for 21 days.

After testing, the authors concluded the wheel tracking test was helpful in determining how the cemented materials react to the abrasive service conditions. Rutting measurements ranged from 0.2 mm to 4.8 mm. Some material/cement content combinations failed the wheel tracking test (>1 mm or rut) while passing other vital design specifications. However, it was concluded that the South African Wheel Tracking test requires specialized equipment and is not readily found in the U.S. The authors recommend this test only be used for research purposes, special studies, or unusual materials that need further study.

2.5.2 Wu and Yang (2012)

Wu and Yang (2012) conducted a study to compare the MEPDG design software to pavement performance data from the pavement management system in Louisiana on 40 strategically selected asphalt concrete pavements including 16 with soil cement bases. Also, the authors used this study to develop local calibrations for the MEPDG model for use in the state. The study used the traffic, climate, materials, and structural characteristics of the region in the model. Conclusions were that the MEPDG over-predicted the rutting of pavements with asphalt concrete over a soil cement base layer. This over-prediction was most likely from the high rutting in the subgrade. The authors indicated that the MEPDG model for rutting does not take into account rutting from the soil cement layer; there is no rutting model for cemented base layers in the MEPDG.

2.6 Practice Review

A survey was developed and made available in order to gather information pertaining to stabilized soil design procedures, testing approaches, results evaluation, and pending concerns within the practice. This survey, found in Appendix D, was available at the 98th AASHTO Subcommittee Meeting on Materials (August 2012) in Biloxi, MS. Also, individuals were given the opportunity to find, complete, and submit the survey via the Construction Materials Research Center (CMRC) webpage found on the MSU Department of Civil and Environmental Engineering website for approximately four months. Responses were compiled and are summarized herein, while not disclosing sensitive information.

Twenty responses were collected, each from a different state department of transportation. The sectors (or divisions) of the departments of transportation included, but were not limited to, construction, materials, geotechnical, research, and testing. The following list contains all states that responded in alphabetical order. Questions as they appeared in the survey are italicized in the following sections, followed by a summary of the received responses.

Alabama	Louisiana	New Mexico	Pennsylvania
Colorado	Maine	North Carolina	South Carolina
Connecticut	Maryland	North Dakota	Tennessee
Delaware	Nebraska	Ohio	Texas
Georgia	Nevada	Oklahoma	Utah

2.6.1 Question 1

Does your state utilize chemically stabilized (i.e. portland cement, fly ash, lime, slag cement, etc) pavement layers for roadway construction?

Most of the responses received indicated that the state DOT, to some extent, utilized chemically stabilized pavement layers for roadway construction. However, two of the twenty responses indicated states do not use chemically stabilized pavement layers because subgrade soils are adequate enough or there is an abundance of good aggregate sources for economical use on projects. One of these states used chemically stabilized pavement layers in some research, but no use as far as commercial projects.

Those responses that specified a state uses chemically stabilized pavement layers showed a variety in chemicals used. Nine of the eighteen responses said that cement was used or frequently used in the state. The most used of the chemical stabilizers seemed to be cement, lime, fly ash, and lime/fly ash. Other chemical stabilizers that were mentioned by a few respondents are cement kiln dust, lime kiln dust, calcium chloride, and sodium chloride. According to the survey, the southern region of the U.S. (per U.S. Census Bureau) seems to use chemically stabilized materials more frequently; however, this is not a strong trend because the use of chemically stabilized pavement layers seems to be widespread. The general trend for the northeast, Midwest, and west regions is the infrequent use of chemically stabilized pavement layers.

2.6.2 Question 2

How is the design stabilizer (e.g. portland cement) content determined? Please list any test types (e.g. unconfined compression), specimen sizes (e.g. 3 in by 6 in), and test requirements (e.g. 200 psi after 7 day cure) that are used to determine the design stabilizer content.

Responses providing information pertaining to the aforementioned question all indicated that the unconfined compression test is used in the design of chemically stabilized pavement layers. A few responses showed that no design is required, but a predetermined amount of stabilizer is used per material type. The specimen size and design strength requirements were not consistent between states that responded. A general range of 689 kPa to 5171 kPa was observed. Table 2.8 gives specimen sizes, strength requirements, and curing descriptions for respondents sorted by *h/d* ratio.

At least ten of the departments use the standard proctor size specimen (102 by 116 mm) for compression strength testing. Depending on the material being used for a stabilizer, the strength requirement range generally falls between 700 and 3500 kPa for the *h/d* ratio of 1.15. Geographically, there seems to be no trend to required compressive strength with respect to region. There are states that share a boarder with differing compressive strength requirements.

Table 2.8 Specimen Size, Strength and Curing for Stabilized Design from DOT Survey

***h/d* Ratio**	**Req'd σ (kPa)**	**Curing Description**
0.76	2068 or 4137	7 day moist, 24 hr soak
1.00	5171	7 days
1.15	1103 to 3447	5 days @ 38 C
	1379 to 2068	7 days
	3103 psi	---
	1034 or 2068	7 days
	1724	---
	No Minimum	---
	345 to 2068	7 days
	2068 to 2758	7 days
	689	7 day + 1 day moist cure
	2068 to 3447	7 days
1.33	1724 to 2620	7 days
1.50	1379 to 3447	7 days
2.00	1724 to 4137	---

2.6.3 Question 3

Once determined, how is the design stabilizer content referenced? Examples might include percent of dry soil mass, by volume…..

When referencing the design amount of stabilizer, two methods are generally used: by volume and by mass. Of the eighteen responses, three states specify the design amount of stabilizer by volume. Thirteen out of eighteen respondents said their institution specifies the design amount of stabilizer on a by mass basis. One institution gives a recommendation of the amount of stabilizer in pounds per square yard per project and one did not specify.

2.6.4 Question 4

What compaction method(s) are used to make specimens for Question 2?

There were seventeen out of twenty responses that gave information pertaining to the compaction method used to make specimens for designing stabilized pavement layers. The one response that did not give compaction information but still uses stabilization for pavement layers has a predetermined percentage by weight of stabilizer for specific material types.

The compaction efforts mostly refer back to AASHTO T 99 and AASHTO T 180. Some reference these specifications specifically while some states have their own specifications based on these test methods. One state uses the Harvard Miniature Compaction effort and specimen size (ASTM D 4609).

2.6.5 Question 5

Is there any replication of the tests performed in Question 2? For example, are three replicate unconfined compression tests averaged to compare to the design strength requirement?

Responses indicate that most state DOTs have some form of replication of testing specimens when designing chemically stabilized pavement layers. Eleven of the eighteen responses that utilize chemical stabilization have some form of replication. Two indicated that only one specimen was made for each stabilizer dosage. Seven entities did not provide information on this question. One indicated using two replicates in the design process. Eight of the responses use an average of three replicates in the design process, while two use five replicates. A respondent explained that they create five specimens per stabilizer amount and after testing all five, omit the highest and lowest, averaging the three remaining values.

2.6.6 Question 6

Is there a maximum time allowed between mixing the chemical stabilizer, soil, and water until compaction must be completed?

Twelve respondents provided information indicating that there was a time limit placed on the amount of time between mixing the chemical stabilizer, soil, and water and completed compaction. There was a wide range in maximum allowable time between mixing and compaction. This time ranged from 30 minutes to 240 minutes. These responses were most likely referring to field times. One response indicated a time allowance of five minutes, and is assumed to be enforced during the design process.

2.6.7 Question 7

Briefly describe any quality control measures that are taken with regard to chemically stabilized pavement layers in your state.

Quality control measures that are used do not seem to diverge from a few core checks. Respondents usually provided multiple quality control measures in answers. Six of the eighteen respondents indicated that field proctors are performed to confirm the compaction of the field mixed material compared to that performed in the laboratory.

Eleven of the eighteen respondents shared that the spread rate of the chemical stabilizer is verified in the field, either by the tarp method or by distance covered per truck. The nuclear method of verifying density on the compacted pavement layer was mentioned by seven of the eighteen responses. One of the responses even indicated that a small test strip must be constructed in order to verify that designs can be met by the construction crew before the job continues.

The formation of field specimens/cores was mentioned by five of the respondents. Three of these make specimens in the field, cure them in the laboratory, and obtain a compressive strength to compare to the design. Mold sizes were not specified in answers, but one of these responses indicated a split proctor mold was used. Two respondents indicated after an amount of time, actual cores were taken from the layer and tested for compressive strength; strengths had to meet design specifications. Coring procedures were not noted in responses, but one of these respondents indicated that 152 mm cores were taken from the job site.

2.6.8 Question 8

Please list any problems or concerns with chemically stabilized pavement layers, their design, or their quality control. Also provide any feedback on areas of needed improvement in design or quality control.

From the survey, there seem to be several problems and concerns about stabilized pavement layers, their design, and quality control efforts and practices. The problems and concerns are summarized in the following bulleted list:

- Difficulty to achieve and verify uniform mixing of materials on site.
- Inconsistent spread rates caused by allowing spreading by blow tubes of tanker can lead to low or high concentrations of chemical stabilizer.

- Need for extensive sampling of borrow pit or in-situ material to ensure mix design properly represents material to be stabilized.
- Crucial to use exact same cement source in design and in field.
- Difficulty in balance between strength and cracking potential (cement content)
- Field strengths may achieve much higher strengths than in design.
- Variability in stabilization based only on soil classification; possibly include other tests for better performance prediction.
- Concern related to duration of required curing before traffic opening.
- Determination of appropriate stabilizer based on in-situ soil conditions.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Overview of Experimental Program

Research contained in this thesis is part of a larger study, MDOT State Study 206. This thesis focuses on strength gain with time, strength variability, wheel tracking, and elastic modulus of soil cement. Approximately 1,109 tests were completed, including 1,035 unconfined compression tests, 54 elastic modulus/unconfined compression tests, 12 PURWheel tests, and 8 Asphalt Pavement Analyzer tests. Three soils and two cement sources were tested. A portion of this research was performed alongside Sullivan (2012); some properties and procedures in this chapter are used simultaneously, and are referenced accordingly.

3.2 Terminology

Each specimen was given a unique identifier. The testing group was given by a series of letters, followed by values describing specimen type, material type, and cement content. For recording purposes, a specimen number followed this label. The specimen identification system is shown in Equation 3.1. Individual components of the format are defined thereafter, using terms often not defined until later in the chapter.

$$12\text{-}34\text{-}5 \qquad \text{(Eq. 3.1)}$$

1: Identifies testing category.

SV: Strength Variability

SVM: Strength Variability using MDOT Curing Method

ST: Strength vs. Time

PW: PURWheel

APA: Asphalt Pavement Analyzer

EM: Elastic Modulus

2: Type of specimen tested.

1: 102 by 116 mm Standard Proctor

2: 100 by 114.6 mm Superpave Gyratory Compactor (SGC)

3: 150 by 75 mm SGC

4: 76 by 152 mm Plastic Mold in Compaction Frame (PM-CF)

5: 293 by 624 mm LAC Slab

6: 150 by 62 mm SGC

7: 76 by 152 mm Plastic Mold (PM)

3: Material Source.

PA: Pit Soil A

PB: Pit Soil B

PC: Pit Soil C

4: Cement index (C_I). The cement index references the percent by volume of a 94 pound US. bag of cement. An adjustment made to the cement index using the *MT-8* and *MT-9* densities converted the value to percent by dry soil mass (C_w). A detailed description of this process along with equations is given in Sullivan (2012). Indices range from 3 to 6.

3: 3% Cement Index

6: 6% Cement Index

5: Individual specimen identifier used primarily for record keeping. Specimens range from 01 to 45. This identifier denotes replicate specimens and is only presented herein when relevant.

01: Specimen 1

45: Specimen 45

As an example, take an individual specimen labeled SV1-PB5-02. This particular specimen belongs to a strength variability testing category and is a 102 by 116 mm standard Proctor compacted sample. The material used for the specimen was from pit soil B with a cement index of 5%, and it was the second replicate produced.

3.3 Materials Tested

3.3.1 Cementitious Materials

Two *ASTM C150* Type I-II portland cements supplied by Holcim (U.S.) Inc. were used herein. The cement used in most of the testing was from the Theodore, AL plant, which is denoted *TH T I-II*. The second cement was obtained from the St. Genevieve plant located in Bloomsdale, MO, which is denoted *GV T I-II*. Table 3.1 summarizes portland cement properties supplied by the manufacturer.

Table 3.1 Properties of Portland Cements Tested

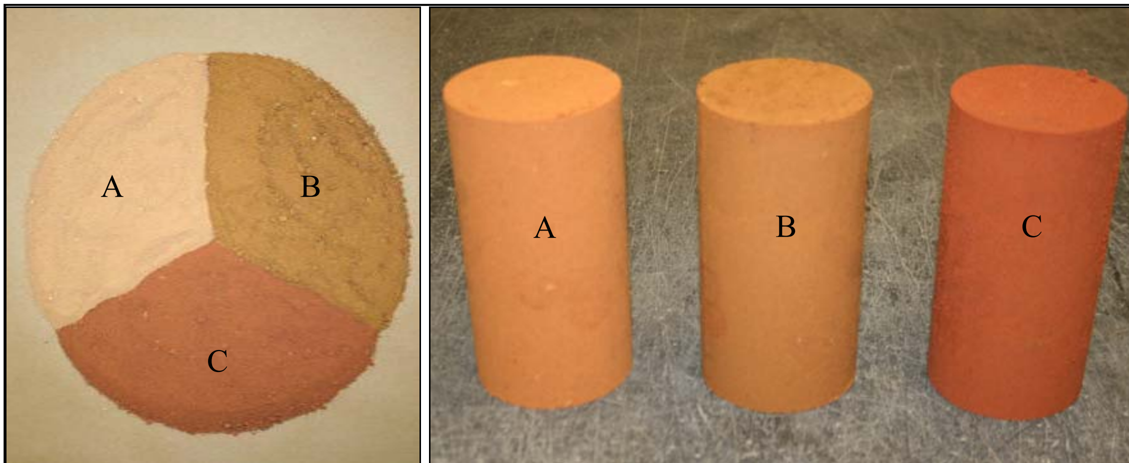
Cement	*TH T I-II*	*GV T I-II*
SiO_2 (%)	19.9	20.0
Al_2O_3 (%)	4.7	4.5
Fe_2O_3 (%)	3.4	3.1
CaO (%)	64.5	64.2
MgO (%)	1.2	2.3
C_3S (%)	60	62
C_2S (%)	11	9
C_3A (%)	7	6
C_4AF (%)	10	9
LOI (%)	2.2	2.7
Blaine (m^2/kg)	379	383
Vicat Initial (min)	101	90
Air (%)	7	7
1-day strength (Mpa)	16.1	15.7
3-day strength (Mpa)	26.4	27.5
7-day strength (Mpa)	33.4	36.1

3.3.2 Pit Soils

The three pit soils used in this thesis were collected from borrow pits for MDOT highway construction projects using soil-cement as a base course (Figure 3.1). A detailed description of the material can be found in Sullivan (2012), with a brief description provided herein. MDOT's first base course project in south, central, and north MS were chosen for the research. Soil samples were obtained from borrow pits in:

1) Central MS: US Interstate 20 interchange project near Meridian (*Pit A*)
2) North MS: US Hwy 45 interchange project near Saltillo (*Pit B*)
3) South MS: US Hwy 84 expansion in Jefferson-Davis County (*Pit C*).

Tests for fundamental properties of the soils were conducted after processing (processing described in Section 3.4). Table 3.2 shows fundamental property results from samples tested for the current research study. Additional tests were conducted by MDOT and Burns Cooley Dennis, Inc. and can be found in Sullivan (2012).



a) Pit Soils (Post-Processing) b) Sample Pit Soil Specimens

Figure 3.1 Pit Soils Tested

Table 3.2 Fundamental Properties of Pit Soils

Source	***Pit A***		***Pit B***		***Pit C***	
Soil Property	**Avg.**[1]	**Rng.**[2]	**Avg.**[1]	**Rng.**[2]	**Avg.**[1]	**Rng.**[2]
$\omega_{natural}$ (%)	9.4	0.1	13.4	0.8	11.0	1.2
Plasticity Index	NP	-	NP	-	NP	-
% Pass 2.00 mm	100	1	100	0	100	2
% Pass 0.425 mm	79	6	95	1	90	4
% Pass 0.250 mm	60	7	62	4	54	6
% Pass 0.150 mm	25	3	27	4	30	0
% Pass 0.105 mm	21	1	25	4	27	1
% Pass 0.075 mm	20	2	24	4	26	3
G_s	2.65	-	2.65	-	2.65	-
USCS	SM	-	SM	-	SM	-
AASHTO Class.	A-2-4	-	A-2-4	-	A-2-4	-
MDOT Class.	9C	-	9C	-	9C	-

1: Average value for the pit soils tested for the current work.
2: The total range of test values.

Mississippi Test Methods 8 and 9 (known hereafter as Protocol 1) were conducted to find standard Proctor test values (raw and cement treated) for each of the materials

(Table 3.3). These were the target density and moisture values used for specimen preparation. Protocol 2 was enacted because of a noticeable drop in maximum dry density with *Pit B* material when noticeable time elapsed between mixing and compaction. In Protocol 2, no material was reused for the Proctor test; each point was batched, mixed, and compacted within 7 minutes. Check points were conducted to determine if a change in cement source would affect Proctor results; tests indicated that there was no meaningful effect on Proctor results with a change in cement source. Protocol 1 and 2, as well as *MT-8* and *MT-9*, are discussed in depth in Sullivan (2012). Also, procedures and data for *MT-25* designs are provided in Sullivan (2012) that pertain to the chosen cement indexes for this study.

Table 3.3 Pit Soil Standard Raw and Cement Proctor Results

Material	Cement Index (%)	Cement Type	γ_d (kg/m^3)	OMC (%)	n
Pit A	0[2]	None	1860	11.6	2
	4	*TH T I/II*	1878	11.8	1
	5[3]	*TH T I/II*	1919	11.8	1
	6	*TH T I/II*	1910	11.8	1
Pit B	0	None	1834	13.8	3
	4[1]	*TH T I/II*	1813	14.5	1
	5[1,3]	*TH T I/II*	1812	14.0	1
	6[1]	*TH T I/II*	1813	14.2	1
Pit C	0	None	1946	11.0	4
	3	*TH T I/II*	1959	10.9	1
	4[3]	*TH T I/II*	1935	11.4	1
	5	*TH T I/II*	1975	11.0	1

1: Protocol 2 procedures were implemented.
2: One test was believed to be suspect and was not included to determine the average value.
3: Design cement index.

3.4 Material Processing

A detailed pit soil processing description can be found in Sullivan (2012). Only a brief synopsis is given herein. Approximately 2,000 kg of each of the pit soils was sampled on site. Material was allowed to air dry on tarps. Once air dry, the material was screened over a 4.75 mm sieve. Material remaining on the 4.75 mm sieve needed further processing. This material was comprised mostly of silt and clay that clumped together. Clumps were lightly tamped until they passed a 4.75 mm sieve, then they were added proportionally by weight to previously sieved material. Material was thoroughly mixed and returned to barrels for long term storage. For precaution against segregation, each barrel was dumped, mixed, and placed into approximately ten 19 L buckets prior to specimen production. Batching for test specimens was from the individual buckets.

3.5 Specimen Preparation

3.5.1 Moisture Content Adjustment

A moisture content adjustment was required to achieve the desired level in specimens. After experimentation, it was determined that adding 0.7% more water by mass than was desired resulted in the correct specimen moisture content. Testing was performed on full batch amounts (approximately 4000 grams) of *Pit B* to check the accuracy of the water content adjustment factor. Figure 3.2 shows a plot of the batched moisture contents in relation to the measured moisture contents that prompted the 0.7% moisture addition. This adjustment was found to be adequate for all batching. It was found that a tolerance of ± 0.5% of desired moisture could be met using this adjustment factor for all pit soils.

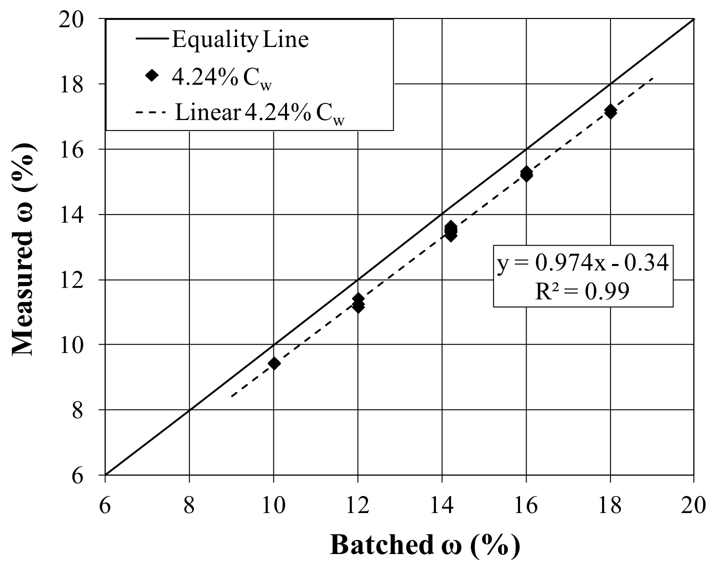


Figure 3.2 Pre-Adjustment Water Contents (*Pit B*)

3.5.2 Batching and Mixing

3.5.2.1 Cylindrical Specimens

Material batching and mixing was almost identical to that described in Sullivan (2012). However, soil and water were not preconditioned to the same temperature before cement was added. Materials were mixed using a 19 L, table mounted bucket mixer. Mixing began with the addition of water to soil. Water was added while the mixer was running at approximately 90 grams per second in order to combat material clumping. A paddle and a hand trowel were the mixing tools. The trowel was used by hand to assist the mixing with the paddle. Once water was added, the material and water was mixed for two minutes. Cement was then added to the homogeneous material and water mixture. This combination was mixed for another two minutes, resulting in approximately four minutes of mixing per batch. A quality control measure was conducted to check moisture contents based on measured wet and dry soil masses throughout the process. Upon complete mixing of material, water, and cement, a sample was taken from the bucket and used for this moisture content check.

3.5.2.2 Slabs

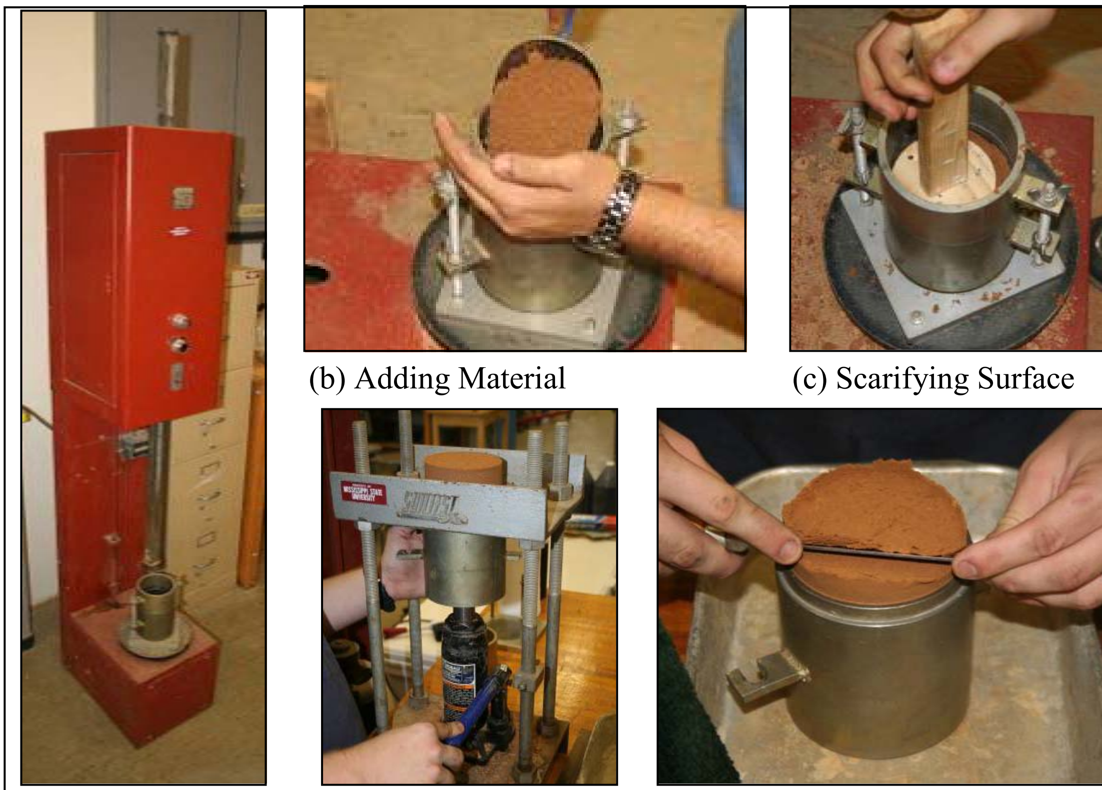
Material for Linear Asphalt Compactor slabs was mixed in a similar fashion to all cylindrical specimens. However, because of the large amount of material needed (i.e. approximately 30 kg), mixing was handled by two separate mixers. Mixers included the aforementioned 19 L table mixer as well as a large 38 L mixer. The amount of material needed to form a slab was not able to be compacted in a single lift; rather, compaction took place in two lifts (Section 3.5.3.5). Material was divided between the two mixers, approximately 40% in the table mixer and 60% in the larger mixer. Material for each mixer was then divided in half to accommodate the two lift procedure.

3.5.3 Compaction

Five different methods were used for compaction. Most specimens were compacted to between 98 and 101 percent of wet density (γ) corresponding to standard proctor maximum dry density, and target moisture contents were ±0.5% of OMC. Two specimens were made from each mixed batch. On some occasions, single specimen batches were required because of an odd number of specimens or a mishap in the production process. Single specimen sets are noted when they occur in the raw Appendix data files. Details pertaining to each compaction method are discussed in the following sections.

3.5.3.1 Mechanical Standard Proctor Hammer

A mechanical standard Proctor hammer (Figure 3.3a) was used to compact approximately 495 specimens. In general, the same compaction procedure used in *MT-8*, a modification of *AASHTO T99*, was used to compact specimens with a mechanical hammer. These specimens were denoted specimen type 1 in Equation 3.1.



(a) Hammer (b) Adding Material (c) Scarifying Surface (d) Extrusion (e) Striking off Surface

Figure 3.3 Mechanical Standard Proctor Hammer Compaction

After material was mixed according to Section 3.5.2.1, compaction occurred in three equal lifts in a 101.6 mm diameter proctor mold with a volume (V) of 943e^{-6} m^3 (Figure 3.3b). Each lift was compacted with 25 equally distributed blows with a 2.5 kg hammer dropped from a height of 305 mm above the top of the soil. Before the second and third lifts, a scarifying tool (produced for this study) was used to partially break up the previous layer to produce a uniform specimen. Once compaction was complete for both specimens (within 20 minutes of cement contact with water), a straightedge was used to strike off excess material before the specimen was extruded. After extrusion, specimens were labeled and placed under a damp towel for 2 $\pm$ 0.5 hours. Thereafter, measurements of height, diameter, and weight were recorded before a curing protocol was initiated. Because the mechanical standard Proctor hammer applied a given compaction energy rather than compacting to a density, some densities fell outside 98 to 101% of γ. If this occurred, those specimens were still included in analysis.

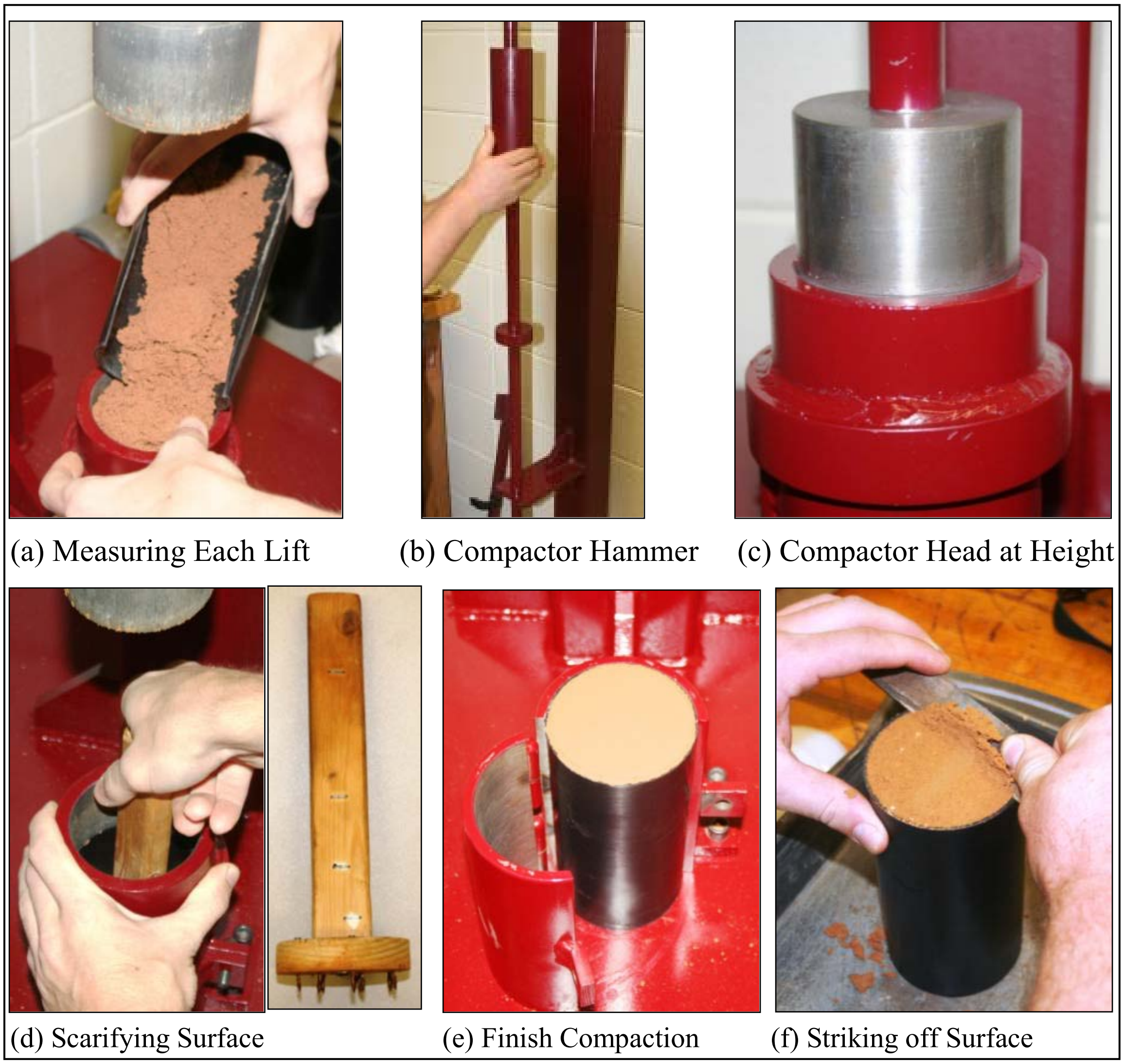
3.5.3.2 Superpave Gyratory Compactor (SGC)

A Pine AFGC 125X Superpave Gyratory Compactor (SGC) was used to compact approximately 143 specimens. Specimens with types 2, 3, and 6 (Equation 3.1) were compacted using the SGC. After material was mixed according to Section 3.5.2.1, a specified amount of material was placed in the SGC mold (100 mm or 150 mm diameter) to achieve 100% of wet density (γ). In most cases, a small amount (e.g. 10 grams) above the design weight was added to counter any lost mass (e.g. soaking of water into spacer paper, etc.). Spacer papers, as well as a thin piece of aluminum foil, were placed between the material and plates to assist in the removal of the top and bottom compaction plates. The SGC compacted the material to the appropriate height (114.6, 75, or 62 mm, respectively). Specimen type 2 (Equation 3.1) was compacted to 114.6 mm tall to attain the same *h/d* ratio as specimen type 1 (Equation 3.1). The specimen was then extruded from the mold; and the top plate, foil, and spacer paper were removed. The specimen was carefully loosened from the bottom plate by manner of a slight shearing action, followed by the removal of the bottom spacer paper and foil. After extrusion, specimens were labeled and placed under a damp towel for 2 $\pm$ 0.5 hours. Thereafter, measurements of height, diameter, and weight were recorded before a curing protocol was initiated.

3.5.3.3 Plastic Mold Compaction Frame (*PM-CF*)

A custom plastic mold compaction frame (*PM-CF*) was made to compact specimens in modified 76.2 by 152.4 mm plastic molds. Sullivan (2012) gives details on the making of the plastic molds used as well as the compaction frame with split mold and collar assembly. The *PM-CF* was used to compact approximately 342 specimens. Specimens compacted with the *PM-CF* were a type 4 specimen as per Equation 3.1.

Figure 3.4 shows major steps in compacting specimens using the *PM-CF*. After mixing (Section 3.5.2.1), material was added to the mold (Figure 3.4a) to be compacted. Each specimen was compacted in three equal lifts, each to a height equal to one third the height of the specimen (Figure 3.4b and 3.4c). After the first and second lifts, the surface was scarified with a tool made for this research to produce a uniform specimen (Figure 3.4d). After compaction, the specimen was struck off with a knife even with the top of the plastic mold (Figure 3.4e). Specimens attained a density of 98 to 101% of γ. Type 4 specimens were capped and used for Sullivan (2012) calorimetry research for 24 hours, then extruded, measured, and placed in the curing environment described in Section 3.5.5 before being re-used for unconfined compression tests.



(a) Measuring Each Lift (b) Compactor Hammer (c) Compactor Head at Height

(d) Scarifying Surface (e) Finish Compaction (f) Striking off Surface

Figure 3.4 Plastic Mold Compaction Frame (*PM-CF*) Compaction

3.5.3.4 Modified Proctor Hammer – Plastic Mold (*PM*)

The split mold and collar assembly (*PM*) of the plastic mold compaction frame was used along with a modified Proctor hammer to compact specimens. These specimens are referred to as specimen type 7 in Equation 3.1. Sullivan (2012) gives additional details on the making of the plastic molds used and the split mold and collar assembly mounted to a steel plate. The *PM* compactor was used to produce 237 specimens.

After mixing, a third of the required amount of material was added to the mold housing containing the plastic mold. A 4.54 kg hammer dropped from a height of 45.7 cm (modified Proctor hammer) was used to compact each specimen. Lifts were compacted with 5 evenly distributed blows. Care was taken to prevent the loss of material from the hammer being removed from the mold between lifts. After the first and second lifts, the surface was scarified (same tool as before) to produce a uniform specimen (Figure 3.4d). Once compaction was complete, the plastic mold was removed from the collar. Excess material was scrapped off the top with a straightedge even with the top of the plastic mold. Specimens were immediately extruded from the plastic molds, and diameter, height, and weight measurements were immediately taken. Because the modified Proctor hammer applied a given compaction energy rather than compacting to a density, some densities fell outside 98 to 101% of γ. If this occurred, those specimens were still included in analysis.

3.5.3.5 Linear Asphalt Compactor (*LAC*)

The Linear Asphalt Compactor (*LAC*) was used to produce soil cement slabs for PURWheel testing. There were 6 soil cement slabs made for this portion of the study. Slabs are referred to as a type 5 specimen in Equation 3.1. Operation and features, including a more detailed procedural description, of the *LAC* in use at MSU can be found in Doyle and Howard (2011). The LAC produces rectangular slabs that are 29.3 by 62.4 cm and between 3.8 and 10.2 cm thick.

For soil cement slabs, a thickness of 7.6 cm was targeted. Two separately compacted lifts were needed to achieve compaction. Material mixing was performed as specified in Section 3.5.2.2. Before material was added, a piece of paper was placed in the bottom of the mold. The first lift of material was added and spread to an even uncompacted height. Compaction plates were set in place. Hydraulic system pressure was set at 2413 kPa; 18 passes were applied to each lift (a pass is defined as compaction energy applied once to a given point). After compaction of the first lift, compaction plates were removed, along with the top release paper and thin sheet of metal. The surface was scarified to produce the most uniform specimen possible. The second lift followed the same approach as the first lift. After compaction, the slab was removed from the mold on an aluminum plate and transported immediately to the curing environment (Section 3.5.5). The curing protocol described in Section 3.5.5.3 was then initiated. Because the Linear Asphalt Compactor applied a given compaction energy rather than compacting to a density, some densities fell outside 98 to 101% of wet density (γ). If this occurred, those specimens were still included in analysis.

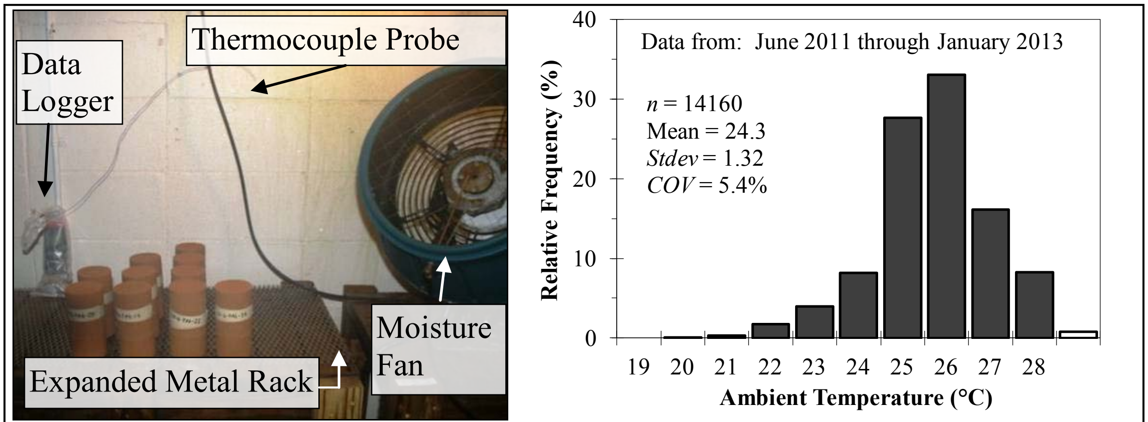
3.5.4 Density Measurements

Completed specimens were measured to determine their density, which was compared to a tolerance of 98 to 101 percent of wet density (γ). This density was compared to a wet density calculated for each soil and cement index combination based on maximum dry density from standard Proctor testing and optimum moisture content. Cylindrical specimen wet weights were measured. Four diameters were measured, two 90° from each other at the top and bottom of the specimen. The average of these was taken as the diameter (D_{AVG}). Heights were measured at four equally spaced locations on each specimen. The average of these was taken as the height (H_{AVG}).

LAC slab weights were measured on each half of the slab after cutting. Cutting was performed after seven days of moist curing using a masonry saw with minimal water to control dust. The saw used was a MK Diamond MK 5000 with a 50.8 cm wet cutting blade (MK-50S). Approximately 10 evenly spaced lengths and widths were measured on each slab half. Three evenly spaced heights were measured on all non-cut sides of each slab half. On each cut side, ten evenly spaced heights were measured. A wet density was calculated for each half of the slab.

3.5.5 Curing Protocols

For this study, three curing protocols were utilized. The moist curing room used is shown in Figure 3.5a. The moisture room was held at a humidity between 99.5 and 100%. To prevent specimens from resting in standing water, shelves were covered with stainless steel expanded metal (12.7 mm #18 style) mounted on wooden dowels. Curing room temperature was monitored every 60 minutes by a SPER Scientific Model 800024 data logger. A relative histogram is provided showing the ambient temperature distribution observed throughout testing (Figure 3.5b).



(a) Moisture Curing Room (b) Ambient Temperature Distribution

Figure 3.5 Moisture Curing Room and Ambient Temperature Distribution

3.5.5.1 Mississippi State University (MSU) Protocol

Specimens subjected to the Mississippi State University (MSU) curing protocol were placed under a damp towel for 2 ± 0.5 hours after compaction. This allowed the specimens to mature enough to prevent damage during measuring and handling. Some specimens could be handled immediately without damage, but the two hour hold time was kept consistent throughout the study. Density measurements were taken according to Section 3.5.4 after two hours under the damp towel. Once measurements were taken, the specimens were immediately placed uncovered in the moist curing room for a prescribed amount of time before testing.

3.5.5.2 Mississippi Department of Transportation (MDOT) Protocol

Specimen curing according to the MDOT protocol was similar to that described in Section 3.5.5.1. However, after measurements were taken, specimens were placed into 3.8 L plastic bags, then allowed to cure in the moist curing environment while in the plastic bags. Five hours before testing, the specimens were removed from the plastic bags and submerged in water stored in the moist curing environment. After five hours submerged in water, the specimens were ready to be tested.

3.5.5.3 Wheel Tracking Protocol (WTP)

All specimens used for wheel tracking were subject to the same curing protocol. Cylindrical specimens (types 3 and 6 of Equation 3.1) were compacted and then placed under a damp towel for two hours before being moved to the moist curing room; specimens remained in the moisture curing room for 56 to 63 days. Thereafter, wheel tracking was performed.

LAC slabs (type 5 of Equation 3.1) were placed in the moist curing room immediately after being compacted. Slabs were removed from the curing room to be sawn in half and measured after seven days. Slabs remained in the moist curing room for a total of 56 to 63 days. Thereafter, wheel tracking was performed.

3.6 Test Methods

Several test methods were used in this study. Methods included the unconfined compression (UC) test, elastic modulus testing of UC specimens with a compressometer, and wheel tracking. Wheel tracking included tests with the PURWheel, Asphalt Pavement Analyzer (APA), and Hamburg Loaded Wheel Tester (HLWT). Details of each test method are provided in the following sections.

3.6.1 Unconfined Compression

Unconfined compression tests were conducted on specimen types 1, 2, 4, and 7 as per *ASTM D 1633* and *MT-26* with a few notable exceptions. Both the load frame and proving ring used had 4536 kg capacity. Specimens were not soaked before testing as prescribed in the aforementioned specifications, unless it is mentioned in the curing procedure in Section 3.5.5. Procedures for conducting the UC tests were the same as given in the specifications.

Two different height to diameter (*h/d*) ratios were used for specimens. Specimen types 1 and 2 are the typical 1.15 *h/d* ratio of soil cement specimens. Specimen types 4 and 7 have an *h/d* ratio of 1.98:1. The approximate 2:1 ratio for these specimens was chosen to better interface thermal measurements and compressive strength data analyzed in Sullivan (2012). According to *ASTM D 1633*, compressive strengths of 2:1 *h/d* ratio specimens can be adjusted to 1.15:1 *h/d* ratio strengths by multiplying strengths by 1.1. For example, a 2:1 *h/d* ratio specimen has a compressive strength of 3000 kPa; multiplying 3000 kPa by 1.1 yields an equivalent 1.15:1 *h/d* ratio specimen compressive strength of 3300 kPa.

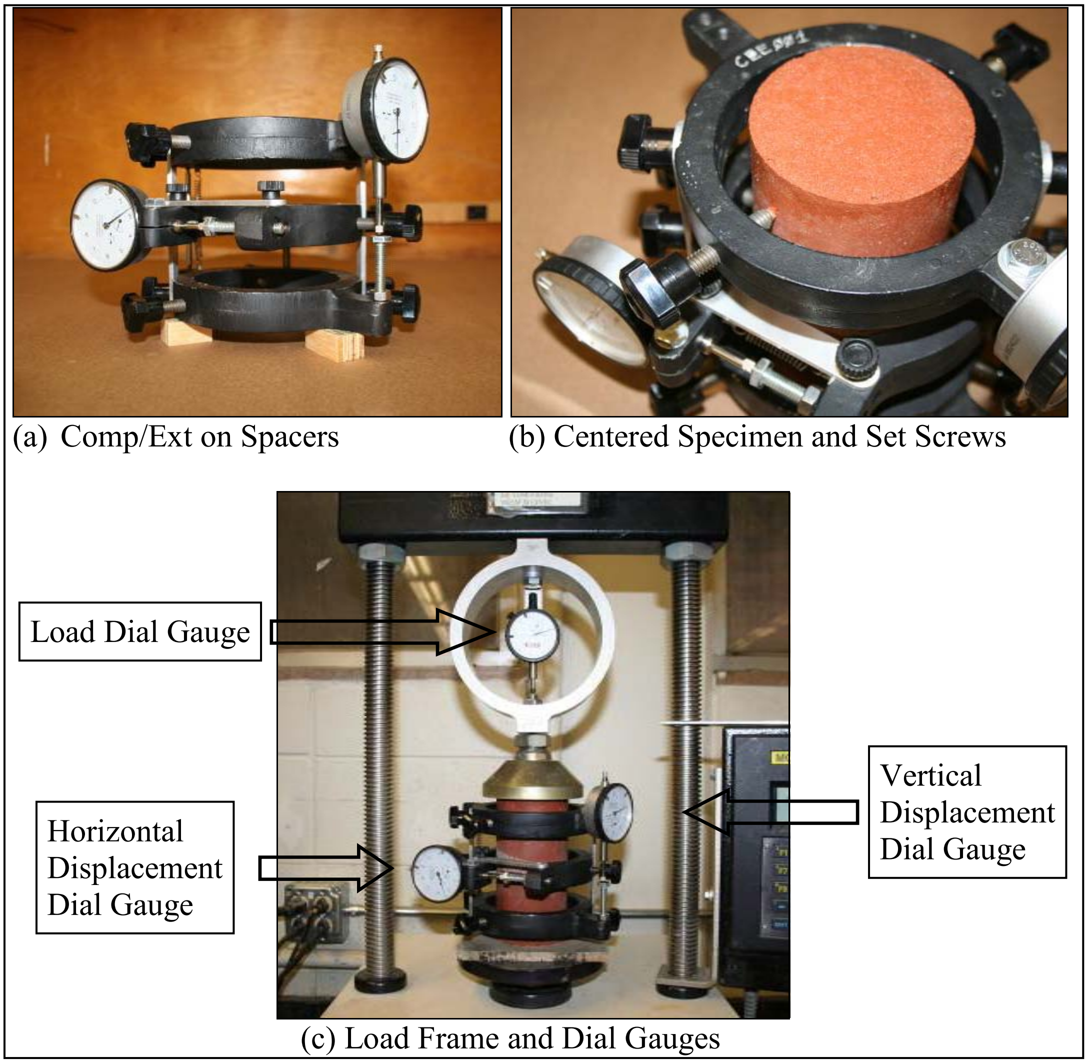
Specimens were tested after curing without capping since the specimen ends were smooth. Testing took place on a load frame fitted with a proving ring and spherically seated swiveling load head. Specimens were tested at a constant rate of 1.27 mm/min; i.e. the load frame platen moved 1.27 mm/min without the presence of a test specimen. Readings from the dial gage were taken every 10 seconds, providing a maximum strength and a stress-strain behavior based on the crosshead displacement using the 1.27 mm/min load rate for calculations. This procedure obtained strain measurements by multiplying the elapsed time of loading by the loading rate. This strain measurement was used in calculating a graphical elastic modulus ($E_{X\text{-}Head}$). The number of points from the linear portion of the stress/strain curve is denoted $n_{X\text{-}Head}$. Also, the maximum strain (ε_{max}) of the specimen was found by this procedure.

3.6.2 Elastic Modulus

Elastic modulus testing was performed on specimen types 4 and 7 of Equation 3.1. *ASTM C 469* was used as a basis for elastic modulus testing. Specimens were tested after the appropriate curing protocol (Section 3.5.5). An H-2919 Compressometer/Extensometer (Comp/Ext) with dial gages supplied by Humboldt Manufacturing Company was used to measure horizontal and vertical deflections.

The compressometer/extensometer was placed on three wooden spacer blocks (Figure 3.6a). These spacers allowed the instrument to be placed so the effective gauge length would be comprised of the middle 101.6 mm of the specimen. A specimen was lowered into the instrument and centered. Seven set screws used to hold the compressometer to the specimen were evenly tightened as to not move the specimen from the center of the instrument (Figure 3.6b). Care was taken not to harm the specimen by only tightening set screws approximately 1.25 rotations after initial contact with the specimen. Bracing screws on the compressometer were then removed.

Specimens with the instrument securely attached were placed in the load frame configuration as described in Section 3.6.1 (Figure 3.6c). Each specimen had a preload applied in order to set the instrumentation. This preload was approximately 40% of the ultimate stress. No data was recorded for this loading. Specimens were preloaded and loaded during testing at a constant rate of 1.27 mm/min. However, specimens were unloaded at a faster rate after the preload because of equipment limitations. Three individuals were used to accurately record load, vertical displacement, and horizontal displacement from dial gauges. Readings were taken every 10 seconds until failure of the specimen. The elastic modulus from the compressometer, denoted E_{Comp}, was reported for the behavior through 40% of σ_{max} for each specimen. The number of points used to calculate E_{Comp} is denoted n_{Comp}. $E_{X\text{-}Head}$, $n_{X\text{-}Head}$, and ε_{max} were also found according to Section 3.6.1.



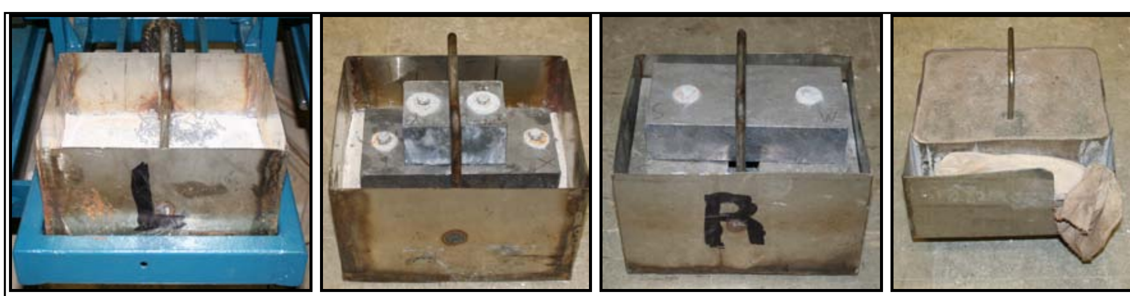
(a) Comp/Ext on Spacers (b) Centered Specimen and Set Screws
(c) Load Frame and Dial Gauges

Figure 3.6 Elastic Modulus Testing

3.6.3 PURWheel Laboratory Wheel Tracker

The PURWheel Laboratory Wheel Tracker was used to test soil cement slabs under multiple loading and environmental conditions. Tests were conducted at 64˚C according to the protocols in Howard et al. (2010), except for the items described as follows. Each slab was first subjected to a dry test. Thereafter, the same slab was tested in either a submerged or soaked condition test. These two tests (dry test and either submerged or soaked test) were conducted within 24 hours of each other. For the submerged condition, slabs were submerged for six hours and also during the test as described by the wet test procedure. For the soaked condition, slabs were submerged for six hours as described by the wet test procedure, however before tracking, water was drained below the slabs. Water was left in the bottom of the PURWheel to maintain 100% humidity in the chamber during soaked testing.

Four loading configurations were used in the PURWheel testing. Lead weights were fabricated to simulate four different downward forces applied to the surface of the *LAC* slabs. Howard et al. (2010) specified a 176 kg applied load for traditional PURWheel testing. This was referenced as 100% load. Weights were fabricated to apply a load to the specimen of approximately 86.4 kg (50% load), 110.6 kg (65% load), and 138.7 kg (80% load). Herein, load configurations are identified by percent referencing the specified load in Howard et al. (2010). Figure 3.7 shows each of the loading configuration labeled blocks used in testing.



(a) 50% load (b) 65% load (c) 80% load (d) 100% load

Figure 3.7 Masses for PURWheel Loading Configurations

3.6.4 Asphalt Pavement Analyzer (APA)

Wheel tracking tests were conducted in the Asphalt Pavement Analyzer (APA) using type 3 specimens at design cement index and optimum moisture content. Each test consisted of 8000 cycles, with a temperature of 64 C. Hose pressure was 690 kPa with a downward force of 445 Newtons. The testing procedure applied to specimens included a dry test followed by a submerged test. This was to simulate the same protocol used in PURWheel testing (Section 3.6.3). Tests were conducted within 24 hours of each other. *Pit A* was chosen to minimally investigate the effects of increased cement content on the performance of the material.

3.6.5 Hamburg Loaded Wheel Tester (HLWT)

A trial run was performed with a Hamburg Loaded Wheel Tester (HLWT) that was based loosely on *AASHTO T 324*; 6 soil cement specimens were tested. Tests consisted of 20,000 passes. Air temperature for the test was 50 C. Before being subject to the 705 Newton wheel load, specimens were soaked under water at 50 C for 30 minutes.

3.7 Test Matrices

3.7.1 Strength Gain with Time

A total of 315 laboratory compacted specimens were evaluated for strength gain versus time (Table 3.4). A minimum of three UC specimens were tested at each curing time. The curing times were: 1, 3, 7, 14, 21, 28, 42, 56, 90, 120, 180, 240, 360, and 540 days. Extra specimens were used as needed to obtain the necessary replication, and all remaining specimens were tested at 540 days. Along with maximum compressive strength (σ_{max}), each specimen was evaluated for modulus by means of crosshead displacement ($E_{X\text{-}Head}$).

Table 3.4 Test Matrix for Strength Gain with Time

Material	Cement Type	Cement Index	Specimen Type	Tests	Cure Method
PA	*TH T I/II*	Design	1	45	MSU
PB	*TH T I/II*	Design	1	45	MSU
PC	*TH T I/II*	Design	1	45	MSU
PA	*TH T I/II*	Design	4	45	MSU
PB	*TH T I/II*	Design	4	45	MSU
PC	*TH T I/II*	Design	4	45	MSU
PC	*TH T I/II*	Design	2	45	MSU

**Raw data is provided in Appendix A in Tables A.1 to A.7.*
Note: Design Cement Indices were 5, 5, and 4 for PA, PB, and PC, respectively.

3.7.2 Strength Variability

A total of 720 laboratory unconfined compression (UC) tests were conducted for strength variability (Table 3.5). Each set consisted of 30 specimens. Along with maximum compressive strength (σ_{max}), each specimen was evaluated for modulus by means of crosshead displacement ($E_{X\text{-}Head}$).

Table 3.5 Test Matrix for Pit Soil Strength Variability

Set	Material	Cement Type	Cement Index	Specimen Type	Tests	Cure Method
	PA	*TH T I/II*	Design	1	30	MSU
1	PA	*TH T I/II*	+1%	1	30	MSU
	PA	*TH T I/II*	-1%	1	30	MSU
	PB	*TH T I/II*	Design	1	30	MSU
2	PB	*TH T I/II*	+1%	1	30	MSU
	PB	*TH T I/II*	-1%	1	30	MSU
	PC	*TH T I/II*	Design	1	30	MSU
3	PC	*TH T I/II*	+1%	1	30	MSU
	PC	*TH T I/II*	-1%	1	30	MSU
	PA	*TH T I/II*	Design	2	30	MSU
4	PB	*TH T I/II*	Design	2	30	MSU
	PC	*TH T I/II*	Design	2	30	MSU
	PA	*TH T I/II*	Design	4	30	MSU
5	PB	*TH T I/II*	Design	4	30	MSU
	PC	*TH T I/II*	Design	4	30	MSU
	PA	*GV T I/II*	Design	4	30	MSU
6	PB	*GV T I/II*	Design	4	30	MSU
	PC	*GV T I/II*	Design	4	30	MSU
	PA	*TH T I/II*	Design	1	30	MDOT
7	PB	*TH T I/II*	Design	1	30	MDOT
	PC	*TH T I/II*	Design	1	30	MDOT
	PA	*TH T I/II*	Design	7	30	MSU
8	PB	*TH T I/II*	Design	7	30	MSU
	PC	*TH T I/II*	Design	7	30	MSU

**Raw data is provided in Appendix A in Tables A.8 to A.31.*

3.7.3 Elastic Modulus

A total of 54 laboratory compacted specimens were tested for elastic modulus (Table 3.6). Three specimens were tested at each cure time, totaling nine tests per material per specimen type. Specimens were evaluated for σ_{max}, modulus from crosshead displacement ($E_{X\text{-}Head}$), and elastic modulus from a compressometer (E_{Comp}).

Table 3.6 Test Matrix for Elastic Modulus

Material	Cement Type	Cement Index	Specimen Type	Cure Method	Tests (per Cure Time)	Cure Time (days)
PA	*TH T I/II*	Design	4	MSU	3	7, 28, 60
PB	*TH T I/II*	Design	4	MSU	3	7, 28, 60
PC	*TH T I/II*	Design	4	MSU	3	7, 28, 60
PA	*TH T I/II*	Design	7	MSU	3	7, 28, 60
PB	*TH T I/II*	Design	7	MSU	3	7, 28, 60
PC	*TH T I/II*	Design	7	MSU	3	7, 28, 60

**Raw data is provided in Appendix A in Tables A.32 to A.37.*

3.7.4 Wheel Tracking

A total of six *LAC* slabs and eight 150 by 62 mm SGC specimens were tested (Table 3.7). Each specimen was tested twice. The first test was dry and the second test was either submerged or soaked. Therefore, 12 PURWheel tests (one *LAC* slab produces two PURWheel specimens) and 8 APA style tests were conducted.

In addition to the testing described in the previous paragraph, HLWT testing was also to be performed. Initial testing of soil cement in the typical testing conditions proved too harsh for the soil cement material. Specimens failed after a small fraction of the passes were completed, and material debris covered the inside of the equipment. No useful data was collected and further testing could be exceedingly harmful to equipment. Therefore, no further HLWT testing was conducted.

Table 3.7 Wheel Tracking Test Matrix

Material	Specimen Type	Loading Conditions (%)	Test Conditions
PA	5	50/100	PURWheel Dry PURWheel Submerged
PB	5	50/100	PURWheel Dry PURWheel Submerged
PB	5	65/80	PURWheel Dry PURWheel Submerged
PB	5	50/100	PURWheel Dry PURWheel Soaked
PB	5	65/80	PURWheel Dry PURWheel Soaked
PC	5	50/100	PURWheel Dry PURWheel Submerged
PA	3	---	Dry-APA Submerged-APA
PA*	3	---	Dry-APA Submerged-APA
PB	3	---	Dry-APA Submerged-APA
PC	3	---	Dry-APA Submerged-APA

Note: Cement used for pit soils was TH I/II at design cement index for all Table 3.7 testing.*
All specimens were cured according to the WTP (Section 3.5.5.3).
**Test performed with +1 Design Cement Index.*
Raw data is provided in Appendix C.

CHAPTER 4

UNCONFINED COMPRESSION TEST RESULTS

4.1 Overview of Unconfined Compression Test Results

This chapter contains unconfined compression (UC) strength test results. The UC test was used to obtain the maximum compressive strength (σ_{max}) of specimens. These strength values are used in a strength gain with time and strength variability analysis. Strength variability study includes investigations of multiple factors influencing strengths and each is discussed within the section. Location of raw data is referenced within respective sections.

4.2 Strength Gain with Time

Figures 4.1 to 4.3 provide strength gain with time results organized by specimen type. Raw data is presented in Appendix A Tables A-1 to A-7. All data in Figures 4.1 to 4.3 used *TH T I/II* cement at design cement index, while cured with the MSU protocol.

All data sets in Figures 4.1 to 4.3 seem to demonstrate generally similar compressive strength behavior with increasing time. A logarithmic trendline and regression equations were fitted to each set of data. The trendlines shown are from the average compressive strength value per time curing time.

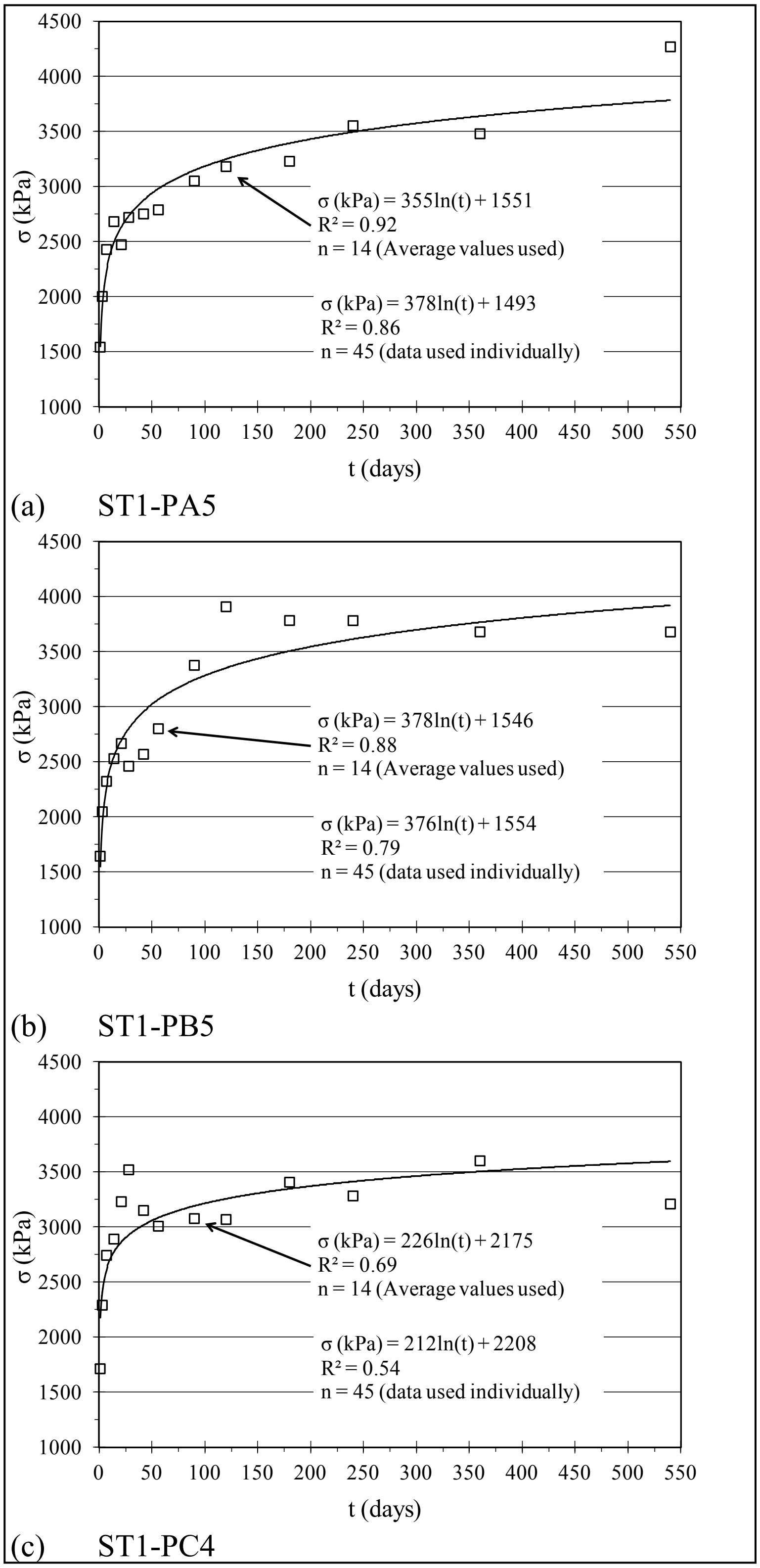


Figure 4.1 Strength Gain with Time – Specimen Type 1

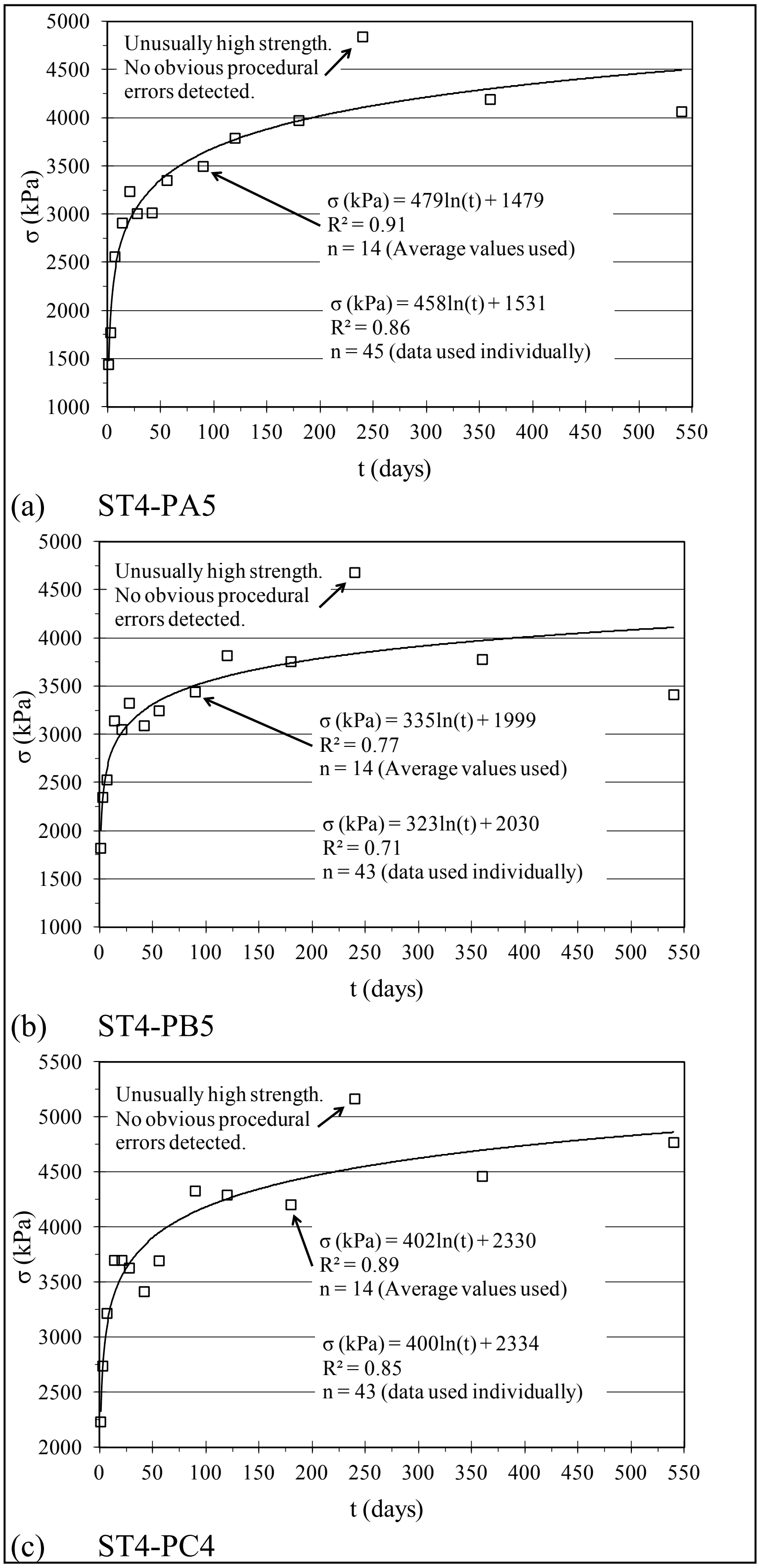


Figure 4.2 Strength Gain with Time – Specimen Type 4

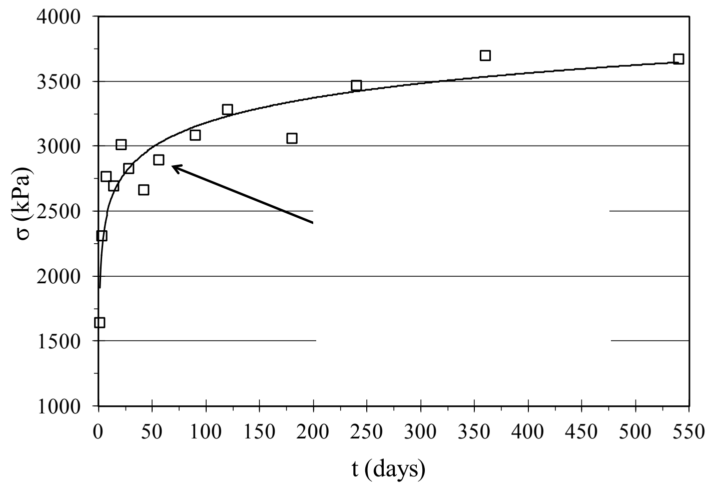


Figure 4.3 Strength Gain with Time – *Pit C* Specimen Type 2

Figures 4.1 to 4.3 also show the logarithmic equation when individual data points are considered. Most of the strength gain occurred within the first 56 days of curing. Using the trendlines shown, data sets achieved 75% to 85% of the highest compressive strength (540 days) at 56 days. After 56 days, the compressive strengths began to level off with increasing curing time. This was also seen in literature for soils stabilized with cement only (Felt and Abrams 1957, George 2006, Okyay and Dias 2010).

Specimens compacted with the PM-CF seemed to produce higher compressive strengths from the trendlines than those specimens compacted with either the proctor method or the SGC. Specimen type 4 has a higher *h/d* ratio, therefore should theoretically produce lower compressive strengths. These specimens actually exhibited a higher compressive strength behavior over time. Effect of compaction type is further investigated in Section 4.3.4.

4.3 Strength Variability

Issues investigated in the following sections include variability and normality; reliability design; and cement source, compaction method, and curing method effects on compressive strength. Outliers were removed before analysis was conducted. The number of outliers in a data set was denoted n_0; the number of data points used in analysis per data set was denoted *n*. Tukey's Method uses the distance between data and the Inter Quartile Range (*IQR*) to identify outliers. The distance between data's 25th (Q_1) and 75th (Q_3) percentiles is the *IQR*. Data falling outside the range of $Q_1 - 1.5IQR$ to $Q_3 + 1.5IQR$ were considered outliers and were not included in the analysis.

4.3.1 Variability and Normality

For all sets of strength variability specimens in this study, variability was evaluated using relative histograms and normality plots. A method developed by Filliben (1975) and presented by Ott and Longnecker (2010) was used to analyze the normality plots for each data set. In this method, the correlation coefficient (r) is used to estimate a *P-value*, which is then used to determine the certainty that the data is normally distributed. Table 4.1 summarizes variability and normality findings; histograms and normality plots are presented in Appendix B Figures B.1 to B.8.

In general, *Pit A* seemed to have the least variability with respect to compressive strength (σ_{max}) of the soils tested; averaging the eight Table 4.1 COV values resulted in a value of 5.6%. Pit B seemed to have the next highest variability; averaging the eight Table 4.1 COV values resulted in a value of 7.9%. *Pit C* generally seemed to have the most variability; averaging the eight Table 4.1 COV values resulted in a value of 9.3%. All sets of data seem to be at least somewhat normally distributed, except for SV4-PB5

(8). This set of data exhibits a poor level of certainty that the data is normally distributed. As part of Sullivan (2012), this set was remade. Results were similar in nature with respect to the normality fit.

Table 4.1 Compressive Strength Variability and Normality

Set	**Cement Source**	***n***	***n_0***	**Mean (kPa)**	**Stdev (kPa)**	**COV (%)**	***P-Value***	**Normality Fit**
SV1-PA4	*TH T I/II*	29	1	1605	67	4.2	0.41	Good
SV1-PA5	*TH T I/II*	30	0	2201	131	5.9	0.72	Excellent
SV1-PA6	*TH T I/II*	30	0	2508	112	4.5	0.71	Excellent
SVM1-PA5	*TH T I/II*	30	0	1982	132	6.7	0.80	Excellent
SV2-PA5	*TH T I/II*	27	3	2239	77	3.4	0.77	Excellent
SV7-PA5	*TH T I/II*	30	0	2077	244	11.7	0.09	Acceptable
SV4-PA5 (1)	*TH T I/II*	29	1	2430	128	5.3	0.41	Good
SV4-PA5 (2)	*GV T I/II*	29	1	2317	95	4.1	0.48	Good
SV1-PB4	*TH T I/II*	30	0	1795	117	6.5	0.08	Acceptable
SV1-PB5	*TH T I/II*	30	0	2293	158	6.9	0.11	Good
SV1-PB6	*TH T I/II*	30	0	2590	216	8.3	0.25	Good
SVM1-PB5	*TH T I/II*	30	0	1766	205	11.6	0.29	Good
SV2-PB5	*TH T I/II*	30	0	2720	168	6.2	0.31	Good
SV7-PB5	*TH T I/II*	28	2	2085	135	6.5	0.43	Good
SV4-PB5 (8)	*TH T I/II*	30	0	2461	243	9.9	0.04	Poor
SV4-PB5 (9)	*GV T I/II*	30	0	2831	200	7.1	0.25	Good
SV1-PC3	*TH T I/II*	30	0	1766	209	11.8	0.28	Good
SV1-PC4	*TH T I/II*	30	0	2165	218	10.1	0.49	Good
SV1-PC5	*TH T I/II*	30	0	2557	372	14.6	0.22	Good
SVM1-PC4	*TH T I/II*	30	0	1875	205	10.9	0.41	Good
SV2-PC4	*TH T I/II*	30	0	2705	143	5.3	0.23	Good
SV7-PC4	*TH T I/II*	29	1	2279	118	5.2	0.42	Good
SV4-PC4 (13)	*TH T I/II*	30	0	3181	179	5.6	0.41	Good
SV4-PC4 (14)	*GV T I/II*	30	0	2668	297	11.1	0.40	Good

Note: Data shown is after removal of all outliers. Numbers in parenthesis signify the Series number in Sullivan (2012) as this data was used in both documents. All data is 7 day compressive strengths.

The data was mostly normally distributed based on the chosen normality test. Therefore, statistical tests were performed assuming a normal distribution for all data sets. Statistics contained in Table 4.1 were used as a basis for all statistical data analysis. Adjustments for *h/d* ratios are noted in analysis.

4.3.2 Reliability Design - Compressive Strength Variability

To investigate potential advantages of a reliability based design, the number of replicates required to achieve some level of confidence (75, 85, or 95%) was found with a predetermined margin of error. Margins of error chosen originated from the relationship between compressive strength and cement index. From Table 4.1, the difference in mean compressive strength over a 1% change in cement index was approximately 300 to 600 kPa. Margins of error of 150, 225, and 300 kPa were chosen to equate to a ± ½% cement index change of the tested indices. The margin of error is evenly distributed on either side of the mean, so, for example, an error margin of 150 kPa equates to the lower end difference resulting from a 1% change in cement content of 300 kPa.

The confidence interval equation taken from Ott and Longnecker (2010) and shown in Equation 4.1 was used to find the number of replicates needed in order to obtain a desired level of confidence with a prescribed margin of error. The margin of error portion of the equation (Equation 4.2) was rearranged to find the number of replicates (Eq. 4.3). Also, Equation 4.2 was used to find the margin of error from existing MDOT practice in MT-25 (n = 1) for comparison with the reliability analysis. An example is provided of the procedure used.

$$\bar{x} \pm z_{\frac{\alpha}{2}} * \frac{Stdev}{\sqrt{n}} \qquad \text{(Eq. 4.1)}$$

$$ME = z_{\frac{\alpha}{2}} * \frac{Stdev}{\sqrt{n}} \qquad \text{(Eq. 4.2)}$$

$$n = \left(\frac{z_{\frac{\alpha}{2}} * Stdev}{ME}\right)^2 \quad \text{(Eq. 4.3)}$$

Where:

$\bar{x}$ = Mean of the sample set (kPa)

$z_{a/2}$ = Z-score for a specified confidence level

For 75% = 1.15

For 85% = 1.44

For 95% = 1.96

n = Number of replicates

Stdev = Standard deviation

ME = Margin of error (kPa)

For example, take the set of data from SV1-PB4; this data set had a mean of 1795 kPa, a standard deviation of 117, and a COV of 6.5%. Using Equation 4.2, the standard deviation (117 kPa), z-score from an 85% level of confidence (1.44), and one replicate (n = 1), the margin of error for the common practice of testing one replicate was 168 kPa.

To find the number of replicates needed for a 150 kPa margin of error at 75, 85, and 95% confidence levels, Equation 4.3 was used. This equation yielded 0.80, 1.26, and 2.34, respectively, for a 150 kPa margin of error. The values were rounded to the nearest 0.25. The procedure was again conducted for margins of error of 225 and 300 kPa.

Table 4.2 contains the results from the reliability analysis. The procedure summarized in the previous paragraph was conducted for each data set and each margin of error. Each row represents a single data set. Analysis included determination of replicates based on reliability and margin of error as well as the present design procedure

Table 4.2 Reliability Analysis of Data Sets

Set	Mean (kPa)	COV (%)	ME^1 when n=1 (kPa)	n with 150 kPa ME			n with 225 kPa ME			n with 300 kPa ME		
				75%	85%	95%	75%	85%	95%	75%	85%	95%
SV1-PA4	1605	4.2	96	0.25	0.50	0.75	<0.25	0.25	0.25	<0.25	<0.25	0.25
SV1-PA5	2201	5.9	189	1.00	1.50	3.00	0.50	0.75	1.25	0.25	0.50	0.75
SV1-PA6	2508	4.5	161	0.75	1.25	2.25	0.25	0.50	1.00	0.25	0.25	0.50
SVM1-PA5	1982	6.7	190	1.00	1.50	3.00	0.50	0.75	1.25	0.25	0.50	0.75
SV2-PA5	2239	3.4	111	0.25	0.50	1.00	0.25	0.25	0.50	0.00	0.25	0.25
SV7-PA5	2077	11.7	351	3.50	5.50	10.25	1.50	2.50	4.50	0.75	1.25	2.50
SV4-PA5 (1)	2430	5.3	184	1.00	1.50	2.75	0.50	0.75	1.25	0.25	0.50	0.75
SV4-PA5 (2)	2317	4.1	137	0.50	0.75	1.50	0.25	0.25	0.75	0.25	0.25	0.50
SV1-PB4	1795	6.5	168	0.75	1.25	2.25	0.25	0.50	1.00	0.25	0.25	0.50
SV1-PB5	2293	6.9	228	1.50	2.25	4.25	0.75	1.00	2.00	0.25	0.50	1.00
SV1-PB6	2590	8.3	311	2.75	4.25	8.00	1.25	2.00	3.50	0.75	1.00	2.00
SVM1-PB5	1766	11.6	295	2.50	3.75	7.25	1.00	1.75	3.25	0.50	1.00	1.75
SV2-PB5	2720	6.2	242	1.75	2.50	4.75	0.75	1.25	2.25	0.50	0.75	1.25
SV7-PB5	2085	6.5	194	1.00	1.75	3.00	0.50	0.75	1.50	0.25	0.50	0.75
SV4-PB5 (8)	2461	9.9	350	3.50	5.50	10.00	1.50	2.50	4.50	0.75	1.25	2.50
SV4-PB5 (9)	2831	7.1	288	2.25	3.75	6.75	1.00	1.75	3.00	0.50	1.00	1.75
SV1-PC3	1766	11.8	301	2.50	4.00	7.50	1.25	1.75	3.25	0.75	1.00	1.75
SV1-PC4	2165	10.1	314	2.75	4.50	8.00	1.25	2.00	3.50	0.75	1.00	2.00
SV1-PC5	2557	14.6	536	8.25	12.75	23.75	3.50	5.75	10.50	2.00	3.25	6.00
SVM1-PC4	1875	10.9	295	2.50	3.75	7.25	1.00	1.75	3.25	0.50	1.00	1.75
SV2-PC4	2705	5.3	206	1.25	2.00	3.50	0.50	0.75	1.50	0.25	0.50	0.75
SV7-PC4	2279	5.2	170	0.75	1.25	2.50	0.25	0.50	1.00	0.25	0.25	0.50
SV4-PC4 (13)	3181	5.6	258	2.00	3.00	5.50	0.75	1.25	2.50	0.50	0.75	1.25
SV4-PC4 (14)	2668	11.1	428	5.25	8.25	15.00	2.25	3.50	6.75	1.25	2.00	3.75
			Average	1.75	3.00	5.50	0.75	1.25	2.50	0.50	0.75	1.25

75, 85, and 95% refer to level of confidence. n values rounded to nearest 0.25. Avg. taken without highest and lowest value of original data; then rounded.
[1]*Margin of error with 85% reliability.*

margin of error. An average number of replicates for each reliability level and margin of error is also shown.

General obvious trends hold true in the reliability analysis table. These trends are that 1) more replicates are needed to achieve a higher level of confidence regardless of the margin of error and 2) a larger margin of error requires less replication of tests. The current design practice of testing one replicate gave an average margin of error for all sets of approximately 250 kPa at 85% reliability. Based on the averages of replicates of all data sets (bottom row of Table 4.2), if the number of replicates was increased to two, then the reliability of design would be as follows: 75% reliability that the mean is contained within a margin of error of 150 kPa; 85% reliability that the mean is contained within a margin of error of 225 kPa; and 95% reliability that the mean is contained within a margin of error of 300 kPa. If the number of replicates was increased, the reliability within each specified margin of error would increase accordingly.

4.3.3 Cement Source Effect on Compressive Strength

To determine if the cement source (e.g. *TH* or *GV*) affected the mean compressive strength (σ_{max}), *t-tests* were performed at a level of significance (α) of 0.05. Tests were performed assuming unequal variances with a two-tailed approach. The null hypothesis (H_0) was set as $\mu_1 = \mu_2$, and the alternative hypothesis (H_a) was $\mu_1 \neq \mu_2$. Compared specimen sets were of the same type (i.e. equal *h/d* ratios); therefore, no adjustments were conducted. Table 4.3 provides the results.

Table 4.3 Effects of Cement Source on Compressive Strength

Term 1	**μ_1 (kPa)**	**Term 2**	**μ_2 (kPa)**	***df***	**t_{crit}**	**t_{stat}**	**H_0 Conclusion**
SV4-PA5 (1)	2430	SV4-PA5 (2)	2317	52	2.01	3.83	Reject
SV4-PB5 (8)	2461	SV4-PB5 (9)	2831	56	2.00	-6.43	Reject
SV4-PC4 (13)	3181	SV4-PC4 (14)	2668	48	2.01	8.11	Reject

Note: Number in parenthesis are series numbers from Sullivan (2012).

The *t-tests* for all soils show that the cement source had a significant effect on the mean compressive strength. *Pit A* and *Pit C* materials treated with *TH* cement produced a higher mean compressive strength than did *Pit A* and *Pit C* treated with *GV T I/II*. However, *Pit B* material treated with *GV T I/II* cement yielded a mean compressive strength higher than *Pit B* treated with *TH T I/II* cement. This indicates that the cement source had a significant effect on the mean compressive strength of the class 9C soils investigated. It is noteworthy the results differed in directionality between different pit soils.

4.3.4 Compaction Method Effect on Compressive Strength

Statistical *t-tests* were utilized to investigate how the compaction method affected the mean compressive strength of similar specimens. Specimens were made with *TH T I/II* cement. Specimens were made with design cement contents compacted to maximum dry density and optimum moisture content. Tests were conducted at a level of significance of 0.05, assuming unequal variances with a two-tailed approach. The null hypothesis (H_0) was $\mu_1 = \mu_2$, and the alternative hypothesis (H_a) was $\mu_1 \neq \mu_2$. Compared specimen sets were not of the same type (i.e. equal *h/d* ratios); therefore, adjustments were conducted to compare all strengths at a *h/d* ratio of 2:1. Tables 4.4 to 4.6 show *t-test* results.

Table 4.4 Effect of Compaction Method on Compressive Strength: *Pit A*

Term 1	μ_1 (kPa)	Term 2	μ_2 (kPa)	*df*	t_{crit}	t_{stat}	H_0 Conclusion
SV1-PA5	2001*	SV2-PA5	2036*	48	2.01	-1.37	Accept
SV1-PA5	2001*	SV4-PA5 (1)	2430	56	2.00	-13.36	Reject
SV1-PA5	2001*	SV7-PA5	2077	42	2.02	-1.54	Accept
SV2-PA5	2036*	SV4-PA5 (1)	2430	44	2.02	-14.46	Reject
SV2-PA5	2036*	SV7-PA5	2077	34	2.03	-0.89	Accept
SV4-PA5 (1)	2430	SV7-PA5	2077	44	2.02	7.01	Reject

** Adjusted compressive strengths to 2:1 h/d ratio. See example in Section 3.6.1.*
Note: Number in parenthesis are Series numbers from Sullivan (2012).

Table 4.5 Effect of Compaction Method on Compressive Strength: *Pit B*

Term 1	μ_1 (kPa)	Term 2	μ_2 (kPa)	*df*	t_{crit}	t_{stat}	H_0 Conclusion
SV1-PB5	2085*	SV2-PB5	2472*	58	2.00	-10.11	Reject
SV1-PB5	2085*	SV4-PB5 (8)	2461	47	2.01	-7.30	Reject
SV1-PB5	2085*	SV7-PB5	2085	56	2.00	0.00	Accept
SV2-PB5	2472*	SV4-PB5 (8)	2461	49	2.01	0.21	Accept
SV2-PB5	2472*	SV7-PB5	2085	56	2.00	10.25	Reject
SV4-PB5 (8)	2461	SV7-PB5	2085	46	2.01	7.36	Reject

** Adjusted compressive strengths to 2:1 h/d ratio. See example in Section 3.6.1.*
Note: Number in parenthesis are Series numbers from Sullivan (2012).

Table 4.6 Effect of Compaction Method on Compressive Strength: *Pit C*

Term 1	μ_1 (kPa)	Term 2	μ_2 (kPa)	*df*	t_{crit}	t_{stat}	H_0 Conclusion
SV1-PC4	1969*	SV2-PC4	2459*	50	2.01	-11.32	Reject
SV1-PC4	1969*	SV4-PC4 (13)	3181	57	2.00	-24.85	Reject
SV1-PC4	1969*	SV7-PC4	2279	48	2.01	-7.32	Reject
SV2-PC4	2459*	SV4-PC4 (13)	3181	53	2.01	-17.85	Reject
SV2-PC4	2459*	SV7-PC4	2279	57	2.00	5.57	Reject
SV4-PC4 (13)	3181	SV7-PC4	2279	50	2.01	22.92	Reject

** Adjusted compressive strengths to 2:1 h/d ratio. See example in Section 3.6.1.*
Note: Number in parenthesis are Series numbers from Sullivan (2012).

The *t-tests* showed different results for each pit soil while a few trends were consistent with all materials. The difference in compressive strength means for type 1 and 2 specimens was significant for *Pit B* and *Pit C* while not significant for *Pit A*. For type 1 and type 4 specimens, the difference in compressive strength means was significant for all pit soils. The difference in compressive strength means for type 1 and type 7 specimens was not significant for *Pit A* and *Pit B* but was significant for *Pit C*. Although *Pit C* showed a significant difference in mean compressive strengths, there seems to be a possible significant trend that specimen type 1 adjusted compressive strength mean is comparable to specimen type 7 compressive strength mean.

The difference in compressive strength means for type 2 and type 4 specimens was not significant for *Pit B* and significant for *Pit A* and *Pit C*. For type 2 and type 7 specimens, the difference in compressive strength means significant for *Pit B* and *Pit C* while not significant for *Pit A*. For type 4 and type 7 specimens, the difference in compressive strength means was significant for all pit soils.

4.3.5 Curing Method Effect on Compressive Strength

Statistical *t-tests* were utilized to investigate how the curing method affected the mean compressive strength of similar specimens. Tests were conducted at a level of significance of 0.05, assuming unequal variances with a two-tailed approach. The null hypothesis (H_0) was $\mu_1 = \mu_2$, and the alternative hypothesis (H_a) was $\mu_1 \neq \mu_2$. Compared specimen sets were of the same type (i.e. equal *h/d* ratios); therefore, no adjustments were conducted. Table 4.7 shows *t-test* results.

Table 4.7 Effects of Curing Method on Compressive Strength

Term 1	**μ_1 (kPa)**	**Term 2**	**μ_2 (kPa)**	***df***	**t_{crit}**	**t_{stat}**	**H_0 Conclusion**
SV1-PA5	2201	SVM1-PA5	1982	58	2.00	6.46	Reject
SV1-PB5	2293	SVM1-PB5	1766	55	2.00	11.15	Reject
SV1-PC4	2165	SVM1-PC4	1875	58	2.00	5.31	Reject

The *t-tests* for all soils show that the method of curing had a significant effect on the mean compressive strength. The MSU curing method yielded a higher mean compressive strength than the MDOT curing method. For *Pit A*, the MSU curing method produced a mean compressive strength of 219 kPa (11%) higher than the MDOT curing method. For *Pit B*, the MSU curing method produced a mean compressive strength of 527 kPa (30%) higher than the MDOT curing method. For *Pit C*, the MSU curing method produced a mean compressive strength of 290 kPa (15%) higher than the MDOT curing method. The curing method had a different relative effect on mean compressive strength between materials.

The MDOT design requirement for soil cement pavement layers (MT-25) specifies the minimum cement content that will produce a compressive strength of 2070 kPa in 14 days. Designs based on MT-25 for the three pit soils were used in this study and specified the design cement index for each pit soil. Specimens made in accordance with MDOT making and curing protocols (testing category SVM) were replicated; Term 2 in Table 4.6 shows the mean value of the compressive strengths for each pit soil. It was noted that the mean value for all three pit soils at design cement index fell below the required compressive strength for design. Since similar making and curing protocols were used, there seems to be no immediate explanation for the discrepancy. However, the results confirm that curing method has a significant effect on the mean compressive strength.

CHAPTER 5

ELASTIC MODULUS AND WHEEL TRACKING TEST RESULTS

5.1 Overview of Elastic Modulus and Wheel Tracking Results

This chapter contains elastic modulus and wheel tracking results. Elastic modulus results are mostly those obtained from the Comp/Ext during UC testing (E_{Comp}). Wheel tracking results include those from the APA and the PURWheel. Location of raw data is referenced within respective sections.

5.2 Elastic Modulus Results

Tables 5.1 to 5.3 provide elastic modulus results organized by pit soil. Raw data is presented in Appendix A Tables A.32 to A.37. All data in Tables 5.1 to 5.3 used *TH T I/II* cement at design cement index, while cured with the MSU protocol (Section 3.5.5.1). The modulus value reported is the value using strain measured with the compressometer (E_{Comp}). When using the assumed crosshead displacement based on load rate, the modulus found was approximately an order of magnitude lower than when using the compressometer. Issues identified were different gauge length and motor/load ring compliance. These values, in MPa, ($E_{X\text{-}Head}$) are reported in Appendix A Tables A.1 to A.37 only for reference. The measured elastic modulus from the Comp/Ext. is denoted E_{Comp} in gigapascals, or GPa. Average values reported are of three test replicates.

Table 5.1 Elastic Modulus Values for *Pit A*

Set ID	**Time (days)**	**Avg. σ_{max} (kPa)**	**Avg. E_{Comp} (GPa)**
EM4-PA5	7	2484	4.6
	28	3111	6.2
	90	3576	6.4
EM7-PA5	7	2312	5.2
	28	2939	6.6
	90	3098	6.5

Table 5.2 Elastic Modulus Values for *Pit B*

Set ID	**Time (days)**	**Avg. σ_{max} (kPa)**	**Avg. E_{Comp} (GPa)**
EM4-PB5	7	2555	4.4
	28	3080	5.4
	90	3794	5.5
EM7-PB5	7	2237	3.3
	28	2768	4.5
	90	3005	4.5

Table 5.3 Elastic Modulus Values for *Pit C*

Set ID	**Time (days)**	**Avg. σ_{max} (kPa)**	**Avg. E_{Comp} (GPa)**
EM4-PC4	7	2671	6.6
	28	3501	9.0
	90	3991	10.8
EM7-PC4	7	2640	5.3
	28	2952	7.0
	90	3407	8.4

The range of values for average elastic modulus was 3.3 GPa (EM7-PB5 7 day) to 10.8 GPa (EM4-PC4 90 day). Results from the elastic modulus testing using the compressometer show that modulus seems to increase with an increase in cure time. This was well documented in the literature with cement stabilized materials (Felt and Abrams 1957 and James et al. 2009) and lime stabilized soils (Thompson 1966). Elastic modulus values for *Pit A* seemed to plateau (type 4) or slightly decrease (type 7) after 28 days. *Pit B* elastic modulus values also seemed to plateau. *Pit C* showed a different behavioral trend than *Pit A* and *Pit B*. For both specimen types (type 4 and type 7), the elastic modulus was still increasing between 28 and 90 day cures. However, the increase in elastic modulus between 28 and 90 day cures for *Pit C* was not as dramatic as increases between 7 and 28 days.

Figure 5.1 plots maximum unconfined compression strength, σ_{max}, (kPa) by measured elastic modulus, E_{Comp}, (GPa). A linear regression line was fitted to the data (LF) with the intercept forced to zero and is shown on the plot. Also, lines encompassing most of the data are provided with the linear fit; these lines are referred to as the upper boundary (UB) and the lower boundary (LB). 98% of the data was contained within the upper and lower boundary lines; one data point was above the upper boundary line.

Relationships for the LF, LB, and UB lines in Figure 5.1 are given in general form in Equation 5.1. This equation resembles Equation 2.4, though in Equation 2.4 a compressive strength was multiplied by a constant to calculate an elastic modulus value, given both are in the same units. Input for Equation 5.1 was compressive strengths in kPa. Output for Equation 5.1 was elastic modulus in GPa. In order to convert between customary units, the constant (C_i) for each line equation was multiplied by 10^{-6}, as shown in Equation 5.1.

$$E_{Comp}\ (\text{GPa}) = C_i * 10^{-6} * \sigma_{max}\ (\text{kPa}) \qquad \text{(Eq. 5.1)}$$

Where:

E_{Comp} = Elastic modulus (GPa)

σ_{max} = Maximum compressive strength (kPa)

C_i = Equation constant for *i* line

C_U = 2900, Constant for Upper Boundary Line

C_F = 2000, Constant for Linear Fit Line

C_L = 1300, Constant for Lower Boundary Line

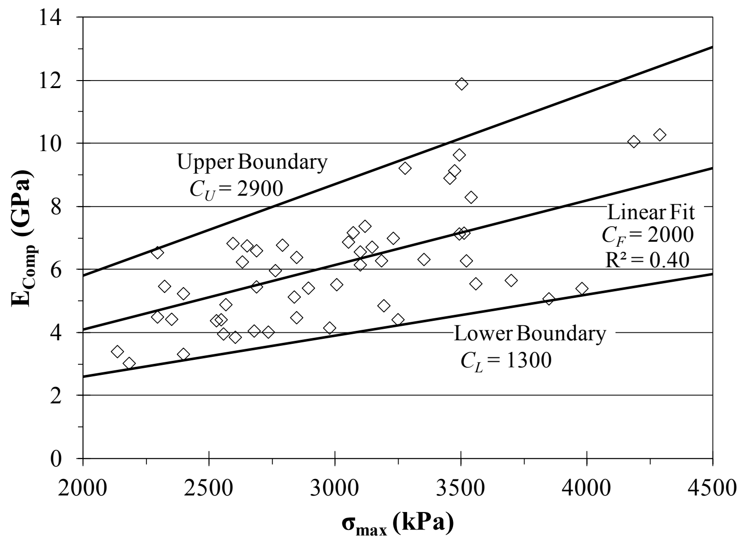


Figure 5.1 Elastic Modulus versus Compressive Strength

Table 5.4 shows the measured elastic modulus distribution based on soil type and specimen type. There were no data points that fell below the lower boundary. *Pit A* seemed to be more evenly distributed between the upper and lower boundaries with 61% between the lower boundary (LB) and linear fit (LF), and 39% between the LF and the upper boundary (UB). *Pit B* was mostly between the lower boundary and the linear fit lines (89%), with the other 11% between the linear fit and upper boundary lines. On the contrary, *Pit C* had more between the linear fit and upper boundary lines (83%), with 11% between the lower boundary and linear fit lines. Specimen type seemed to be more evenly distributed between the lower and upper boundary lines. The distribution showed different pit soils had slightly different trends when comparing unconfined compression strength and elastic modulus. C_i values for Pit A (C_A), Pit B (C_B), and Pit C (C_C) when considering only one pit soil at a time were 2000, 1600, and 2500, respectively.

Table 5.4 Distribution of Elastic Modulus Given Parameters

		Percentage in Region (%)			
Parameter	***n***	**< LB**	**LB-LF**	**LF-UB**	**> UB**
Pit A	18	0	61	39	0
Pit B	18	0	89	11	0
Pit C	18	0	11	83	6
Type 4	27	0	52	44	4
Type 7	27	0	56	44	0

Type 4 and Type 7 refer to the specimen type as per Equation 3.1.

Correlations found in literature were investigated with the data obtained from elastic modulus testing. Figure 5.2 shows the relationship between these correlations and the data collected. Equations 2.2 to 2.4 were used to calculate elastic modulus with σ_{max} and/or gradation modulus; then units were converted for plotting consistency. Equation 2.2 from Thompson (1966) was derived to find elastic modulus given unconfined compression strength of lime stabilized materials. The calculated elastic modulus from the compressive strength test data using Equation 2.2 severely under predicted elastic modulus values measured herein. This was explained because the equation was developed for a separate stabilized material. Equation 2.4 referenced in James et al. (2009) finds elastic modulus of cement stabilized base layers from the unconfined compressive strength for the MEPDG. The MEPDG uses this equation as a level 2 input. The calculated elastic modulus from the compressive strength test data using Equation

2.4 predicts values that somewhat align with the lower boundary of the tested specimens; i.e. the equation predicted a conservative elastic modulus value.

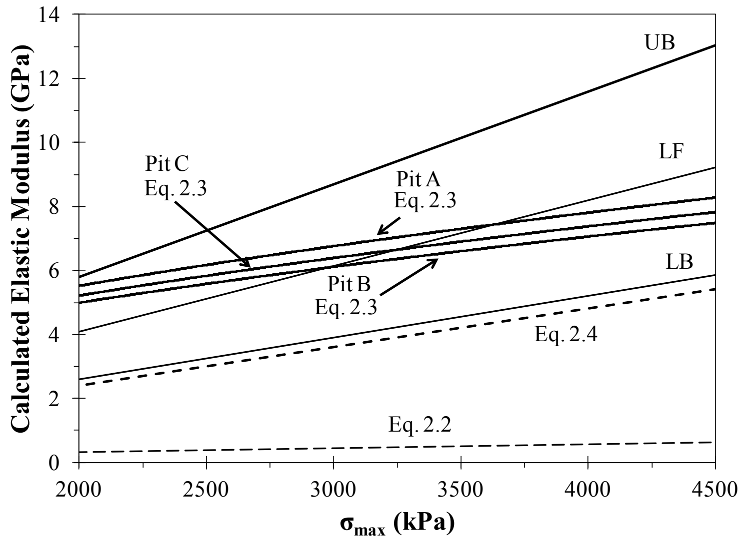


Figure 5.2 Elastic Modulus Correlations from Literature (Dashed Lines) with Present Study (Solid Lines)

Equation 2.3 from Kolias and Williams (1984) used the compressive strength and a gradation modulus to find the elastic modulus. A gradation modulus was determined for *Pit A*, *Pit B* and *Pit C*; the gradation modulus values were 8.92, 9.21, and 9.09, respectively. The calculated elastic modulus from the compressive strength and the respective gradation modulus using Equation 2.3 seems to predict relatively accurate elastic modulus values compared to the best linear fit of the test data. Although the equation seems to slightly over predict modulus values for the design strength region (i.e. strengths between 2000 and 2500 kPa), the equation better predicts elastic modulus values when strengths reach those seen during the performance of the pavement layer (i.e. greater than around 2500 kPa that occur at later ages). Equation 2.3 from Kolias and

Williams (1984) seems to better predict the actual elastic modulus of the materials while Equation 2.4 yields a conservative elastic modulus value typically used for design.

5.3 Wheel Tracking Results

Wheel tracking was performed on soil cement specimens to investigate material performance under loaded traffic. Tests include tracking with the Asphalt Pavement Analyzer (APA) and with the PURWheel. Results and discussion related to each method are provided in the following sections. PURWheel raw data is presented in Appendix C.

5.3.1 APA Results

APA data obtained from each test was fitted with a logarithmic trend line (Figure 5.3). The trend lines are labeled with the soil, cement index, trend line equation, and the R^2 value for each test. Figure 5.3 (top) shows results from the dry tests; Figure 5.3b (bottom) shows results from the submerged tests. Each plot shows rutting for that test only; the total rut measurement after both tests would be the sum of the two final rut depths (d_{fr}) in mm. For example, *Pit B* specimens rutted 1.5 mm during the dry test and 8.2 mm during the submerged test; therefore, Pit B had a total rut depth of approximately 9.7 mm after 16,000 cycles.

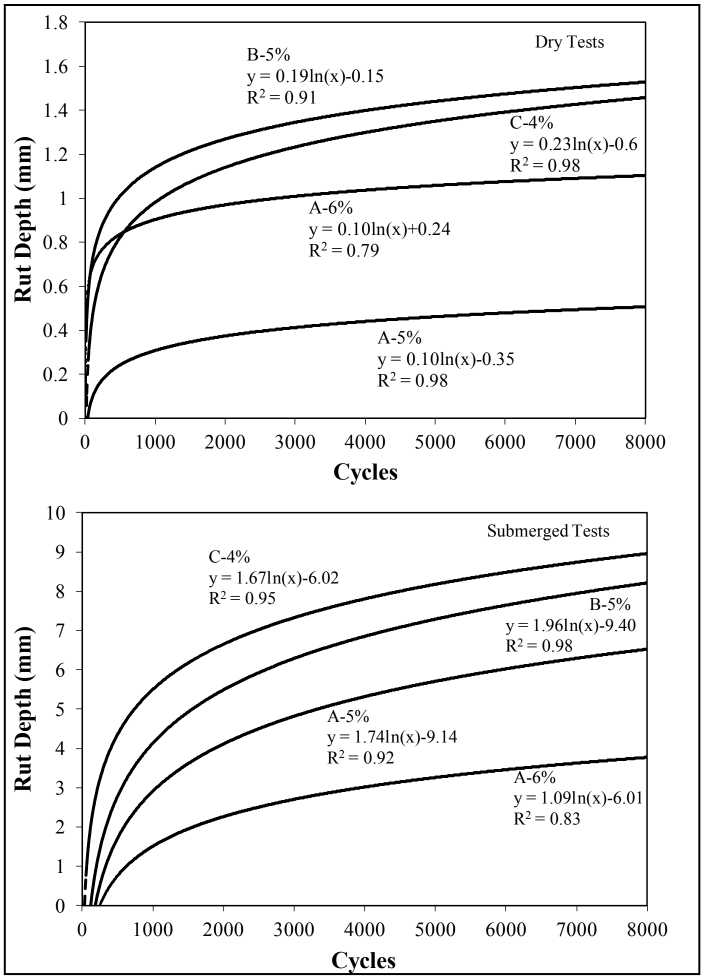


Figure 5.3 APA Results – Dry and Submerged Tests

Data shows that for all the dry tests, there is minimal rutting (e.g. a maximum of 1.5 mm rut). *Pit B* exhibited the most rutting in the dry test, followed closely by *Pit C*. Both cement indexes tested with *Pit A* provided less rutting than *Pit B* or *Pit C*. Interestingly, *Pit A* specimens with a cement index of 6% rutted approximately 0.6 mm more than specimens with 5% cement index. Again, the difference in final rut depths of all materials in the dry tests was within one millimeter and less than 1.5 mm; this shows that for the dry condition, these materials are not susceptible to rutting at the given loading.

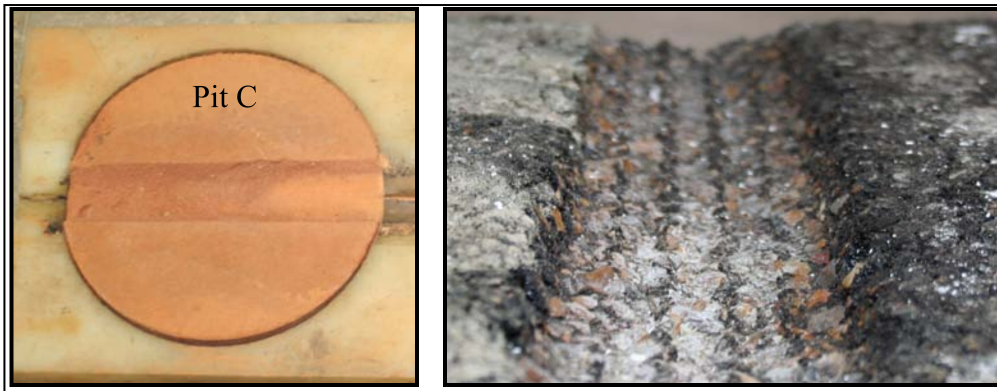
Higher APA rutting was observed in the data from the submerged tests. Table 5.5 shows final rut depths (d_{fr}) of the four tested materials, along with a rutting rate (mm/1000 cycles) from 0 to 2000 cycles and 2000 to 8000 cycles. Trendlines are used to obtain values at 2000 and 8000 cycles; it was assumed that there was no rutting at zero cycles. These values are then used to calculate the slope between 0 and 2000 cycles and 2000 and 8000 cycles by subtracting the calculated rut values and dividing by the number of thousand cycles. This procedure yields mm per 1000 cycles. Intervals were chosen based on observed changes in behavior (e.g. noticeable change in slope).

Table 5.5 APA Submerged Test Results

Soil	C_I (%)	d_{fr} (mm)	Rutting Rate (mm/1000 cycles)	
			0-2000	2000-8000
A	5	6.5	2.0	0.8
A	6	3.8	1.1	0.5
B	5	8.2	2.7	0.9
C	4	9.0	3.3	1.0

The different behaviors under wheel load testing are evident even with a small test matrix. *Pit A*, with both the 5 and 6% cement indexes, exhibited the least rut deformation, and followed by *Pit B* and then *Pit C*. *Pit C* had the highest final rut depth of 9 mm. This indicates that rutting behavior in a wet condition is dependent on the material, even when the cement content meets the design requirement. Also, *Pit A* at 6% C_I has less final rut depth and lower rutting rates than *Pit A* at 5% C_I. Most rutting occurred within the first 2000 cycles. The rutting rate noticeably decreased in the last three quarters of the test.

Figure 5.4a shows a post-testing specimen photograph. The rutting in soil cement specimens seems to be an abrasive carving or displacement of the material rather than pushing displacement of a material within a specimen (e.g. rutting of asphalt in PURWheel due to shear, Figure 5.4b). The environment in which the materials are subject to during testing had a considerable effect on the rutting behavior.



(a) Tested APA Specimen (b) Asphalt Rutting Behavior

Figure 5.4 Soil Cement (APA) and Asphalt Rutting Behavior

5.3.2 PURWheel Results

PURWheel data obtained from twelve tests are examined in this section. Final rut depths, and/or passes to failure are used in this analysis. Data used is found in Appendix C. The maximum rut depth measured for a dry test was 2.0 mm at 20,000 passes. This was during a 100% loading on *Pit A* and *Pit B*. In all dry tests, minimal rutting was observed. Dry conditions seem to be somewhat resistant to permanent rut deformation and are not further discussed. The remainder of this section covers permanent rut deformation from the soaked and submerged condition tests (Table 5.6).

Table 5.6 PURWheel Soaked/Submerged Results

Pit Soil	C_I (%)	Test Conditions	Loading (%)	Final Rut Depth (mm)	Passes to Failure
A	5	Submerged	50	0.1	
			100	---	8,774
B	5	Submerged	50	2.6	
			65	11.2	
			80	---	16,938
			100	---	6,356
C	4	Submerged	50	0.3	
			100	3.4	
B	5	Soaked	50	0.4	
			65	0.3	
			80	0.0	
			100	-1.5*	

(---) signifies failure (actual rut depth ≥23 mm) according to Howard et al. (2010).
Final rut depths taken after 20,000 passes (full test) unless failure occurred.
** Data collection error, but minimal rutting observed (<2mm).*

Results show that for all 50% loadings, submerged and soaked, there was essentially no permanent rutting deformation. *Pit B* had the highest rutting measurement with a 50% loading of 2.6 mm. *Pit A* and *Pit B* specimens, when submerged and subject to the 100% loading, failed between 6000 and 9000 passes. This was less than half the length of a full test. *Pit C* showed 3.4 mm of permanent rut deformation under submerged conditions with a 100% applied load. However, as seen in Appendix C Figure C.6b, *Pit C* may have been beginning to fail towards the end of the test. It started to demonstrate similar behaviors to *Pit A* and *Pit B* just before failure.

Pit B submerged testing with the 65% and 80% loadings further demonstrated the progression of damage to the material. The 65% submerged loading showed a higher final rut depth than the 50% loading while the 80% submerged loading failed with a higher number passes to failure than the 100% loading. The progression of damage with the increase in load suggests that with given environmental conditions, there was a loading threshold up to which materials could perform satisfactorily.

Results from the *Pit B* soaked tests with 50, 65, 80 and 100% loadings showed essentially no rutting for the scope of this study. To experience considerable damage, specimens had to be submerged in water during testing. Soaked testing did not result in meaningful amounts of damage.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis was part of a larger study (State Study 206) and focused on factors that influence the design and performance of soil cement base layers in Mississippi. Factors included in the study were strength gain with time, strength variability, elastic modulus, and wheel tracking. Also, a practice review was conducted to obtain information pertaining to the chemical stabilization practices within state DOT's across the U.S. To this end, conclusions pertinent to the research are summarized by category.

6.1.1 Practice Review

- The practice review (survey) showed there to be no universal or standard criteria for stabilized soil design within the state DOT's who responded. Widespread use of compression strength for design was noted; however, no standard strength requirement was used.

6.1.2 Strength Gain with Time

- Strength gain with time behavior was similar for all pit soils and all compaction methods. Most of the strength gain was seen in the first 60 days of curing (75 to 85% of 540 day strengths). Although designed with at least 2070 kPa strengths at 7 or 14 days, pit soils exhibited continued strength gain and achieved 3550 to 3950 kPa (Specimen type 1) after 540 days of curing based on regression equations.

6.1.3 Strength Variability

- Replication of tested specimens during the design of soil cement pavement layers increases the reliability of the design within a certain acceptable margin of error. Results showed that using two replicates instead of one would increase the reliability of design and lower the margin of error with minimal additional effort to existing practices.

- Cement source and curing method had a significant effect on the compressive strength of soil cement mixtures. Compaction method had a significant effect on compressive strength for all soils when comparing specimen type 1 and 4 and specimen type 4 and 7. Significance of compaction method was dependent on soil type for all other comparisons.

6.1.4 Elastic Modulus

- A conservative value for elastic modulus was found by using the maximum compressive strength and Equation 2.4. Equation 2.3 gave elastic modulus comparable to the actual measured elastic modulus values found in this study, especially during the performance period of a soil cement pavement layer. Measured elastic modulus values seem to be at least somewhat dependent on soil type.

- Elastic modulus values measured using the compressometer/extensometer were reasonable relative to those found in literature for similar materials and cement contents.

6.1.5 Wheel Tracking

- Wheel tracking of soil cement provided somewhat useful yet somewhat limited insight into evaluating performance of soil cement pavement layers. Rutting does not seem to be an issue with soil cement layers in Mississippi, even in unrealistically harsh conditions. Testing showed failure took place only when at least 80% of highway surface loading was directly applied and the specimen was submerged in hot water during testing.

6.2 Recommendations

Based on the work contained in this thesis, recommendations related to the design and performance of soil cement pavement layers are as follows.

- Multiple agencies should consider establishing a standard preparation and testing protocol for soil cement design although curing and compressive strength criteria could continue to be dictated by location, material availability, and utilization.

- Agencies should consider the following two cases for design:
  - Case A: If the agency expects a 7 day design to govern, then make and test the number of replicates indicated in Table 4.2 (n_{reps}) at 4 and 6% cement index at 7 days and test n_{reps} only at 4% cement index at 14 days. If the agency expects a 14 day design to govern then make and test n_{reps} at only 4% cement index at 7 days and test n_{reps} at 4 and 6% cement index at 14 days. An extrapolation between the 4% and 6% strengths could be used to find the design cement index assuming the compressive strength to cement index relationship is linear. The number of specimens required would be dictated by n_{reps}.
  - Case B: If the agency expects a 7 day design to govern, then make and test two replicates at 4, 5, and 6% cement index at 7 days and test two replicates at 5% cement index at 14 days. If the agency expects a 14 day design to govern, then make and test two replicates at 5% cement index at 7 days and test two replicates at 4, 5, and 6% cement index at 14 days. Extrapolation, as stated in Case A, could be used to find the design cement index. This procedure would always require 8 specimens.

- Agencies should consider preparing and testing replicates at selected cement contents to obtain the strength to cement content relationship. After plotting a curve, the design cement content could be selected from the curve. Note this approach could slightly lower design cement contents.

- Agencies should consider investigating the linearity relationship between average compressive strength and cement content. The author recommends expanding the testing scope herein to ±2% cement index of design as only ±1% was tested in this thesis.

- It is recommended that field and laboratory (design) specimens be compacted using the same procedure and practice. Also, the cement used in design should ideally be from the same source used for the construction project.

- Equation 2.4 appears to be a conservative estimate for the elastic modulus of soil cement in Mississippi. A more precise estimate of the elastic modulus seen during the performance of the pavement layer appears to be available using Equation 2.3. The author recommends additional investigations to explore the strength and elastic modulus versus density behavior of soil cement mixtures. This could provide valuable information on how density affects the design and performance of soil cement pavement layers.

- It is recommended that further study not focus on wheel tracking of soil cement pavement layers. The research found that soil cement layers are only substantially influenced by combined loading and environmental effects not commonly seen in soil cement layers (submerged and fully loaded direct contact). The information presented in this thesis appears to be sufficient for Class 9C Mississippi soils from the perspective of wheel tracking.

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APPENDIX A

UNCONFINED COMPRESSION RAW DATA

Table A.1 Strength Gain with Time: ST1-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	1	116.53	101.46	1991.57	11.8	2.114	1563	2.7	72.0	12
02	1	116.69	101.34	1986.73	11.8	2.111	1598	2.7	73.6	12
03	1	116.59	101.46	1994.10	11.9	2.115	1462	2.6	76.6	10
04	3	116.68	101.44	1995.59	11.9	2.116	2065	2.7	94.8	11
05	3	116.50	101.45	1992.53	11.9	2.116	1906	2.6	94.7	11
06	3	116.39	101.43	1990.77	11.9	2.117	2034	2.9	94.7	11
07	7	116.20	101.28	1990.89	12.0	2.127	2575	2.9	110.0	12
08	7	116.18	101.25	1997.75	12.0	2.136	2354	2.7	110.1	10
09	7	116.20	101.13	1998.88	12.0	2.142	2354	2.7	107.5	11
10	14	116.15	101.13	1997.06	12.0	2.141	2540	2.9	112.0	12
11	14	116.23	101.10	1995.94	11.9	2.139	2563	2.6	122.5	11
12	14	116.13	101.10	2000.04	11.9	2.145	2941	2.9	128.9	12
13	21	116.23	101.07	2007.63	11.9	2.153	2676	3.1	108.5	13
14	21	116.85	101.50	2004.88	11.9	2.120	2806	3.1	116.1	13
15	21	116.60	101.74	2007.48	11.9	2.118	1932	2.6	95.0	11
16	28	116.77	101.49	2000.79	11.9	2.118	2686	3.1	109.7	13
17	28	116.52	101.41	2004.49	11.9	2.130	2468	2.9	105.4	13
18	28	116.50	101.39	1999.95	11.9	2.126	3003	3.3	121.4	14
19	42	116.48	101.44	1998.52	11.9	2.123	2742	3.3	113.8	12
20	42	116.53	101.50	1997.08	11.9	2.118	2754	3.1	111.1	13
21	42	116.49	101.55	2004.09	12.0	2.124	2757	2.9	116.6	13
22	56	116.54	101.49	1993.89	12.0	2.115	2939	3.3	116.5	13
23	56	116.63	101.52	2004.30	11.6	2.123	2774	3.1	110.8	14
24	56	116.82	101.56	2006.65	11.6	2.121	2651	3.1	106.5	14

Table A.1 Strength Gain with Time: ST1-PA5 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	116.65	101.49	2003.20	12.0	2.123	3108	3.1	120.1	14
26	90	116.68	101.58	1997.45	12.0	2.112	3165	3.1	123.5	14
27	90	116.67	101.46	2003.29	11.6	2.124	2877	3.3	108.5	14
28	120	116.83	101.52	2004.08	11.6	2.119	3133	3.5	115.0	14
29	120	116.76	101.52	2009.12	11.6	2.126	3164	3.3	113.6	15
30	120	116.61	101.49	2000.52	11.6	2.121	3245	3.3	118.5	14
31	180	116.73	101.56	1999.97	11.6	2.115	3409	3.6	119.3	14
32	180	116.81	101.48	2002.08	11.6	2.119	3320	3.5	119.8	14
33	180	116.73	101.46	2002.23	11.6	2.122	2957	3.3	115.3	13
34	240	116.70	101.44	1993.90	11.6	2.114	3465	3.8	115.4	16
35	240	116.60	101.43	1999.22	11.5	2.122	3513	3.6	117.2	16
36	240	116.54	101.42	1995.00	11.5	2.119	3678	3.6	121.9	16
37	360	116.57	101.51	2000.65	11.6	2.121	3571	3.6	117.9	16
38	360	116.59	101.42	2001.38	11.6	2.125	3472	3.6	117.6	16
39	360	116.64	101.40	2002.28	11.5	2.126	3393	3.5	123.7	13
40	540	116.61	101.41	1997.30	11.5	2.121	3568	3.6	124.2	15
41	540	116.43	101.42	1998.28	11.8	2.125	4386	4.0	131.7	18
42	540	116.38	101.51	1993.95	11.8	2.117	4420	4.0	129.9	19
43	540	116.22	101.50	1995.71	11.9	2.122	4348	4.0	130.5	19
44	540	116.40	101.54	1996.53	11.9	2.118	4418	4.0	131.3	19
45*	540	116.07	101.31	1997.96	11.9	2.135	4470	4.2	129.3	19

Single specimen batch.

Table A.2 Strength Gain with Time: ST1-PB5 Raw Data

Specimen ID	**Test Time (day)**	H_{AVG} **(mm)**	D_{AVG} **(mm)**	**Weight (g)**	$\omega_{measured}$ **(%)**	γ **(g/cm^3)**	σ_{max} **(kPa)**	ε_{max} **(%)**	$E_{X\text{-}Head}$ **(MPa)**	$n_{X\text{-}Head}$
01	1	116.95	101.15	1908.45	14.0	2.031	1626	2.2	91.5	10
02	1	116.40	101.18	1886.82	14.0	2.016	1524	2.2	90.4	9
03	1	116.65	101.18	1916.46	13.9	2.044	1779	2.4	96.6	10
04	3	116.63	101.23	1890.33	13.9	2.014	2021	2.4	101.5	10
05	3	116.30	101.28	1919.12	14.0	2.048	2077	2.2	110.5	9
06	3	116.28	101.25	1884.72	14.0	2.013	2041	2.4	103.3	10
07	7	116.67	101.49	1932.86	13.9	2.048	2385	2.7	104.4	12
08	7	116.69	101.46	1886.68	13.9	2.000	2149	2.4	111.1	10
09	7	116.66	101.53	1933.82	14.0	2.048	2510	2.7	113.5	12
45*	7	116.65	101.08	1923.86	14.1	2.055	2245	0.0	105.1	12
10	14	116.67	101.48	1905.83	14.0	2.020	2423	2.7	115.7	11
11	14	116.74	101.55	1920.00	14.0	2.031	2509	2.7	115.8	11
12	14	116.45	101.49	1893.87	14.0	2.010	2654	2.9	116.2	12
13	21	116.55	101.46	1920.56	14.0	2.038	2841	2.9	119.1	12
14	21	116.66	101.45	1900.55	14.0	2.016	2424	2.7	112.5	12
15	21	116.55	101.49	1931.29	14.0	2.049	2734	3.1	113.5	13
16	28	116.41	101.48	1901.38	14.0	2.020	2412	2.7	108.6	12
17	28	116.65	101.24	1924.63	14.0	2.050	2418	2.7	110.5	12
18	28	116.16	101.18	1894.30	14.0	2.028	2548	2.6	119.8	11
19	42	116.78	101.28	1920.09	14.0	2.041	2453	2.6	117.1	11
20	42	116.80	101.25	1898.48	14.0	2.019	2412	2.6	114.2	11
21	42	116.73	101.40	1923.58	14.1	2.041	2839	2.7	121.0	12
22	56	116.80	101.25	1897.55	14.1	2.018	2598	2.6	121.5	11
23	56	116.85	101.28	1925.24	14.1	2.045	3058	3.1	118.8	13
24	56	116.70	101.18	1903.68	14.1	2.029	2745	2.9	118.2	12

**Single specimen batch.*

Table A.2 Strength Gain with Time: ST1-PB5 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	116.90	101.23	1916.56	14.1	2.037	3628	3.5	134.2	13
26	90	116.80	101.35	1904.17	14.1	2.021	2953	3.1	125.2	11
27	90	116.68	101.48	1918.57	14.1	2.033	3547	3.6	122.1	14
28	120	116.55	101.48	1902.86	14.1	2.019	3521	3.6	123.6	14
29	120	116.38	101.40	1927.09	14.1	2.051	4350	4.0	130.8	18
30	120	116.25	101.35	1891.40	14.1	2.017	3852	3.8	128.3	16
31	180	116.50	101.43	1920.96	14.1	2.041	3920	3.8	123.0	16
32	180	116.33	101.48	1878.16	14.1	1.996	3505	3.6	121.2	15
33	180	116.38	101.50	1925.12	14.2	2.044	4067	3.8	131.4	16
40	180	116.52	101.37	1913.97	14.3	2.035	3639	3.6	129.9	14
34	240	116.43	101.40	1908.46	14.2	2.030	4012	3.8	131.3	16
35	240	116.68	101.57	1936.19	14.2	2.048	4168	3.8	132.8	16
36	240	116.62	101.50	1921.78	14.2	2.037	3166	3.3	124.3	13
37	360	116.64	101.43	1946.50	14.2	2.065	3370	3.5	120.7	15
38	360	116.52	101.47	1922.28	14.2	2.040	3563	3.5	128.2	15
39	360	116.42	101.43	1938.45	14.3	2.061	4105	3.8	131.9	16
41	540	116.67	101.38	1940.43	14.3	2.061	4231	3.8	137.0	16
42	540	116.64	101.36	1903.94	14.3	2.023	3365	3.3	125.2	16
43	540	116.55	101.37	1935.60	14.2	2.058	3597	3.5	131.2	16
44	540	116.59	101.30	1906.03	14.2	2.028	3522	3.3	131.5	16

Table A.3 Strength Gain with Time: ST1-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	1	116.54	101.51	2032.15	11.5	2.155	1593	2.4	81.6	11
02	1	116.61	101.50	2023.46	11.5	2.145	1750	2.2	90.0	11
03	1	116.93	101.73	2025.42	11.5	2.131	1794	2.9	84.8	12
04	3	116.83	101.62	2023.13	11.5	2.135	2430	3.8	77.0	18
05	3	116.60	101.56	2022.06	11.5	2.141	2167	3.3	72.8	17
06	3	116.73	101.51	2018.10	11.5	2.136	2272	3.6	71.4	18
07	7	117.05	101.57	2033.15	11.5	2.144	2890	3.3	96.2	17
08	7	116.84	101.61	2014.82	11.5	2.127	2963	3.3	104.8	16
09	7	116.74	101.66	2026.12	11.6	2.138	2374	3.3	80.7	16
10	14	116.78	101.51	2008.47	11.6	2.125	2859	5.3	63.2	26
11	14	116.64	101.67	2027.39	11.5	2.141	2747	4.9	64.2	24
12	14	116.81	101.53	2012.43	11.5	2.128	3063	5.1	68.2	25
13	21	116.75	101.58	2027.05	11.6	2.143	3240	3.1	119.8	15
14	21	116.84	101.63	2008.94	11.6	2.119	3147	3.1	121.8	14
15	21	116.77	101.67	2034.40	11.5	2.146	3302	3.3	116.9	16
16	28	116.61	101.50	2015.46	11.5	2.136	3593	3.6	122.6	17
17	28	116.57	101.41	2024.50	11.6	2.150	3594	3.5	123.8	16
18	28	116.67	101.68	2015.69	11.6	2.128	3370	3.3	123.5	15
19	42	116.43	101.36	2028.11	11.7	2.159	3153	3.3	118.8	15
20	42	116.57	101.48	2011.96	11.7	2.134	3114	3.3	121.3	14
21	42	116.52	101.40	2026.18	11.8	2.154	3182	3.3	121.0	14
22	56	116.74	101.61	2018.11	11.8	2.132	2885	3.1	115.6	14
23	56	116.75	101.55	2029.70	11.7	2.147	2957	2.9	117.2	14
24	56	116.50	101.38	2021.06	11.7	2.149	3178	3.1	124.3	14

Table A.3 Strength Gain with Time: ST1-PC4 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	116.79	101.58	2028.00	11.5	2.143	2981	3.1	120.2	14
26	90	116.87	101.55	2014.58	11.5	2.128	3294	3.1	128.4	14
27	90	116.82	101.62	2039.50	11.5	2.153	2952	3.1	111.6	14
28	120	116.85	101.70	2020.81	11.5	2.129	2554	2.9	112.2	14
29	120	116.81	101.49	2014.54	11.5	2.132	3620	3.6	130.4	15
30	120	116.81	101.39	2018.55	11.5	2.140	2844	3.1	113.5	13
40	120	116.46	101.46	2004.87	11.6	2.129	3252	3.3	117.6	16
31	180	116.74	101.44	2026.00	11.5	2.147	3793	3.6	129.0	16
32	180	116.60	101.37	2012.56	11.5	2.139	3110	3.1	122.5	13
33	180	116.47	101.47	2010.95	11.6	2.135	3315	3.5	121.4	15
34	240	116.68	101.46	2014.87	11.6	2.136	3379	3.5	125.7	14
35	240	116.68	101.50	2021.77	11.1	2.142	3118	3.5	104.7	17
36	240	116.64	101.46	2018.32	11.1	2.140	3347	3.5	124.9	15
37	360	116.49	101.44	2023.86	11.6	2.150	3476	3.1	129.3	14
38	360	116.75	101.43	2013.06	11.6	2.134	3645	3.5	129.7	15
39	360	116.66	101.45	2026.34	11.6	2.149	3681	3.6	121.0	16
41	540	116.55	101.40	2014.20	11.4	2.140	2643	3.1	112.9	12
42	540	116.48	101.44	2007.37	11.4	2.133	2921	3.1	120.9	12
43	540	116.61	101.40	2029.00	11.6	2.155	3780	3.5	131.7	15
44	540	116.61	101.42	2013.04	11.6	2.137	3292	3.5	119.6	15
45*	540	116.59	101.47	2030.38	11.5	2.154	3405	3.3	128.0	15

Single specimen batch.

Table A.4 Strength Gain with Time: ST4-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	1	150.72	76.64	1465.27	11.6	2.107	1406	1.4	127.5	8
02	1	150.78	76.62	1468.57	11.6	2.113	1463	1.4	141.4	7
03	1	150.75	76.66	1467.49	11.7	2.109	1443	1.3	153.3	6
04	3	150.73	76.65	1470.27	11.7	2.114	1924	1.4	195.1	6
05	3	150.53	76.38	1473.42	11.8	2.137	2137	1.4	154.0	8
06	3	150.45	76.42	1470.93	11.8	2.132	2132	1.3	167.7	8
07	7	150.53	76.53	1470.26	11.6	2.123	2524	1.5	213.2	8
08	7	150.50	76.52	1482.06	11.6	2.141	2525	1.5	209.5	9
09	7	150.56	76.61	1480.42	11.5	2.133	2621	1.5	210.9	9
10	14	150.53	76.50	1481.77	11.5	2.142	2916	1.7	222.3	10
11	14	150.58	76.65	1478.68	11.6	2.128	2766	1.7	211.1	10
12	14	150.56	76.63	1478.35	11.6	2.129	3036	1.7	222.3	10
13	21	150.42	76.62	1480.17	11.7	2.135	3333	1.8	217.3	11
14	21	150.52	76.52	1479.35	11.7	2.137	3341	1.7	233.0	11
15	21	150.50	76.54	1477.79	11.7	2.134	3024	1.8	222.0	9
16	28	150.34	76.56	1464.51	11.7	2.116	2903	1.8	213.2	9
17	28	150.37	76.62	1471.37	11.7	2.122	3056	1.7	229.0	9
18	28	150.37	76.64	1475.76	11.7	2.128	3054	2.0	206.2	10
19	42	150.52	76.58	1473.10	11.6	2.125	3021	1.7	226.1	9
20	42	150.55	76.56	1473.09	11.6	2.125	3134	1.8	229.6	9
21	42	150.58	76.61	1474.44	11.5	2.124	2880	1.8	213.1	9
22	56	150.52	76.61	1473.36	11.5	2.123	3371	1.8	230.7	10
23	56	150.66	76.60	1476.33	11.6	2.127	3335	1.8	230.6	10
24	56	150.60	76.56	1466.33	11.6	2.115	3338	1.8	232.4	10

Table A.4 Strength Gain with Time: ST4-PA5 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	150.70	76.61	1479.30	11.6	2.130	3538	1.8	243.7	10
26	90	150.63	76.64	1471.61	11.6	2.118	3461	1.8	235.9	10
27	90	150.61	76.61	1476.26	11.6	2.127	3482	1.7	247.2	9
28	120	150.57	76.64	1471.72	11.6	2.119	3748	2.0	236.2	11
29	120	150.65	76.65	1477.47	11.6	2.126	3784	2.1	231.8	11
30	120	150.65	76.59	1476.30	11.6	2.127	3827	2.1	235.5	11
31	180	150.65	76.71	1478.50	11.7	2.124	4129	2.3	235.5	11
32	180	150.52	76.55	1472.97	11.7	2.126	3942	2.3	242.3	10
33	180	150.75	76.75	1469.87	11.6	2.108	3839	2.1	251.6	11
34	240	150.69	76.67	1480.31	11.6	2.128	5011	2.4	268.6	13
35	240	150.68	76.52	1474.30	11.7	2.128	4595	2.5	240.0	12
36	240	150.65	76.54	1476.80	11.7	2.131	4908	2.4	256.5	13
37	360	150.69	76.54	1483.16	11.6	2.139	4369	2.1	264.1	12
38	360	150.52	76.46	1476.62	11.6	2.136	4165	2.1	254.2	12
39	360	150.44	76.49	1479.45	11.6	2.140	4032	2.1	245.9	12
40	540	150.76	76.54	1480.02	11.6	2.134	4222	2.5	245.0	10
41	540	150.77	76.52	1477.18	11.7	2.130	3899	2.3	244.9	11
42	540	150.65	76.58	1478.41	11.7	2.130	3540	2.0	238.1	10
43	540	150.78	76.55	1480.72	11.6	2.134	4462	2.1	270.1	11
44	540	150.69	76.61	1482.67	11.6	2.134	4713	2.3	270.0	11
45*	540	150.68	76.54	1471.73	11.6	2.123	3535	1.8	241.0	11

Single specimen batch.

Table A.5 Strength Gain with Time: ST4-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	1	150.38	76.75	1429.33	14.0	2.054	1865	1.5	158.3	8
02	1	150.19	76.75	1425.01	14.0	2.051	1894	2.0	122.0	11
03	1	150.31	76.64	1429.16	14.0	2.061	1691	1.4	144.3	8
04	3	150.23	76.81	1429.34	14.0	2.053	2385	2.5	113.1	14
05	3	150.25	76.67	1428.32	14.1	2.059	2408	2.8	99.6	17
06	3	150.19	76.71	1420.81	14.1	2.047	2241	2.7	97.6	17
07	7	150.15	76.48	1421.93	14.0	2.061	2314	1.4	201.0	8
08	7	150.18	76.71	1423.24	14.0	2.050	2641	1.5	203.3	9
09	7	150.24	76.57	1422.54	14.0	2.056	2624	1.5	203.6	9
10	14	150.32	76.57	1418.61	14.0	2.049	3068	1.7	219.1	10
11	14	150.16	76.56	1428.69	13.9	2.067	3097	1.7	216.4	10
12	14	150.09	76.51	1421.46	13.9	2.060	3250	1.8	226.5	10
14	21	150.14	76.57	1418.61	14.1	2.052	3198	1.7	237.4	10
15	21	150.09	76.58	1422.57	14.0	2.058	3160	1.5	243.1	10
40	21	150.03	76.35	1416.88	13.8	2.063	2788	1.5	229.3	9
16	28	150.26	76.58	1424.98	14.0	2.059	3281	1.8	235.8	9
17	28	150.19	76.54	1421.83	14.0	2.058	3321	1.8	223.8	10
18	28	150.02	76.59	1420.24	14.0	2.055	3364	2.0	219.9	10
19	42	149.98	76.70	1419.09	13.8	2.048	3159	1.8	215.1	10
20	42	149.98	76.62	1421.35	13.8	2.055	3194	1.8	226.4	10
21	42	150.07	76.57	1420.37	14.0	2.055	2911	1.7	211.0	9
22	56	150.23	76.63	1421.32	14.0	2.052	3416	2.0	237.5	10
23	56	150.15	76.45	1419.59	14.0	2.060	3171	1.7	235.1	10
24	56	150.13	76.23	1415.28	14.0	2.066	3143	1.8	219.5	10

Table A.5 Strength Gain with Time: ST4-PB5 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	150.20	76.53	1426.50	14.2	2.065	3341	1.8	233.3	10
26	90	150.01	76.38	1418.32	14.2	2.064	3205	1.8	228.5	10
27	90	150.18	76.43	1420.89	14.1	2.063	3769	2.1	244.1	10
28	120	150.13	76.40	1418.97	14.1	2.062	4097	2.0	263.1	11
29	120	150.15	76.35	1416.90	14.2	2.061	3580	1.8	246.0	10
30	120	150.13	76.43	1419.01	14.2	2.060	3769	2.0	239.4	11
31	180	150.00	76.28	1421.39	14.0	2.074	3662	2.0	247.0	10
32	180	150.05	76.48	1419.17	14.0	2.059	3885	2.0	250.0	11
33	180	150.00	76.63	1417.56	14.0	2.049	3712	1.8	241.2	11
34	240	149.98	76.50	1415.40	14.0	2.053	4727	2.3	254.1	13
35	240	150.05	76.43	1419.68	14.0	2.062	4578	2.3	250.9	13
36	240	150.10	76.35	1422.32	14.0	2.070	4727	2.3	263.9	12
37	360	150.03	76.45	1421.21	13.9	2.064	4054	0.0	257.9	10
38	360	149.98	76.40	1413.16	13.9	2.055	3678	0.0	244.9	10
39	360	150.00	76.50	1415.22	13.8	2.053	3594	0.0	239.0	10
41	540	150.05	76.28	1420.54	14.0	2.072	3466	1.8	247.0	10
42	540	150.05	76.38	1413.84	14.0	2.057	3438	1.7	247.8	9
43	540	150.00	76.53	1416.13	14.1	2.053	3202	1.8	224.5	9
44	540	150.00	76.45	1418.68	14.1	2.060	3534	1.8	242.2	9

Table A.6 Strength Gain with Time: ST4-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	1	150.46	76.54	1483.86	11.4	2.143	2324	1.7	166.1	9
02	1	150.45	76.67	1486.90	11.4	2.141	2338	2.0	149.2	11
03	1	150.72	76.64	1489.56	11.4	2.143	2027	2.0	126.6	11
04	3	150.44	76.63	1478.34	11.4	2.131	2668	2.4	121.8	16
05	3	150.51	76.80	1493.21	11.4	2.142	2788	2.5	128.0	16
06	3	150.51	76.78	1495.21	11.4	2.146	2753	2.5	125.9	17
07	7	150.30	76.63	1496.45	11.5	2.159	3116	1.7	227.9	10
08	7	150.29	76.55	1488.98	11.5	2.153	3325	2.4	167.5	14
09	7	150.33	76.71	1492.76	11.4	2.149	3203	2.1	188.4	13
10	14	150.43	76.54	1494.03	11.4	2.159	3767	1.8	247.6	11
11	14	150.47	76.72	1492.00	11.4	2.145	3601	1.8	250.3	10
12	14	150.41	76.63	1490.83	11.4	2.149	3721	1.8	249.4	10
13	21	150.55	76.57	1490.39	11.5	2.150	4061	1.8	268.4	11
14	21	150.00	76.58	1480.64	11.5	2.143	3503	1.7	258.2	9
40	21	150.33	76.65	1487.47	11.4	2.145	3525	1.8	243.1	11
16	28	150.11	76.59	1484.24	11.6	2.147	3632	1.8	255.8	10
17	28	150.40	76.59	1488.30	11.5	2.148	3688	1.5	283.2	10
18	28	150.27	76.58	1491.65	11.5	2.155	3559	1.5	267.9	10
19	42	150.53	76.70	1491.16	11.5	2.144	3262	1.7	232.5	10
20	42	150.40	76.81	1485.33	11.5	2.131	3381	1.7	254.1	9
21	42	150.26	76.60	1482.53	11.3	2.141	3594	1.7	256.9	10
22	56	150.10	76.67	1487.15	11.3	2.146	3514	1.5	259.1	10
23	56	150.52	76.54	1491.68	11.3	2.154	3767	1.8	259.1	9
24	56	150.10	76.61	1489.03	11.3	2.152	3797	2.0	268.6	10

Table A.6 Strength Gain with Time: ST4-PC4 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	150.36	76.61	1487.77	11.4	2.147	4334	2.1	269.9	11
26	90	150.24	76.59	1489.21	11.4	2.152	4494	2.1	273.4	11
27	90	150.43	76.52	1487.94	11.3	2.151	4149	2.0	267.4	10
28	120	150.32	76.44	1487.09	11.3	2.156	4223	2.0	275.0	10
29	120	150.39	76.76	1488.90	11.4	2.139	4289	2.0	269.9	11
30	120	150.32	76.34	1489.03	11.4	2.164	4356	2.0	275.7	11
31	180	150.37	76.65	1483.95	11.6	2.139	3932	2.0	267.9	10
32	180	150.29	76.65	1491.59	11.6	2.151	4552	2.5	266.3	11
33	180	150.37	76.62	1491.94	11.6	2.152	4120	2.3	263.3	10
34	240	150.34	76.64	1488.86	11.6	2.147	5080	2.4	275.5	12
35	240	150.21	76.49	1491.33	11.3	2.161	5231	2.4	280.0	12
36	240	150.35	76.54	1488.09	11.3	2.151	5177	2.5	264.6	14
38	360	150.37	76.66	1487.27	11.5	2.143	4578	2.1	276.9	11
39	360	150.34	76.59	1485.58	11.4	2.145	4290	2.0	261.3	11
41	360	150.47	76.62	1485.81	11.4	2.141	4508	2.3	268.2	11
42	540	150.16	76.66	1482.19	11.4	2.138	5105	2.1	299.0	11
43	540	150.35	76.64	1486.62	11.4	2.143	4802	2.1	294.1	11
44	540	150.33	76.65	1486.50	11.4	2.143	4949	2.1	293.9	11
45*	540	150.31	76.64	1486.53	11.3	2.144	4210	2.1	252.5	12

**Single specimen batch.*

Table A.7 Strength Gain with Time: ST2-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01*	1	114.33	100.31	1949.00	11.4	2.157	1600	3.3	51.2	12
02*	1	114.49	100.29	1949.30	11.4	2.155	1654	3.5	52.4	13
03	1	114.87	100.19	1949.50	11.4	2.153	1673	3.9	47.8	20
04	3	114.90	100.19	1949.30	11.4	2.152	2348	3.3	78.3	17
05	3	114.66	100.19	1949.00	11.5	2.156	2304	3.7	68.9	18
06	3	114.79	100.19	1949.80	11.5	2.155	2280	4.1	61.4	21
07	7	114.86	100.16	1949.70	11.5	2.154	2715	5.2	56.8	27
08	7	114.58	100.16	1949.30	11.5	2.159	2799	5.2	57.2	27
09	7	114.80	100.24	1949.20	11.4	2.152	2788	5.0	59.6	27
10	14	114.76	100.15	1949.50	11.4	2.157	2796	3.3	93.7	17
11	14	114.84	100.23	1949.40	11.5	2.152	2630	3.3	91.3	17
12	14	114.73	100.19	1949.40	11.5	2.155	2659	3.1	95.3	16
13	21	114.87	100.19	1949.60	11.5	2.153	2967	3.5	94.8	17
14	21	114.67	100.16	1949.70	11.5	2.158	2991	3.3	98.4	17
15	21	114.64	100.20	1941.00	11.7	2.147	3080	3.5	101.7	17
16	28	114.17	100.19	1941.10	11.7	2.157	2848	3.0	107.5	15
17	28	114.45	100.30	1942.10	11.6	2.148	2620	3.0	100.2	15
18	28	114.56	100.24	1942.60	11.6	2.149	3018	3.0	108.9	15
19	42	114.54	100.25	1941.90	11.6	2.148	2520	3.0	92.7	16
20	42	114.25	100.21	1941.60	11.6	2.155	2566	3.1	97.7	14
21	42	114.50	100.20	1941.60	11.6	2.151	2907	3.7	98.4	16
22	56	114.47	100.22	1942.50	11.6	2.151	2971	3.1	104.4	16
23	56	114.54	100.23	1941.70	11.6	2.149	2765	3.0	103.0	15
24	56	114.13	100.20	1941.20	11.6	2.157	2950	3.1	104.1	16

**Single specimen batch.*

Table A.7 Strength Gain with Time: ST2-PC4 Raw Data (Continued)

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
25	90	114.35	100.14	1941.20	11.5	2.156	2976	3.3	101.8	16
26	90	114.49	100.13	1941.00	11.5	2.153	3307	3.3	108.7	17
27	90	114.51	100.17	1940.50	11.4	2.150	2974	3.1	103.9	16
28	120	114.58	100.13	1940.70	11.4	2.151	3112	3.1	105.5	17
29	120	114.33	100.19	1936.00	11.6	2.148	3384	3.5	113.3	17
30	120	114.21	100.17	1940.30	11.6	2.156	3353	3.3	110.6	17
31	180	114.42	100.21	1940.40	11.5	2.150	3085	3.1	105.9	17
32	180	114.17	100.19	1940.20	11.5	2.155	3140	3.3	107.6	17
33	180	114.52	100.17	1940.40	11.5	2.150	2958	3.3	102.0	17
34	240	114.34	100.16	1940.30	11.5	2.154	3197	3.3	105.9	17
35	240	114.21	100.23	1940.50	11.5	2.153	3376	3.3	112.9	17
36	240	114.12	100.21	1940.30	11.5	2.156	3832	3.5	117.6	19
37	360	114.32	100.26	1940.00	11.5	2.150	3807	3.7	121.6	17
38	360	114.02	100.26	1940.40	11.5	2.156	3785	3.9	120.3	17
39	360	113.99	100.27	1940.30	11.5	2.156	3503	3.7	117.3	16
40	540	113.91	100.27	1940.30	11.5	2.157	3557	3.3	121.9	14
41	540	114.30	100.19	1940.90	11.5	2.154	3509	3.5	115.7	16
42	540	114.25	100.17	1940.60	11.5	2.155	3591	3.7	116.5	16
43	540	114.14	100.21	1940.70	11.5	2.156	3734	3.7	121.2	16
44	540	114.08	100.24	1940.20	11.5	2.155	3781	3.5	125.4	15
45*	540	113.87	100.24	1940.10	11.4	2.159	3857	3.5	125.3	15

Single specimen batch.

Table A.8 Unconfined Compressive Strength Variability: SV1-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.50	101.36	1997.87	11.7	2.125	2079	2.9	92.4	11
02	7	116.63	101.49	2010.22	11.7	2.130	2538	2.9	116.7	11
03	7	116.38	101.41	2006.77	11.9	2.135	2241	2.9	101.1	11
04	7	116.91	101.35	2004.09	11.9	2.125	1937	2.7	91.5	10
05	7	117.05	101.30	2002.30	11.8	2.123	2050	2.7	95.1	10
06	7	116.80	101.39	2008.00	11.8	2.130	2342	2.7	107.0	11
07	7	116.56	101.46	2006.33	12.1	2.129	2202	2.9	97.6	11
08	7	116.53	101.43	1998.21	12.1	2.122	2314	2.7	105.7	11
09*	7	116.68	101.59	2010.75	11.5	2.126	2006	2.6	97.0	11
10*	7	116.56	101.43	2003.60	11.8	2.127	2414	2.9	107.6	12
11	7	116.41	101.43	2004.25	11.8	2.131	2129	2.7	101.7	11
12	7	116.52	101.40	1999.68	11.8	2.125	2215	2.7	100.8	11
13	7	116.36	101.46	2001.51	11.8	2.127	2175	2.7	102.5	10
14	7	116.48	101.42	2002.79	11.8	2.128	2277	2.6	108.3	11
15	7	116.63	101.40	2009.63	11.9	2.134	2067	2.6	99.1	11
16	7	116.58	101.44	2001.62	11.9	2.125	2245	2.7	110.4	10
17	7	116.48	101.40	2002.56	11.9	2.129	2178	2.7	100.7	11
18	7	116.55	101.46	2005.45	11.9	2.128	2149	2.7	99.6	11
19	7	116.29	101.45	2007.20	11.8	2.136	2049	2.9	89.6	11
20	7	116.57	101.42	2003.63	11.8	2.128	2325	2.7	105.3	11
21	7	116.53	101.51	2006.28	11.9	2.128	2158	2.7	105.0	10
22	7	116.52	101.46	1998.55	11.9	2.121	2217	2.9	104.3	10
23	7	116.37	101.39	2004.19	11.9	2.133	2157	2.7	101.2	11
24	7	116.48	101.45	2001.23	11.9	2.126	2324	2.7	108.1	11
25	7	116.53	101.44	2008.03	11.7	2.132	2234	2.7	100.0	11
26	7	116.52	101.42	1999.32	11.7	2.124	2203	2.9	97.3	12
27	7	116.64	101.41	2014.62	11.6	2.138	2215	2.7	101.5	11
28	7	116.51	101.41	2000.19	11.6	2.126	2352	2.7	105.6	12
29	7	116.53	101.57	1999.48	11.5	2.118	2229	2.9	98.8	12
30	7	116.75	101.49	2002.36	11.5	2.120	2005	2.6	93.4	12

**Single specimen batch.*

Table A.9 Unconfined Compressive Strength Variability: SV1-PA6 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.68	101.51	2020.68	11.9	2.140	2600	3.3	103.3	13
02	7	116.66	101.46	2013.80	11.9	2.135	2629	3.1	104.4	13
03	7	116.70	101.56	2019.93	11.7	2.137	2419	3.1	103.2	12
04	7	116.76	101.54	2016.28	11.7	2.133	2541	2.9	109.5	12
05	7	116.84	101.56	2016.50	11.8	2.131	2493	2.9	103.6	13
06	7	116.81	101.54	2018.20	11.8	2.134	2456	2.9	104.2	12
07	7	116.73	101.58	2020.24	11.9	2.136	2423	2.9	103.4	11
08	7	116.76	101.52	2013.80	11.9	2.131	2553	3.1	107.6	11
09	7	116.65	101.43	2017.14	11.8	2.140	2488	3.1	106.5	11
10	7	116.63	101.42	2010.90	11.8	2.134	2631	3.1	108.4	12
11	7	116.53	101.56	2018.36	11.9	2.138	2535	3.1	103.1	11
12	7	116.67	101.41	2013.45	11.9	2.137	2489	3.1	106.3	11
13	7	116.75	101.39	2016.20	11.9	2.139	2548	3.1	109.8	10
14	7	116.71	101.38	2014.56	11.9	2.138	2708	3.1	111.6	11
15	7	116.62	101.37	2017.34	12.0	2.144	2634	3.1	111.3	11
16	7	116.83	101.44	2013.15	12.0	2.132	2562	3.1	105.3	10
17	7	116.81	101.57	2018.13	11.9	2.132	2545	3.1	107.9	11
18	7	116.77	101.51	2013.98	11.9	2.131	2627	3.1	110.1	11
19	7	116.66	101.45	2018.84	11.9	2.141	2503	3.1	106.8	11
20	7	116.62	101.43	2013.56	11.9	2.137	2657	3.1	113.2	11
21	7	116.64	101.40	2022.44	12.0	2.147	2284	3.3	102.5	10
22	7	116.71	101.35	2021.03	12.0	2.146	2667	3.1	115.1	10
23	7	116.74	101.40	2021.21	11.9	2.144	2453	2.9	107.3	11
24	7	116.81	101.35	2018.67	11.9	2.142	2461	2.9	112.8	11
25	7	116.77	101.40	2021.47	11.9	2.144	2358	2.9	102.2	11
26	7	116.79	101.35	2013.15	11.9	2.137	2344	2.9	108.1	12
27	7	116.68	101.33	2015.79	12.0	2.142	2424	3.1	102.6	11
28	7	116.84	101.29	2020.64	12.0	2.146	2273	3.1	90.4	12
29	7	116.41	101.19	2012.92	12.0	2.150	2394	3.1	99.8	12
30	7	116.60	101.18	2016.83	12.0	2.151	2549	3.1	105.1	12

Table A.10 Unconfined Compressive Strength Variability: SV1-PA4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.61	101.34	2002.22	11.9	2.129	1503	2.4	83.3	8
02	7	116.78	101.38	2000.57	11.9	2.122	1544	2.4	84.7	8
03	7	116.78	101.42	2001.74	12.0	2.122	1564	2.6	80.4	10
04	7	116.66	101.39	2004.40	12.0	2.128	1686	2.6	84.8	10
05	7	116.76	101.41	1997.33	11.9	2.118	1601	2.6	84.5	10
06	7	116.79	101.36	1998.76	11.9	2.121	1666	2.4	87.9	9
07	7	116.83	101.40	1999.47	11.9	2.119	1681	2.6	90.4	9
08	7	116.83	101.37	1997.70	11.9	2.119	1645	2.6	89.7	9
09	7	116.73	101.42	2005.93	12.0	2.127	1670	2.6	89.2	9
10	7	116.79	101.38	2004.91	12.0	2.127	1581	2.4	92.6	8
11	7	116.80	101.53	1997.77	12.0	2.113	1518	2.2	89.3	8
12	7	116.71	101.38	2005.56	12.0	2.129	1555	2.6	78.0	10
13	7	116.84	101.57	2008.29	12.0	2.122	1575	2.6	77.2	10
14	7	116.93	101.46	2006.06	12.0	2.122	1716	2.6	84.8	10
15	7	116.75	101.60	2002.18	12.0	2.115	1653	2.6	83.5	10
16	7	116.87	101.55	2005.97	12.0	2.119	1634	2.6	90.0	6
17	7	116.97	101.53	2002.27	12.0	2.114	1640	2.6	84.3	9
18	7	116.64	101.40	2001.37	12.0	2.125	1686	2.6	84.5	10
19	7	116.76	101.59	2004.94	12.0	2.118	1554	2.4	82.2	10
20	7	116.99	101.60	2001.86	12.0	2.111	1590	2.4	81.9	10
21	7	116.86	101.66	1999.56	12.0	2.108	1373	2.2	80.0	8
22	7	116.81	101.50	2004.76	12.0	2.121	1551	2.6	80.6	10
23	7	116.58	101.61	1997.07	11.9	2.113	1427	2.4	79.7	10
24	7	116.87	101.61	2003.81	11.9	2.115	1579	2.6	80.9	10
25	7	116.87	101.64	2004.43	12.0	2.114	1626	2.6	89.3	8
26	7	116.77	101.48	2000.86	12.0	2.118	1652	2.6	87.1	8
27	7	116.61	101.57	1992.20	11.9	2.109	1560	2.6	83.6	9
28	7	116.77	101.57	2000.76	11.9	2.115	1707	2.6	90.4	9
29	7	116.82	101.49	2003.74	11.9	2.120	1567	2.6	82.9	9
30	7	116.99	101.52	2001.43	11.9	2.114	1603	2.6	88.3	9

Table A.11 Unconfined Compressive Strength Variability: SV1-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.71	101.32	1915.96	13.9	2.036	2277	2.2	119.9	10
02	7	116.63	101.30	1884.78	13.9	2.005	1997	2.0	118.4	9
03	7	116.68	101.37	1922.82	14.0	2.042	2343	2.4	122.9	10
04	7	116.63	101.25	1899.59	14.0	2.023	2195	2.2	117.9	10
05	7	116.12	101.45	1915.48	13.8	2.041	2461	2.6	117.3	10
06	7	116.27	101.50	1898.64	13.8	2.018	2427	2.4	122.9	10
07	7	116.39	101.51	1921.00	13.7	2.040	2395	2.4	122.2	10
08	7	116.03	101.44	1891.08	13.7	2.017	2367	2.6	113.8	11
09	7	116.34	100.95	1922.35	13.7	2.065	2299	2.2	121.4	10
10	7	116.39	101.33	1892.58	13.7	2.016	2318	2.4	120.0	10
11	7	116.37	101.37	1909.17	13.8	2.033	2349	2.4	122.9	10
12	7	116.37	101.35	1896.33	13.8	2.020	2434	2.4	125.9	10
13	7	116.28	101.37	1914.73	13.8	2.040	2444	2.4	121.8	10
14	7	116.27	101.44	1883.47	13.8	2.004	2155	2.4	114.1	10
15	7	116.33	101.48	1928.20	13.8	2.050	2159	2.2	117.1	10
16	7	116.42	101.48	1884.88	13.8	2.002	2058	2.6	124.4	10
17	7	116.56	101.42	1930.94	14.0	2.051	2241	2.4	120.3	9
18	7	116.59	101.46	1901.58	14.0	2.017	1885	2.2	114.1	8
19	7	116.50	101.36	1920.77	14.1	2.043	2323	2.4	120.6	9
20	7	116.60	101.36	1914.58	14.1	2.035	2090	2.0	121.4	8
21	7	116.49	101.37	1940.06	14.0	2.064	2565	2.4	127.2	9
22	7	116.37	101.28	1921.72	14.0	2.050	2300	2.4	117.7	9
23	7	116.37	101.27	1930.41	14.0	2.059	2427	2.4	123.4	9
24	7	116.34	101.33	1925.34	14.0	2.052	2372	2.4	121.1	9
25	7	116.43	101.61	1921.68	14.0	2.035	2369	2.4	123.1	9
26	7	116.53	101.49	1914.20	14.0	2.031	2259	2.4	119.4	9
27	7	116.59	101.44	1929.31	14.1	2.048	2313	2.2	120.4	10
28	7	116.69	101.46	1927.77	14.1	2.044	2466	2.4	123.3	10
29	7	116.61	101.43	1936.57	14.1	2.055	2446	2.4	124.7	10
30	7	116.81	101.44	1915.41	14.1	2.029	2060	2.2	113.6	10

Table A.12 Unconfined Compressive Strength Variability: SV1-PB6 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.22	101.34	1927.26	14.0	2.056	2916	3.3	106.7	14
02	7	116.15	101.33	1900.40	14.0	2.029	2694	3.5	101.0	14
03	7	115.99	101.38	1923.70	14.0	2.055	2935	3.5	105.7	14
04	7	115.96	101.39	1899.60	14.0	2.029	2443	3.1	102.3	12
05	7	115.84	101.35	1927.37	14.0	2.062	2868	3.3	108.7	13
06	7	115.79	101.36	1898.42	14.0	2.032	2455	3.1	93.6	14
07	7	115.96	101.35	1921.74	14.1	2.054	2736	3.3	98.8	15
08	7	116.42	101.27	1903.41	14.1	2.030	2369	3.3	90.7	13
09	7	116.23	101.30	1935.01	14.0	2.066	2807	3.1	111.3	13
10	7	116.25	101.33	1890.61	14.0	2.017	2567	2.9	106.7	13
11	7	116.13	101.35	1919.76	14.2	2.049	2752	3.5	96.1	15
12	7	116.12	101.50	1917.32	14.2	2.041	2823	3.3	102.9	15
13	7	115.94	101.41	1914.39	14.2	2.044	2775	3.3	99.8	14
14	7	116.10	101.44	1915.45	14.2	2.041	2847	3.3	102.5	13
15	7	116.79	101.33	1944.47	14.1	2.065	2414	2.6	112.5	10
16	7	116.78	101.33	1921.31	14.1	2.040	2477	2.7	115.4	10
17	7	116.81	101.38	1948.50	14.1	2.067	2523	2.7	114.5	10
18	7	116.62	101.36	1929.79	14.1	2.051	2190	2.6	109.5	11
19	7	116.70	101.26	1931.58	14.2	2.055	2375	2.7	110.2	12
20	7	116.67	101.30	1930.06	14.2	2.053	2378	2.6	112.8	11
21	7	116.76	101.29	1951.66	14.1	2.074	2855	3.1	110.9	11
22	7	116.71	101.19	1918.11	14.1	2.044	2346	2.6	114.6	10
23	7	116.63	101.18	1948.98	14.2	2.078	2787	2.9	109.9	14
24	7	116.54	101.12	1934.26	14.2	2.067	2365	2.6	111.4	11
25	7	116.59	101.44	1952.42	14.2	2.072	2604	2.9	109.9	11
26	7	116.74	101.42	1926.13	14.2	2.043	2584	2.9	111.1	13
27	7	116.63	101.48	1939.75	14.3	2.056	2602	2.9	110.0	13
28	7	116.50	101.42	1929.18	14.3	2.050	2446	2.7	108.1	13
29	7	116.51	101.41	1942.85	14.3	2.064	2574	2.9	110.1	13
30	7	116.54	101.48	1896.36	14.3	2.012	2196	2.6	110.0	11

Table A.13 Unconfined Compressive Strength Variability: SV1-PB4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.17	101.49	1921.27	14.4	2.044	1836	2.6	89.7	10
02	7	115.98	101.51	1903.51	14.4	2.028	1857	2.6	89.1	10
03	7	115.90	101.50	1917.28	14.3	2.045	1899	2.7	87.2	10
04	7	116.11	101.51	1910.45	14.3	2.033	1916	2.6	90.3	10
05	7	115.90	101.40	1919.91	14.3	2.052	1845	2.6	86.9	10
06	7	116.21	101.38	1907.06	14.3	2.033	1851	2.4	95.3	10
07	7	116.07	101.38	1921.96	14.3	2.051	1941	2.6	91.2	10
08	7	116.18	101.35	1898.38	14.3	2.026	1931	2.4	98.1	9
09	7	116.10	101.35	1924.97	14.4	2.055	1947	2.4	100.6	9
10	7	116.20	101.31	1897.20	14.4	2.025	1832	2.4	101.5	9
11	7	116.70	101.48	1932.00	14.5	2.047	1578	2.7	92.4	8
12	7	116.80	101.51	1917.06	14.5	2.028	1635	2.2	96.9	8
13	7	116.76	101.35	1951.18	14.4	2.071	1804	2.4	94.6	9
14	7	116.35	100.97	1926.19	14.4	2.068	1861	2.4	97.3	9
15	7	116.69	101.34	1934.01	14.5	2.055	1921	2.6	98.3	10
16	7	116.58	101.30	1905.07	14.5	2.028	1695	2.4	93.2	8
17	7	116.95	101.23	1947.13	14.5	2.069	1676	2.2	97.0	8
18	7	116.77	101.38	1927.35	14.5	2.045	1708	2.2	97.8	9
19	7	116.73	101.44	1932.52	14.5	2.049	1648	2.4	92.9	9
20	7	116.50	101.45	1929.26	14.5	2.049	1869	2.4	100.3	9
21	7	116.70	101.53	1944.03	14.4	2.058	1703	2.4	89.8	9
22	7	116.68	101.43	1916.95	14.4	2.034	1770	2.4	97.2	9
23	7	116.78	101.50	1949.15	14.5	2.063	1852	2.6	96.8	9
24	7	116.55	101.38	1934.67	14.5	2.057	1973	2.6	98.6	10
25	7	116.75	101.51	1940.75	14.6	2.054	1624	2.4	89.4	10
26	7	116.77	101.33	1929.43	14.6	2.049	1609	2.4	94.8	8
27	7	116.17	101.36	1911.83	14.6	2.040	1804	2.4	90.6	8
28	7	115.80	101.45	1891.90	14.6	2.021	1611	2.6	78.8	10
29	7	115.53	101.45	1905.57	14.6	2.041	1838	2.7	83.9	10
30	7	116.03	101.40	1896.62	14.6	2.024	1808	2.7	88.8	10

Table A.14 Unconfined Compressive Strength Variability: SV1-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.79	101.87	2023.40	11.4	2.126	1697	2.6	78.5	12
02	7	116.87	101.74	2016.90	11.4	2.123	1812	2.6	91.6	11
03	7	117.13	101.85	2048.80	11.5	2.147	1933	2.9	86.6	12
04	7	117.09	101.49	2027.10	11.5	2.140	2327	2.7	98.1	14
05	7	116.98	101.88	2061.60	11.6	2.162	2000	2.6	92.0	13
06	7	116.84	101.43	2024.40	11.6	2.144	2351	2.6	106.4	13
07	7	117.09	101.49	2046.40	11.5	2.161	2137	2.7	97.3	11
08	7	117.21	101.84	2054.90	11.5	2.152	2332	2.7	104.3	12
09	7	116.95	101.85	2062.00	11.5	2.164	2489	2.7	107.1	13
10	7	116.96	101.41	2032.10	11.5	2.151	2458	2.9	112.9	11
11	7	116.85	101.47	2040.80	11.6	2.160	2428	2.8	103.4	14
12	7	116.92	101.82	2034.20	11.6	2.137	2050	2.4	99.3	12
13	7	116.92	101.83	2061.20	11.5	2.165	2490	2.7	103.4	14
14	7	116.86	101.47	2034.40	11.5	2.153	2217	2.4	109.4	11
15	7	117.80	101.32	2064.10	11.6	2.173	1837	2.7	80.9	9
16	7	116.49	101.55	2027.70	11.6	2.149	2003	2.7	93.7	10
17	7	117.30	101.35	2055.80	11.5	2.172	1915	3.1	82.6	12
18	7	116.79	101.42	2001.80	11.5	2.122	2034	3.6	74.9	13
19	7	117.46	101.89	2043.20	11.3	2.134	1979	2.4	89.3	11
20	7	116.62	101.46	1996.00	11.3	2.117	2138	2.6	107.0	10
21	7	117.25	101.30	2039.30	11.5	2.158	2156	0.0	96.4	11
22	7	117.98	101.73	2043.60	11.5	2.131	2232	0.0	97.5	11
23	7	117.45	101.43	2058.60	11.7	2.169	1976	2.9	81.4	11
24	7	116.95	101.35	2012.10	11.7	2.133	2280	0.0	106.2	11
25	7	117.27	101.50	2048.10	11.4	2.159	2258	2.9	99.0	12
26	7	117.02	101.64	2047.80	11.4	2.157	2420	2.7	110.3	12
27	7	116.74	101.66	2023.10	11.4	2.135	2204	2.7	99.4	12
28	7	118.27	101.61	2051.70	11.4	2.139	2311	2.9	85.5	14
29	7	117.78	101.55	2050.10	11.4	2.149	2061	2.9	79.4	14
30	7	117.19	101.48	2039.60	11.4	2.152	2438	2.7	102.6	14

Table A.15 Unconfined Compressive Strength Variability: SV1-PC5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.07	101.32	1971.40	11.1	2.107	2652	2.7	121.0	12
02	7	116.06	101.33	1956.55	11.1	2.090	2451	2.7	112.9	12
03	7	116.16	101.43	2003.91	10.8	2.135	3069	2.9	121.8	14
04	7	116.22	101.44	1987.32	10.8	2.116	2947	2.9	119.3	14
05	7	116.08	101.37	1996.37	10.8	2.131	2740	2.7	120.8	13
06	7	116.22	101.51	1992.37	10.8	2.118	2901	2.7	129.1	12
07	7	116.30	101.42	2001.49	10.9	2.130	2674	2.7	117.8	13
08	7	116.25	101.42	1985.40	10.9	2.114	2795	2.7	120.4	13
09	7	116.22	101.44	2017.30	10.9	2.148	3095	2.9	125.2	14
10	7	116.22	101.46	1989.33	10.9	2.117	2941	2.9	127.2	13
11	7	116.35	101.35	1997.94	10.6	2.129	3011	2.9	126.8	14
12	7	116.42	101.38	1958.08	10.6	2.084	2909	2.9	123.6	14
13	7	116.78	101.35	2021.44	10.9	2.146	2206	2.6	116.1	11
14	7	116.80	101.37	1992.87	10.9	2.114	2153	2.4	123.0	10
15	7	116.70	101.46	2027.91	10.9	2.150	2545	2.6	116.5	12
16	7	116.76	101.36	2001.35	10.9	2.124	2000	2.2	110.7	10
17	7	116.57	101.49	2018.57	11.0	2.140	2997	3.1	121.5	14
18	7	116.69	101.35	1998.20	11.0	2.123	1926	2.0	118.6	9
19	7	116.65	101.48	2022.18	11.0	2.143	2544	2.6	119.4	11
20	7	116.70	101.37	1996.07	11.0	2.119	2015	2.2	118.0	10
21	7	116.71	101.49	2005.37	11.0	2.124	1831	2.0	114.0	8
22	7	116.54	101.44	1993.28	11.0	2.117	2028	2.2	121.3	9
23	7	116.54	101.39	1998.52	10.7	2.124	2395	2.4	116.7	11
24	7	116.63	101.38	1988.97	10.7	2.113	2301	2.4	119.0	10
25	7	116.05	101.55	1991.86	10.9	2.119	2382	2.7	110.4	12
26	7	116.10	101.58	1994.43	10.9	2.120	2539	2.9	103.2	14
27	7	116.14	101.58	2017.23	10.9	2.143	2650	2.7	114.0	13
28	7	116.11	101.55	1984.02	10.9	2.110	2936	3.1	111.4	14
29	7	116.12	101.57	2005.07	11.0	2.131	2661	2.9	113.4	13
30	7	116.02	101.57	1985.95	11.0	2.113	2424	2.9	99.2	14

Table A.16 Unconfined Compressive Strength Variability: SV1-PC3 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.43	101.27	2007.25	10.9	2.140	1595	1.8	108.6	9
02	7	116.24	101.29	2000.35	10.9	2.136	1616	1.8	104.7	9
03	7	116.31	101.37	1985.81	11.1	2.115	1941	2.0	104.6	9
04	7	116.63	101.43	1965.95	11.1	2.086	1997	2.0	115.6	10
05	7	116.53	101.37	2004.66	10.7	2.132	2121	2.0	123.0	10
06	7	116.32	101.39	1987.02	10.7	2.116	1988	2.2	94.3	10
07	7	116.19	101.45	1991.55	10.9	2.121	1949	2.2	108.2	11
08	7	116.24	101.48	1989.56	10.9	2.116	2132	2.4	107.5	12
09	7	116.24	101.44	1985.81	11.0	2.114	1611	1.8	106.8	9
10	7	116.34	101.38	1968.23	11.0	2.096	2031	2.0	120.1	9
11	7	116.18	101.42	2004.50	10.9	2.136	1998	2.0	120.7	9
12	7	116.29	101.37	1976.62	10.9	2.106	1878	2.2	105.8	10
13	7	116.77	101.57	2008.70	11.0	2.123	1654	2.0	103.2	9
14	7	116.68	101.53	1997.00	11.0	2.114	1656	1.8	109.5	9
15	7	116.70	101.53	2023.30	11.0	2.142	1803	2.2	114.9	8
16	7	116.66	101.52	1986.80	11.0	2.104	1730	2.0	115.3	8
17	7	116.62	101.52	2008.71	11.1	2.128	1535	2.0	99.6	9
18	7	116.74	101.52	2000.68	11.1	2.118	1646	2.0	106.3	9
19	7	117.06	101.61	2001.53	11.1	2.109	1485	2.0	100.4	8
20	7	116.75	101.46	1985.51	11.1	2.104	1563	2.0	109.2	8
21	7	116.73	101.43	2012.43	11.2	2.134	2055	2.4	118.6	10
22	7	116.75	101.39	1993.37	11.2	2.115	1470	1.6	106.2	8
23	7	116.58	101.44	1999.30	11.1	2.122	1621	1.8	104.6	9
24	7	116.68	101.41	1997.03	11.1	2.119	1517	1.6	104.8	9
25	7	116.69	101.28	2013.51	11.1	2.142	1865	2.0	115.0	9
26	7	116.63	101.33	1991.20	11.1	2.117	1657	1.8	112.5	8
27	7	116.66	101.44	2003.88	11.1	2.126	1416	1.6	104.7	8
28	7	116.60	101.40	1991.03	11.1	2.115	1755	1.8	109.2	10
29	7	116.66	101.36	2011.79	11.1	2.137	1862	2.2	112.5	9
30	7	116.62	101.35	1998.50	11.1	2.124	1842	1.8	116.1	9

Table A.17 Unconfined Compressive Strength Variability: SV2-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	114.60	100.27	1939.52	12.0	2.143	2287	3.7	81.4	13
02	7	114.55	100.15	1932.92	12.0	2.142	2292	3.1	94.9	9
03	7	114.70	100.08	1930.94	11.9	2.140	2214	3.3	86.7	10
04	7	114.85	100.08	1930.90	11.9	2.137	2230	3.3	82.3	9
05	7	115.25	100.38	1930.23	11.9	2.117	2072	3.3	82.0	9
06	7	114.72	100.62	1930.51	11.9	2.116	2206	3.1	85.5	9
07	7	116.96	100.63	1919.35	11.8	2.064	1015	3.5	86.9	11
08	7	114.46	100.54	1930.61	11.8	2.125	2258	3.3	84.1	12
09	7	114.93	100.48	1926.75	11.7	2.114	1814	3.1	75.8	9
10	7	114.50	100.67	1929.85	11.7	2.118	2285	3.1	84.5	11
11	7	114.29	100.87	1930.21	11.9	2.113	1944	3.1	79.8	11
12	7	114.87	100.54	1931.11	11.9	2.117	2194	3.5	80.4	11
13	7	114.46	100.16	1930.22	11.8	2.140	2156	3.1	84.7	11
14	7	114.65	100.05	1930.48	11.8	2.142	2242	3.5	77.3	10
15	7	114.96	100.04	1931.20	11.7	2.137	2140	3.3	79.5	11
16	7	115.02	100.05	1930.39	11.7	2.135	2123	3.3	74.4	9
17	7	114.45	100.09	1931.28	11.8	2.145	2273	3.1	82.0	10
18	7	114.45	100.19	1931.58	11.8	2.141	2361	3.1	87.2	10
19	7	114.41	100.12	1930.85	11.9	2.143	2283	3.1	85.2	10
20	7	114.26	100.13	1930.57	11.9	2.146	2326	3.3	82.8	9
21	7	114.14	100.28	1930.60	11.8	2.142	2438	3.3	95.5	12
22	7	114.37	100.22	1931.33	11.8	2.141	2338	3.1	92.3	10
23	7	114.63	100.15	1929.05	11.8	2.136	2200	3.0	90.6	11
24	7	114.70	100.11	1930.66	11.8	2.139	2229	3.3	85.3	12
25	7	114.51	100.74	1930.04	11.9	2.115	2260	3.3	85.5	10
26	7	114.26	100.13	1930.57	11.9	2.146	2200	3.3	79.8	10
27	7	114.14	100.28	1930.60	11.9	2.142	2229	3.3	79.4	11
28	7	114.37	100.22	1931.33	12.1	2.141	2260	3.3	82.1	11
29	7	114.63	100.15	1929.05	12.1	2.136	2231	3.7	83.5	11
30	7	114.70	100.11	1930.66	11.9	2.139	2191	3.1	83.0	11

Table A.18 Unconfined Compressive Strength Variability: SV2-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	113.64	100.03	1856.92	13.9	2.079	2754	3.0	112.5	13
02	7	113.63	99.99	1856.84	13.9	2.081	2887	3.0	114.3	14
03	7	113.70	100.01	1856.11	13.8	2.078	2788	2.8	114.4	13
04	7	113.62	99.99	1856.65	13.8	2.081	2843	3.0	114.8	13
05	7	113.59	100.03	1855.75	13.8	2.079	2428	2.8	106.7	13
06	7	113.23	99.97	1838.30	13.8	2.068	2790	3.0	115.3	13
07	7	113.85	100.03	1855.41	13.8	2.074	2711	2.8	112.8	13
08	7	113.35	99.76	1855.81	13.8	2.095	2928	3.0	116.8	14
09	7	113.76	99.99	1855.32	13.9	2.077	2707	3.0	108.8	14
10	7	113.46	99.92	1855.01	13.9	2.085	2722	2.8	112.4	13
11	7	114.36	100.03	1855.20	13.8	2.064	2553	2.8	107.6	13
12	7	113.64	100.03	1855.46	13.8	2.078	2830	3.0	114.1	14
13	7	113.74	100.00	1855.57	13.9	2.077	2636	2.8	111.1	13
14	7	113.47	100.00	1855.66	13.9	2.082	2875	3.0	113.6	14
15	7	113.85	100.00	1854.88	13.9	2.075	2636	2.8	108.7	14
16	7	113.68	99.95	1855.20	13.9	2.080	2981	3.0	117.4	14
17	7	114.56	99.96	1855.06	13.8	2.063	2823	2.8	115.1	13
18	7	114.53	99.92	1855.11	13.8	2.066	2972	3.0	118.7	14
19	7	114.39	99.95	1854.78	14.1	2.067	2454	2.8	109.4	12
20	7	114.36	99.95	1855.25	14.1	2.068	2568	2.8	109.9	12
21	7	114.61	100.03	1853.88	13.9	2.058	2721	2.8	114.8	13
22	7	114.69	100.06	1854.49	13.9	2.056	2704	2.8	114.9	13
23	7	114.45	100.12	1855.97	13.8	2.060	2820	3.0	116.3	13
24	7	114.39	100.00	1855.22	13.8	2.065	2843	3.0	117.0	13
25	7	114.46	100.14	1855.20	14.0	2.058	2303	2.6	106.1	12
26	7	114.47	100.14	1855.19	14.0	2.058	2466	2.6	110.5	12
27	7	114.76	100.14	1855.33	13.9	2.053	2623	2.8	111.9	13
28	7	114.50	100.18	1855.13	13.9	2.056	2784	3.0	114.9	13
29	7	114.80	100.14	1855.62	13.9	2.052	2564	2.6	110.7	13
30	7	114.96	100.14	1873.33	13.9	2.069	2873	3.0	117.0	13

Table A.19 Unconfined Compressive Strength Variability: SV2-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	114.15	100.32	1951.62	11.5	2.163	2727	3.3	96.0	15
02	7	114.09	100.33	1951.67	11.5	2.164	2565	3.0	101.2	14
03	7	114.60	100.28	1950.89	11.6	2.155	2518	3.1	89.7	15
04	7	114.14	100.29	1951.17	11.6	2.164	2805	3.3	95.2	16
05	7	114.31	100.28	1949.92	11.6	2.160	2611	3.1	96.5	15
06	7	114.33	100.23	1950.64	11.6	2.162	2472	3.0	92.6	15
07	7	114.00	100.10	1934.93	11.3	2.157	2869	3.1	97.1	16
08	7	113.95	100.11	1918.77	11.3	2.139	2961	3.1	111.1	15
09	7	114.30	100.15	1936.52	11.4	2.151	2547	3.1	92.5	15
10	7	114.33	100.13	1936.76	11.4	2.151	2635	3.1	91.6	15
11	7	113.86	100.16	1935.72	11.4	2.158	2536	2.8	110.0	7
12	7	113.84	100.16	1936.27	11.4	2.159	2877	2.8	115.0	12
13	7	113.82	100.15	1936.23	11.4	2.160	2807	3.0	105.7	15
14	7	114.07	100.14	1936.12	11.4	2.155	2797	2.8	110.4	14
15	7	113.97	100.14	1934.35	11.5	2.155	2759	3.0	109.3	14
16	7	114.05	100.14	1935.33	11.5	2.155	2726	2.8	105.8	15
17	7	114.24	100.32	1935.14	11.4	2.143	2538	2.6	105.9	14
18	7	114.01	100.15	1935.37	11.4	2.155	2709	3.0	109.6	14
19	7	113.83	100.41	1935.95	11.5	2.148	2701	3.0	110.1	14
20	7	114.14	100.12	1935.74	11.5	2.154	2819	2.8	113.0	14
21	7	114.21	100.18	1935.97	11.5	2.151	2556	3.0	98.9	15
22	7	113.50	100.12	1919.63	11.5	2.148	2787	3.0	109.2	15
23	7	114.33	100.15	1936.17	11.6	2.150	2542	2.8	100.9	14
24	7	114.07	100.17	1935.86	11.6	2.154	2806	3.0	109.5	15
25	7	114.07	100.23	1936.07	11.6	2.151	2775	2.8	111.4	14
26	7	114.00	100.22	1935.80	11.6	2.153	2884	2.8	113.3	14
27	7	114.27	100.15	1936.31	11.6	2.151	2682	3.0	99.7	15
28	7	113.63	100.15	1918.95	11.6	2.144	2991	3.0	117.1	15
29	7	114.14	100.16	1935.16	11.6	2.152	2530	3.0	94.5	15
30	7	113.73	100.18	1935.56	11.6	2.159	2610	2.6	108.0	14

Table A.20 Unconfined Compressive Strength Variability: SV4-PA5 TH Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.61	76.59	76.59	11.8	2.123	2381	1.7	197.3	8
02	7	150.59	76.59	76.59	11.8	2.133	2566	1.7	205.7	8
03	7	150.29	76.48	76.48	11.8	2.150	2593	1.7	203.7	9
04	7	150.34	76.41	76.41	11.8	2.144	2625	1.7	203.6	9
05	7	150.55	76.47	76.47	11.8	2.128	2426	1.5	201.1	9
06	7	150.62	76.55	76.55	11.8	2.130	2625	1.7	213.0	9
07	7	150.61	76.72	76.72	11.8	2.121	2484	1.7	208.2	8
08	7	150.58	76.62	76.62	11.8	2.120	2426	1.5	200.7	8
09	7	150.78	76.72	76.72	11.8	2.120	2318	1.5	217.9	7
10	7	150.61	76.64	76.64	11.8	2.131	2147	1.5	204.9	7
11	7	150.41	76.41	76.41	11.9	2.133	2569	1.7	200.7	9
12	7	150.46	76.44	76.44	11.9	2.128	2586	1.7	199.3	9
13	7	150.45	76.48	76.48	11.9	2.132	2425	1.5	206.1	8
14	7	150.48	76.54	76.54	11.9	2.127	1874	1.4	175.7	7
15	7	150.49	76.42	76.42	11.8	2.131	2392	1.5	186.6	9
16	7	150.45	76.42	76.42	11.8	2.136	2513	1.7	190.9	10
17	7	150.47	76.40	76.40	11.9	2.132	2514	1.7	198.5	9
18	7	150.45	76.40	76.40	11.9	2.133	2263	1.4	202.1	8
19	7	150.50	76.43	76.43	11.8	2.137	2317	1.5	186.2	9
20	7	150.51	76.46	76.46	11.8	2.131	2417	1.7	189.9	9
21	7	150.44	76.51	76.51	11.8	2.134	2349	1.5	193.4	9
22	7	150.41	76.50	76.50	11.8	2.122	2266	1.5	190.4	9
23	7	150.49	76.50	76.50	11.9	2.127	2275	1.5	187.2	9
24	7	150.49	76.47	76.47	11.9	2.130	2277	1.5	184.2	9
25	7	150.58	76.51	76.51	11.9	2.126	2256	1.5	188.2	9
26	7	150.63	76.53	76.53	11.9	2.127	2478	1.5	208.6	8
27	7	150.65	76.46	76.46	11.9	2.143	2566	1.5	233.0	8
28	7	150.58	76.52	76.52	11.9	2.136	2469	1.5	207.5	8
29	7	150.72	76.56	76.56	11.8	2.134	2466	1.5	206.4	8
30	7	150.67	76.54	76.54	11.8	2.137	2486	1.5	198.0	9

Table A.21 Unconfined Compressive Strength Variability: SV4-PB5 TH Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.08	76.48	1426.68	13.6	2.070	2704	1.5	217.5	8
02	7	150.14	76.50	1423.04	13.6	2.062	2666	1.5	210.1	9
03	7	150.18	76.62	1422.28	13.8	2.054	2713	1.7	208.5	8
04	7	149.98	76.75	1423.73	13.8	2.052	2731	1.7	212.3	8
05	7	150.24	76.68	1425.24	13.8	2.055	2579	1.5	199.5	8
06	7	150.36	76.76	1427.80	13.8	2.052	2777	1.7	202.6	9
07	7	150.15	76.64	1423.98	13.8	2.056	2739	1.5	217.6	8
08	7	150.27	76.60	1421.00	13.8	2.052	2742	1.5	216.1	8
09	7	150.25	76.42	1422.68	14.0	2.064	2624	1.5	205.5	8
10	7	150.15	76.69	1428.48	14.0	2.060	2856	1.5	218.2	8
11	7	150.27	76.67	1430.56	14.1	2.062	2857	1.7	217.6	8
12	7	150.14	76.64	1422.38	14.1	2.054	2656	1.7	210.3	8
13	7	150.56	76.55	1430.35	13.7	2.065	2236	1.4	211.9	7
14	7	150.53	76.53	1429.56	13.7	2.065	2608	1.5	215.1	7
15	7	150.59	76.69	1424.20	13.7	2.048	2190	1.5	196.6	7
16	7	150.46	76.55	1418.64	13.7	2.049	2180	1.5	190.9	7
17	7	150.48	76.20	1417.53	13.8	2.066	2163	1.5	190.1	7
18	7	150.44	76.53	1415.95	13.8	2.046	2153	1.4	199.1	7
19	7	150.36	76.52	1414.13	13.7	2.045	2107	1.4	186.6	7
20	7	150.55	76.57	1420.24	13.7	2.049	2410	1.5	217.7	7
21	7	150.57	76.52	1417.98	13.8	2.048	2219	1.5	196.5	7
22	7	150.65	76.63	1415.33	13.8	2.037	2259	2.0	144.8	9
23	7	150.55	76.54	1418.67	13.7	2.048	2366	1.5	193.9	9
24	7	150.54	76.56	1416.50	13.7	2.044	2318	1.5	198.5	8
25	7	150.55	76.52	1415.41	13.7	2.044	2348	1.5	196.6	8
26	7	150.45	76.63	1415.89	13.7	2.040	2379	1.5	203.2	8
27	7	150.54	76.59	1419.20	15.1	2.046	2187	1.5	202.2	9
28	7	150.47	76.59	1423.22	15.1	2.053	2539	1.5	193.4	9
29	7	150.49	76.48	1429.00	13.9	2.067	2174	1.5	184.7	7
30	7	150.38	76.39	1419.62	13.9	2.060	2217	1.4	196.7	7

Table A.22 Unconfined Compressive Strength Variability: SV4-PC4 TH Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.25	76.70	1481.31	10.9	2.134	3218	1.8	221.1	11
02	7	150.04	76.77	1480.81	10.9	2.132	3371	2.5	160.1	14
03	7	150.28	76.65	1475.45	10.8	2.128	3130	2.5	149.5	14
04	7	150.20	76.63	1480.14	10.8	2.137	3477	3.0	150.2	16
05	7	150.32	76.59	1483.08	10.9	2.141	3307	1.1	354.4	7
06	7	150.20	76.57	1477.42	10.9	2.136	3308	2.8	136.7	16
07	7	150.21	76.66	1478.53	10.8	2.132	3265	3.1	128.5	18
08	7	150.43	76.81	1480.67	10.8	2.124	3303	3.0	133.4	18
09	7	150.13	76.57	1471.56	10.9	2.129	3093	2.8	132.4	16
10	7	150.48	76.69	1472.66	10.9	2.119	3033	2.8	135.7	16
11	7	150.29	76.61	1479.58	11.1	2.136	3478	3.0	144.4	16
12	7	150.39	76.81	1484.77	11.1	2.131	3195	2.8	140.1	16
13	7	149.81	76.63	1469.40	10.8	2.127	3282	3.1	138.6	16
14	7	150.30	76.73	1475.75	10.8	2.123	3158	2.8	144.5	15
15	7	150.39	76.46	1482.33	11.0	2.147	3412	1.7	243.7	10
16	7	150.59	76.59	1484.47	11.0	2.140	3379	1.8	224.1	11
17	7	150.70	76.71	1483.76	11.2	2.130	2930	1.7	205.3	11
18	7	150.57	76.54	1480.38	11.2	2.137	3203	1.8	214.1	11
19	7	150.17	76.30	1482.68	11.1	2.160	3333	2.0	223.5	11
20	7	150.41	76.39	1474.74	11.1	2.140	2492	1.5	202.0	9
21	7	150.38	76.61	1481.04	11.2	2.137	3273	1.7	226.1	10
22	7	150.44	76.57	1482.26	11.2	2.140	3314	1.8	208.1	11
23	7	150.58	76.51	1483.77	11.2	2.143	3348	1.8	216.3	11
24	7	150.57	76.53	1482.05	11.2	2.140	3252	1.8	216.1	11
25	7	150.43	76.56	1485.61	11.2	2.145	3239	1.8	218.9	11
26	7	150.40	76.63	1482.50	11.2	2.137	3212	1.7	224.0	10
27	7	150.27	76.60	1482.65	11.2	2.141	3281	1.8	226.7	9
28	7	150.30	76.64	1484.18	11.2	2.141	2992	1.8	224.0	10
29	7	150.27	76.60	1481.27	11.3	2.139	3157	1.8	201.8	11
30	7	150.22	76.62	1480.86	11.3	2.138	2958	1.5	232.5	10

Table A.23 Unconfined Compressive Strength Variability: SV4-PA5 GV Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.67	76.53	1479.97	11.8	2.135	2394	1.5	207.2	8
02	7	150.55	76.42	1479.46	11.8	2.143	2494	1.5	214.7	8
03	7	150.72	76.52	1474.84	11.7	2.128	2330	1.4	204.0	8
04	7	150.60	76.54	1480.41	11.7	2.137	2394	1.5	210.8	8
05	7	150.68	76.48	1479.40	11.8	2.137	2462	1.5	204.3	9
06	7	150.69	76.50	1479.19	11.8	2.136	2387	1.5	192.3	9
07	7	150.69	76.54	1479.40	11.9	2.134	2431	1.7	199.1	9
08	7	150.65	76.55	1481.10	11.9	2.136	2504	1.5	206.9	9
09	7	150.76	76.55	1480.01	11.8	2.133	1864	1.7	154.8	8
10	7	150.64	76.54	1481.53	11.8	2.137	2217	1.4	213.7	7
11	7	150.67	76.51	1483.33	11.8	2.142	2238	1.4	214.1	7
12	7	150.68	76.54	1478.86	11.8	2.133	2180	1.5	202.8	7
13	7	150.73	76.54	1482.48	11.7	2.138	2199	1.4	213.2	7
14	7	150.74	76.48	1481.51	11.7	2.139	2416	1.5	204.7	8
15	7	150.74	76.56	1478.18	11.8	2.130	2337	1.5	204.3	8
16	7	150.68	76.51	1481.20	11.8	2.138	2367	1.5	208.1	8
17	7	150.62	76.49	1480.68	11.9	2.139	2276	1.5	200.1	8
18	7	150.69	76.52	1480.69	11.9	2.137	2283	1.7	200.0	8
19	7	150.67	76.53	1480.98	11.9	2.137	2348	1.5	219.9	7
20	7	150.65	76.61	1480.89	11.9	2.133	2334	1.5	216.3	7
21	7	150.81	76.51	1476.58	11.9	2.130	2210	1.5	203.4	7
22	7	150.69	76.48	1481.05	11.9	2.139	2304	1.5	208.1	7
23	7	150.72	76.51	1481.20	11.6	2.138	2275	1.4	206.0	8
24	7	150.84	76.47	1480.01	11.6	2.137	2380	1.4	218.8	8
25	7	150.71	76.49	1478.42	11.4	2.135	2165	1.4	199.5	8
26	7	150.75	76.54	1478.57	11.4	2.131	2338	1.5	204.2	8
27	7	150.79	76.50	1480.36	11.6	2.136	2238	1.4	212.7	7
28	7	150.74	76.50	1478.03	11.6	2.133	2238	1.4	213.9	7
29	7	150.80	76.54	1480.05	11.6	2.133	2227	1.5	191.3	8
30	7	150.75	76.46	1477.60	11.6	2.135	2222	1.5	198.0	8

Table A.24 Unconfined Compressive Strength Variability: SV4-PB5 GV Raw Data

Specimen ID	**Test Time (day)**	**H_{AVG} (mm)**	**D_{AVG} (mm)**	**Weight (g)**	**$\omega_{measured}$ (%)**	**γ (g/cm^3)**	**σ_{max} (kPa)**	**ε_{max} (%)**	**$E_{X\text{-}Head}$ (MPa)**	**$n_{X\text{-}Head}$**
01	7	150.94	76.75	1427.85	13.8	2.045	2750	1.7	204.7	8
02	7	150.87	76.80	1424.17	13.8	2.038	2737	1.5	217.9	8
03	7	150.92	76.71	1425.58	13.8	2.044	2771	1.5	228.5	7
04	7	150.46	76.87	1429.89	13.8	2.048	2797	1.7	22.6	7
05	7	150.63	76.80	1426.25	14.0	2.044	2700	1.7	205.9	9
06	7	150.54	76.79	1422.43	14.0	2.040	2562	1.5	211.8	8
07	7	150.48	76.80	1423.81	13.8	2.043	2442	1.5	191.7	8
08	7	150.40	76.89	1420.39	13.8	2.034	2584	1.5	203.2	8
09	7	150.46	76.83	1423.31	13.9	2.040	2569	1.5	207.4	8
10	7	150.62	76.81	1423.46	13.9	2.039	2625	1.7	194.5	9
11	7	148.87	76.76	1428.33	13.9	2.073	2767	1.5	222.5	8
12	7	150.50	76.66	1426.41	13.9	2.053	2922	1.8	212.8	9
13	7	150.52	76.81	1425.86	13.9	2.044	2681	1.5	221.3	7
14	7	150.58	76.79	1426.44	13.9	2.046	2636	1.5	216.0	7
15	7	150.66	76.77	1422.17	14.1	2.039	2665	1.7	207.4	8
16	7	150.53	76.74	1422.28	14.1	2.043	2833	1.7	217.0	8
17	7	150.54	76.71	1426.78	14.0	2.051	2845	1.7	222.7	8
18	7	150.67	76.74	1427.80	14.0	2.049	2824	1.7	219.3	8
19	7	150.59	76.76	1426.75	14.0	2.048	2740	1.7	210.8	8
20	7	150.60	76.84	1424.08	14.0	2.039	2798	1.7	214.8	8
21	7	150.69	76.70	1424.18	13.8	2.046	3086	1.7	224.5	8
22	7	150.67	76.76	1422.16	13.8	2.040	2998	1.7	222.5	8
23	7	150.65	76.81	1424.82	13.8	2.041	3068	1.7	229.0	8
24	7	150.63	76.88	1419.89	13.8	2.031	3117	1.7	232.4	8
25	7	150.58	76.72	1423.86	13.9	2.045	3186	1.8	224.4	9
26	7	150.59	76.86	1422.98	13.9	2.036	3100	1.7	223.3	9
27	7	150.52	76.82	1430.70	13.9	2.051	3086	1.8	225.8	9
28	7	150.60	76.77	1426.81	13.9	2.047	3089	1.7	232.9	9
29	7	150.57	76.83	1426.48	13.9	2.043	3057	1.7	227.7	9
30	7	150.58	76.80	1422.24	13.9	2.039	2885	1.5	232.8	8

Table A.25 Unconfined Compressive Strength Variability: SV4-PC4 GV Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.72	76.63	1485.30	11.0	2.137	2018	1.3	212.9	7
02	7	150.63	76.59	1489.22	11.0	2.146	2372	1.4	234.6	7
03	7	150.78	76.60	1487.39	11.3	2.141	2418	1.3	237.8	7
04	7	150.64	76.60	1487.75	11.3	2.143	2659	1.4	242.8	7
05	7	150.72	76.54	1486.98	11.2	2.144	2588	1.4	224.0	8
06	7	150.85	76.55	1492.63	11.2	2.150	2328	1.3	226.1	7
07	7	150.81	76.66	1491.90	11.5	2.144	2118	1.5	190.6	8
08	7	150.87	76.79	1486.44	11.5	2.128	2489	1.4	219.5	8
09	7	150.79	76.69	1487.94	11.5	2.136	2597	1.5	225.0	8
10	7	150.81	76.66	1492.34	11.5	2.144	2784	1.5	237.4	8
11	7	150.70	76.59	1493.04	11.5	2.150	2483	1.4	226.2	8
12	7	150.73	76.64	1493.22	11.5	2.148	2739	1.5	226.7	9
13	7	150.85	76.81	1493.29	11.6	2.137	2700	1.5	224.2	9
14	7	150.74	76.75	1494.31	11.6	2.143	2851	1.5	224.9	9
15	7	150.82	76.83	1496.20	11.6	2.140	3039	1.7	230.5	10
16	7	150.75	76.80	1493.53	11.6	2.139	3050	1.7	231.2	9
17	7	150.87	76.74	1487.77	11.5	2.132	2538	1.4	222.6	8
18	7	150.78	76.75	1480.12	11.5	2.122	2261	1.3	203.2	8
19	7	150.83	76.79	1490.13	11.6	2.133	2775	1.5	237.1	8
20	7	150.77	76.66	1488.86	11.6	2.140	3098	1.5	239.8	9
21	7	150.79	76.75	1480.80	11.6	2.123	2390	1.4	221.7	8
22	7	150.97	76.86	1482.94	11.6	2.117	2355	1.4	205.2	8
23	7	150.84	76.73	1491.80	11.2	2.139	2853	1.5	225.2	9
24	7	150.89	76.73	1486.80	11.2	2.131	2714	1.5	220.7	9
25	7	150.80	76.73	1491.15	11.2	2.139	2964	1.5	240.9	9
26	7	150.80	76.73	1489.50	11.2	2.136	2889	1.5	233.4	9
27	7	150.92	76.73	1490.75	11.2	2.136	2991	1.5	242.2	9
28	7	150.68	76.75	1491.65	11.2	2.140	3073	1.5	244.2	9
29	7	150.79	76.73	1491.09	11.2	2.138	2954	1.5	243.0	9
30	7	150.76	76.69	1487.10	11.2	2.135	2939	1.5	238.0	9

Table A.26 Unconfined Compressive Strength Variability: SVM1-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.76	101.35	2007.57	11.8	2.131	2085	2.7	101.7	10
02	7	116.82	101.53	2008.16	11.8	2.123	2183	2.7	106.8	10
03	7	115.76	101.68	1999.13	11.8	2.127	2055	3.1	88.9	12
04	7	116.07	101.50	1991.73	11.8	2.121	2116	3.1	85.8	13
05	7	115.96	101.54	1991.79	11.8	2.121	2024	3.1	85.1	13
06	7	116.12	101.55	1998.54	11.8	2.125	2171	3.1	90.5	13
07	7	115.72	101.43	1977.33	11.9	2.115	1828	2.7	82.1	12
08	7	115.84	101.42	1979.13	11.9	2.115	1966	2.9	87.3	12
09	7	116.72	101.36	2016.71	11.8	2.142	1809	2.6	89.4	11
10	7	116.55	101.43	1998.99	11.8	2.123	2002	2.6	98.3	11
11	7	115.31	101.40	1987.34	11.9	2.134	2130	2.9	87.2	13
12	7	115.31	100.94	1984.52	11.9	2.151	2129	3.1	87.3	13
13	7	116.41	101.52	2002.58	12.0	2.125	1899	2.6	97.1	10
14	7	116.60	101.50	2000.15	12.0	2.120	1883	2.4	94.4	11
15	7	117.03	101.53	2004.75	11.7	2.116	1982	2.9	88.9	11
16	7	116.46	101.55	1998.87	11.7	2.119	2240	2.7	107.1	10
17	7	116.81	101.64	2003.66	11.9	2.114	1794	2.6	96.0	9
18	7	116.49	101.56	1997.03	11.9	2.116	1960	2.7	99.5	10
19	7	116.61	101.43	2004.85	11.9	2.128	1727	2.7	85.3	10
20	7	116.64	101.46	2001.00	11.9	2.122	2059	2.7	101.7	10
21	7	116.66	101.40	2005.40	12.0	2.129	1876	2.6	94.2	10
22	7	116.57	101.41	2009.49	12.0	2.135	2008	2.7	94.3	10
23	7	116.65	101.46	2005.90	12.0	2.127	1896	2.7	91.9	10
24	7	116.63	101.41	2006.21	12.0	2.130	1887	2.6	93.3	11
25	7	116.08	101.75	2009.52	11.9	2.129	1822	2.6	86.9	11
26	7	116.78	101.50	2005.42	11.9	2.122	1910	2.7	90.1	11
27	7	116.42	101.34	2015.24	11.9	2.146	2164	2.9	98.9	11
28	7	116.65	101.47	2002.47	11.9	2.123	1879	2.6	96.2	10
29	7	116.79	101.49	2008.74	11.8	2.126	1947	2.6	96.1	10
30	7	116.71	101.48	2006.38	11.8	2.125	2027	2.6	97.2	11

Table A.27 Unconfined Compressive Strength Variability: SVM1-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01*	7	116.40	101.14	1910.21	14.0	2.043	2152	2.2	117.2	8
02*	7	116.64	101.41	1890.98	13.9	2.007	1823	2.0	117.2	8
03	7	116.78	101.43	1913.84	13.9	2.028	1944	2.2	104.8	8
04	7	116.43	101.49	1901.42	13.9	2.019	1736	2.4	89.4	9
05	7	116.55	101.46	1940.12	14.4	2.059	1716	2.0	104.7	8
06	7	116.58	101.42	1926.06	14.4	2.045	1818	2.0	106.9	8
07	7	116.68	101.35	1956.18	14.2	2.078	1910	2.4	98.4	8
08	7	116.71	101.34	1928.05	14.2	2.048	1821	2.2	100.0	8
09	7	116.67	101.29	1947.30	14.2	2.071	1992	2.4	104.0	9
10	7	116.67	101.23	1925.27	14.2	2.050	1893	2.2	107.7	8
11	7	116.70	101.33	1946.29	14.2	2.068	2038	2.6	100.6	9
12	7	116.58	101.27	1915.28	14.2	2.040	2094	2.6	116.2	7
13	7	116.78	101.43	1928.88	14.2	2.044	1812	2.2	110.8	7
14	7	116.71	101.35	1923.94	14.2	2.043	1556	2.0	105.5	6
15	7	116.71	101.34	1942.71	14.1	2.064	1694	2.2	102.3	7
16	7	116.67	101.35	1920.16	14.1	2.040	1619	2.0	101.0	7
17	7	116.71	101.37	1939.62	14.1	2.059	1587	2.0	92.9	8
18	7	116.78	101.32	1933.87	14.1	2.054	1742	2.2	100.4	8
19	7	116.68	101.24	1929.38	14.1	2.054	1458	2.0	92.9	8
20	7	116.67	101.32	1927.76	14.1	2.049	1482	1.8	98.2	8
21	7	116.75	101.37	1936.50	14.2	2.055	1534	2.0	95.5	8
22	7	116.75	101.30	1918.32	14.2	2.039	1541	1.8	104.3	4
23	7	116.72	101.32	1936.82	14.2	2.058	1774	2.0	105.8	7
24	7	116.59	101.33	1914.95	14.2	2.037	1546	2.0	98.3	7
25	7	116.73	101.48	1955.18	14.4	2.071	1837	2.4	95.9	9
26	7	116.76	101.42	1943.15	14.4	2.060	1564	2.0	99.6	8
27	7	116.75	101.38	1966.79	14.2	2.087	1740	2.2	97.0	8
28	7	116.68	101.43	1947.78	14.2	2.066	1553	2.0	99.7	8
29	7	116.66	101.35	1960.52	14.4	2.083	1778	2.4	91.8	8
30	7	116.39	101.41	1949.37	14.4	2.074	2241	2.6	107.5	10

Single specimen batch.

Table A.28 Unconfined Compressive Strength Variability: SVM1-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	116.49	101.43	2014.21	11.5	2.140	1807	2.4	93.4	11
02	7	116.59	101.44	2008.19	11.5	2.131	2118	2.4	104.0	11
03	7	116.42	101.46	2013.42	11.5	2.139	2027	2.4	103.2	11
04	7	116.34	101.47	2008.01	11.5	2.135	2101	2.4	108.6	10
05	7	116.41	101.37	2009.80	11.7	2.139	1878	2.2	101.3	10
06	7	116.39	101.40	2012.20	11.7	2.141	1977	2.4	103.9	10
07	7	116.40	101.43	2020.67	11.6	2.148	2192	2.4	105.1	12
08	7	116.26	101.33	1995.92	11.6	2.129	2107	2.4	108.2	11
09	7	116.41	101.40	2020.23	11.7	2.149	2215	2.6	104.5	12
10	7	116.40	101.38	1999.30	11.7	2.128	2142	2.2	110.1	11
11*	7	116.63	101.34	2032.82	11.7	2.161	1963	2.6	93.5	12
12*	7	116.75	101.60	2013.80	11.6	2.128	1764	2.2	100.7	9
13	7	116.71	101.39	2030.62	11.6	2.155	1993	2.6	94.7	11
14	7	116.94	101.45	2015.11	11.6	2.132	1558	1.8	96.1	9
15	7	116.66	101.40	2017.62	11.6	2.142	1517	2.2	88.3	9
16	7	116.78	101.49	2022.49	11.6	2.141	1705	2.0	94.3	11
17	7	116.55	101.42	2021.26	11.6	2.147	1633	2.2	90.7	10
18	7	116.75	101.37	2026.57	11.6	2.151	1576	2.4	92.5	8
19	7	116.63	101.44	2026.26	11.6	2.150	1981	2.6	92.7	12
20	7	116.73	101.41	2026.65	11.6	2.150	1818	2.4	93.4	11
21	7	116.66	101.38	2027.57	11.6	2.153	1766	2.4	88.2	11
22	7	116.74	101.43	2024.02	11.6	2.146	1749	2.4	93.5	10
23	7	116.60	101.34	2026.34	11.6	2.155	1778	2.2	92.9	11
24	7	116.69	101.43	2024.41	11.6	2.147	1913	2.4	97.6	11
25	7	116.86	101.37	2027.97	11.6	2.150	1735	2.4	71.7	11
26	7	116.73	101.39	2021.24	11.6	2.145	1925	2.4	94.9	12
27	7	116.67	101.45	2039.75	11.6	2.163	2075	2.6	93.0	13
28	7	116.77	101.40	2032.00	11.6	2.155	1628	2.4	89.8	9
29	7	116.70	101.37	2042.87	11.7	2.169	2042	2.6	89.8	9
30	7	116.86	101.31	2033.21	11.7	2.158	1578	2.0	90.0	9

**Single specimen batch.*

Table A.29 Unconfined Compressive Strength Variability: SV7-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.72	76.47	1460.72	11.6	2.110	2119	1.5	178.9	8
02	7	150.55	76.31	1458.22	11.6	2.118	2212	1.5	200.2	7
03	7	150.74	76.61	1461.87	11.9	2.104	2306	1.7	199.4	7
04	7	150.60	76.25	1465.26	11.9	2.131	2309	1.7	190.8	8
05	7	150.68	76.58	1467.07	12.1	2.114	2206	1.7	179.0	8
06	7	150.43	76.42	1468.26	12.1	2.128	2420	1.8	192.9	8
07	7	150.55	76.58	1463.81	12.0	2.111	2243	1.5	204.2	7
08	7	150.28	76.57	1470.85	11.9	2.126	2410	1.7	183.7	9
09	7	150.38	76.49	1456.62	11.9	2.108	2174	1.5	184.7	8
10	7	150.46	76.61	1460.57	12.1	2.106	2278	1.7	185.0	8
11	7	150.37	76.53	1466.24	12.1	2.120	2264	1.7	196.5	7
12	7	150.49	76.28	1459.64	12.1	2.122	2270	1.5	191.1	8
13	7	150.27	76.50	1457.25	12.1	2.110	2210	1.5	198.0	7
14	7	150.54	76.51	1455.81	12.3	2.103	2228	1.8	171.2	8
15	7	150.57	76.49	1470.03	12.3	2.125	2360	1.8	183.1	8
16	7	150.46	76.25	1455.40	11.9	2.119	2300	1.7	196.4	8
17	7	150.24	76.42	1475.91	11.9	2.142	2038	1.8	151.6	8
18	7	150.55	76.25	1461.00	12.0	2.125	2001	1.4	174.3	8
19	7	150.47	76.33	1460.73	12.0	2.121	1912	1.4	171.3	8
20	7	150.57	76.38	1456.67	11.9	2.112	1807	1.3	175.9	4
21	7	150.20	76.19	1463.02	11.9	2.137	1601	1.7	138.2	7
22	7	150.34	76.27	1451.45	12.0	2.113	1673	1.4	165.9	6
23*	7	150.39	76.54	1449.71	12.0	2.095	1577	1.3	162.7	7
24*	7	150.43	76.49	1464.84	12.0	2.119	2081	1.4	189.8	7
25	7	150.35	76.48	1463.61	12.0	2.119	2081	1.4	188.7	7
26	7	150.34	76.27	1453.77	12.0	2.117	1766	1.5	168.8	7
27	7	150.59	76.20	1447.70	12.0	2.108	1844	1.4	172.5	7
28	7	150.53	76.50	1451.21	12.0	2.098	1839	1.5	164.2	8
29	7	150.46	76.47	1464.44	12.0	2.119	1850	1.5	163.2	7
30	7	150.23	76.75	1445.61	11.6	2.080	1928	1.4	183.1	7

**Single specimen batch.*

Table A.30 Unconfined Compressive Strength Variability: SV7-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.71	76.56	1401.52	14.1	2.020	2247	1.7	178.4	8
02	7	150.85	76.50	1396.00	14.1	2.013	2108	1.4	186.6	8
03	7	150.83	76.73	1403.25	14.2	2.012	2132	1.7	164.3	9
04	7	150.70	76.61	1387.00	14.2	1.997	2093	1.4	181.9	8
05	7	150.55	76.52	1402.57	14.1	2.026	2172	1.5	174.9	9
06	7	150.79	76.36	1385.25	14.1	2.006	2004	1.4	175.0	8
07	7	150.73	76.19	1407.26	14.1	2.048	2041	1.5	175.0	8
08	7	150.72	76.27	1388.33	14.1	2.016	1915	1.4	175.9	8
09	7	150.69	76.24	1415.92	14.1	2.058	2338	1.7	179.7	9
10	7	151.24	76.63	1392.22	14.1	1.996	2074	1.4	179.9	8
11	7	150.84	76.42	1407.37	14.2	2.034	2094	1.4	186.2	8
12	7	150.89	76.42	1390.12	14.2	2.009	2159	1.4	189.2	8
13	7	150.74	76.60	1402.69	14.1	2.019	2251	1.4	198.8	8
14	7	150.76	76.57	1388.72	14.1	2.001	2067	1.5	177.8	9
15	7	150.76	76.49	1397.89	14.2	2.018	1960	1.7	171.7	8
16	7	150.53	76.35	1393.65	14.2	2.022	2126	1.4	189.6	8
17	7	150.67	76.38	1405.35	14.4	2.036	2236	1.4	193.8	8
18	7	150.64	76.46	1383.00	14.4	2.000	1748	1.3	178.4	7
19	7	150.47	76.34	1380.37	14.0	2.005	1670	1.7	138.4	7
20	7	150.66	76.60	1407.90	14.0	2.028	1630	1.3	166.9	7
21	7	150.65	76.64	1399.32	14.2	2.014	2063	1.4	182.9	8
22	7	150.74	76.63	1374.44	14.2	1.977	1796	1.4	165.3	7
23	7	150.72	76.39	1427.52	14.0	2.067	2189	1.8	154.2	9
24	7	150.81	76.51	1399.34	14.0	2.018	2145	1.5	175.2	9
25	7	150.65	76.27	1405.54	14.1	2.042	2093	1.5	166.9	9
26	7	150.79	76.48	1385.33	14.1	2.000	2007	1.5	174.1	9
27	7	150.77	76.45	1395.76	14.2	2.017	2037	1.4	185.1	8
28	7	150.81	76.42	1392.28	14.2	2.013	2047	1.4	178.7	8
29	7	150.87	76.39	1401.47	14.3	2.027	2282	1.4	193.3	9
30	7	150.76	76.48	1378.61	14.3	1.990	1942	1.5	157.5	8

Table A.31 Unconfined Compressive Strength Variability: SV7-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$
01	7	150.73	76.68	1487.93	11.5	2.138	2523	1.7	185.4	10
02	7	150.74	76.69	1478.15	11.5	2.123	2662	1.7	198.7	10
03	7	150.76	76.70	1494.43	11.5	2.145	2513	1.8	178.8	9
04	7	150.89	76.59	1474.18	11.5	2.120	2390	1.7	173.5	10
05	7	150.77	76.76	1491.42	11.6	2.138	2408	1.7	178.4	9
06	7	150.78	76.63	1483.86	11.6	2.134	2249	1.5	176.6	9
07*	7	150.60	76.64	1483.59	11.5	2.136	2369	1.7	182.5	9
08*	7	150.54	76.37	1484.58	11.5	2.153	2153	1.4	174.2	8
09	7	150.74	76.69	1484.92	11.7	2.133	2227	1.7	176.7	8
10	7	150.65	76.66	1482.49	11.7	2.132	2377	1.7	190.9	9
11	7	150.74	76.76	1472.98	11.6	2.111	2186	1.7	165.2	9
12	7	150.65	76.69	1471.75	11.6	2.115	2163	1.5	194.7	8
13	7	150.74	76.68	1489.13	11.6	2.139	2052	1.5	171.3	9
14	7	150.69	76.50	1475.94	11.6	2.131	2312	1.4	199.1	8
15	7	150.74	76.52	1481.50	11.7	2.137	2163	1.5	169.9	9
16	7	150.75	76.43	1472.82	11.7	2.129	2158	1.5	189.7	8
17	7	150.85	76.52	1484.05	11.8	2.139	2506	1.7	200.0	8
18	7	150.63	76.50	1470.24	11.8	2.124	2248	1.5	190.7	8
19	7	150.81	76.25	1475.33	11.5	2.142	2244	1.5	181.0	8
20	7	150.78	76.44	1467.74	11.5	2.121	2204	1.7	183.6	8
21	7	150.83	76.50	1478.83	11.6	2.133	2303	1.7	185.4	9
22	7	150.82	76.55	1461.65	11.6	2.106	2124	1.4	181.5	8
23	7	150.76	76.49	1482.86	11.6	2.141	2341	1.7	184.8	9
24	7	150.58	76.50	1461.90	11.6	2.112	2257	1.7	182.0	9
25	7	150.70	76.44	1472.37	11.7	2.129	2307	1.8	140.3	12
26	7	150.65	76.19	1457.58	11.7	2.122	2172	1.4	202.5	7
27	7	150.65	76.48	1492.84	11.5	2.157	2230	1.7	166.1	10
28	7	150.74	76.54	1465.06	11.5	2.112	2347	1.5	197.5	9
29	7	150.89	76.52	1476.89	11.8	2.128	2283	1.7	168.1	9
30	7	150.87	76.50	1457.80	11.8	2.102	2266	1.4	185.5	9

**Single specimen batch.*

Table A.32 Elastic Modulus: EM4-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$	E_{Comp} (MPa)	n_{Comp}
1	7	150.46	76.68	1477.68	12.1	2.127	2602	1.1	174.1	5	3860.7	6
2	28	150.25	76.53	1465.66	12.1	2.121	3005	1.7	214.1	10	5529.3	6
3	60	150.34	76.50	1479.44	12.0	2.141	3520	1.5	252.7	10	6284.6	6
4	7	150.54	76.54	1480.33	12.0	2.137	2527	1.0	179.4	5	4385.8	5
5	28	150.51	76.47	1480.12	12.1	2.141	3145	1.5	237.8	10	6718.9	6
6	60	150.46	76.54	1478.25	12.1	2.135	3510	1.7	236.5	11	7163.7	6
7	7	150.43	76.59	1479.43	12.2	2.135	2321	1.0	164.1	5	5476.5	6
8	28	150.17	76.50	1477.24	12.2	2.140	3183	1.7	229.7	10	6286.7	6
9*	60	150.29	76.57	1476.88	11.9	2.134	3697	1.7	255.7	9	5662.7	6

Single specimen batch.

Table A.33 Elastic Modulus: EM4-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$	E_{Comp} (MPa)	n_{Comp}
1	7	150.34	76.76	1424.21	14.3	2.047	2546	1.4	207.6	9	4416.5	5
2	28	150.26	76.81	1427.55	14.3	2.050	3248	1.5	227.5	10	4418.1	6
3	60	150.40	76.76	1428.98	14.2	2.053	3847	1.8	232.0	12	5398.0	7
4	7	150.48	76.86	1430.45	14.2	2.049	2565	1.4	205.4	8	4894.7	5
5	28	150.36	76.72	1431.70	14.2	2.060	3211	1.7	214.0	11	5973.9	6
6	60	150.45	76.76	1425.07	14.2	2.047	3557	1.7	237.2	10	5557.6	6
7	7	150.37	76.68	1429.24	14.3	2.058	2555	1.4	203.0	9	3965.1	5
8	28	150.39	76.76	1427.87	14.3	2.052	3229	1.5	217.4	9	5863.7	5
9*	60	150.27	76.70	1433.36	14.3	2.064	3978	1.8	241.7	11	5645.2	7

Single specimen batch.

Table A.34 Elastic Modulus: EM4-PC4 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$	E_{Comp} (MPa)	n_{Comp}
1	7	150.35	76.65	1501.33	11.4	2.164	2789	1.4	219.6	9	6781.8	5
2	28	150.37	76.64	1485.64	11.4	2.142	3538	1.5	249.2	11	8300.2	6
3	60	150.59	76.66	1489.88	11.6	2.144	3501	1.5	250.7	10	11896.3	6
4	7	150.44	76.70	1490.28	11.6	2.144	2593	1.4	226.1	8	6836.2	5
5	28	150.34	76.68	1484.27	11.6	2.138	3473	1.7	249.5	10	9140.8	6
6	60	150.35	76.66	1486.02	11.6	2.142	4287	1.8	261.8	12	10282.5	7
7	7	150.43	76.62	1485.66	11.7	2.142	2630	1.3	240.1	8	6249.1	5
8	28	150.47	76.79	1489.83	11.7	2.138	3491	1.5	242.9	11	9643.6	6
9*	60	150.66	76.44	1487.00	11.7	2.151	4184	1.7	268.5	11	10066.5	6

Single specimen batch.

Table A.35 Elastic Modulus: EM7-PA5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$	E_{Comp} (MPa)	n_{Comp}
1	7	150.20	76.60	1451.09	11.0	2.097	2293	1.7	158.5	10	4503.9	6
2	28	150.36	76.56	1464.43	11.0	2.116	3098	1.7	208.9	11	6567.4	6
3	60	150.06	76.20	1457.01	11.7	2.129	3351	1.7	230.8	11	6328.4	6
4	7	150.12	76.62	1457.86	11.7	2.106	2349	1.7	175.2	9	4431.3	6
5	28	150.32	76.33	1457.42	11.8	2.119	2649	1.7	190.3	9	6759.8	5
6	60	150.18	76.54	1440.94	11.8	2.085	2846	1.5	212.2	10	6394.0	5
7	7	150.18	76.66	1459.11	11.7	2.105	2293	1.8	157.9	10	6544.3	7
8	28	150.20	76.61	1468.08	11.7	2.120	3070	1.8	200.4	10	6375.4	5
9*	60	150.23	76.64	1449.46	11.7	2.092	3098	1.7	224.6	10	6666.3	6

Single specimen batch.

Table A.36 Elastic Modulus: EM7-PB5 Raw Data

Specimen ID	Test Time (day)	H_{AVG} (mm)	D_{AVG} (mm)	Weight (g)	$\omega_{measured}$ (%)	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	$n_{X\text{-}Head}$	E_{Comp} (MPa)	n_{Comp}
1	7	150.29	76.31	1399.52	13.9	2.036	2396	1.7	179.4	9	3322.5	6
2	28	150.25	76.20	1396.01	13.9	2.038	2733	1.7	178.6	11	4024.5	6
3	60	150.26	76.69	1407.53	14.1	2.028	3192	1.7	213.0	11	4860.9	6
4	7	150.56	76.45	1394.44	14.1	2.018	2134	1.7	153.6	10	3406.9	7
5	28	150.23	76.50	1389.15	13.8	2.012	2677	1.4	203.4	10	4059.6	5
6	60	150.33	76.21	1399.58	13.8	2.041	2977	1.7	192.1	11	4155.3	6
7	7	150.27	76.63	1389.89	14.0	2.006	2181	1.8	149.1	10	3033.3	7
8	28	150.39	76.70	1405.21	14.0	2.023	2892	1.5	187.1	9	5419.4	5
9*	60	150.63	76.46	1416.56	14.1	2.048	2846	1.8	192.1	11	4155.3	6

Single specimen batch.

Table A.37 Elastic Modulus: EM7-PC4 Raw Data

Specimen ID	Test Time (d)	Height (mm)	Diameter (mm)	Weight (g)	Measured ω %	γ (g/cm^3)	σ_{max} (kPa)	ε_{max} (%)	$E_{X\text{-}Head}$ (MPa)	n	E_{Comp} (MPa)	n
1	7	150.25	76.53	1469.95	11.5	2.127	2396	1.4	196.1	9	5243.4	5
2	28	150.39	76.43	1466.68	11.5	2.126	2686	1.4	213.9	9	6605.0	5
3	60	150.39	76.39	1479.08	11.5	2.146	3276	1.7	204.5	12	9222.7	6
4	7	150.38	76.55	1468.76	11.5	2.122	2686	1.7	191.8	10	5459.2	5
5	28	150.52	76.59	1492.99	11.5	2.153	3051	1.5	227.4	10	6879.9	5
6	60	150.25	76.62	1475.07	11.5	2.129	3454	1.5	237.0	11	8905.3	6
7	7	150.41	76.56	1483.57	11.5	2.143	2836	1.5	220.4	9	5137.6	5
8	28	150.33	76.63	1467.58	11.5	2.117	3117	1.5	233.3	10	7381.4	5
9*	60	150.44	76.60	1481.71	11.6	2.137	3491	1.5	240.7	11	7137.1	6

Single specimen batch.

APPENDIX B

UNCONFINED COMPRESSION HISTOGRAM AND NORMALITY PLOTS

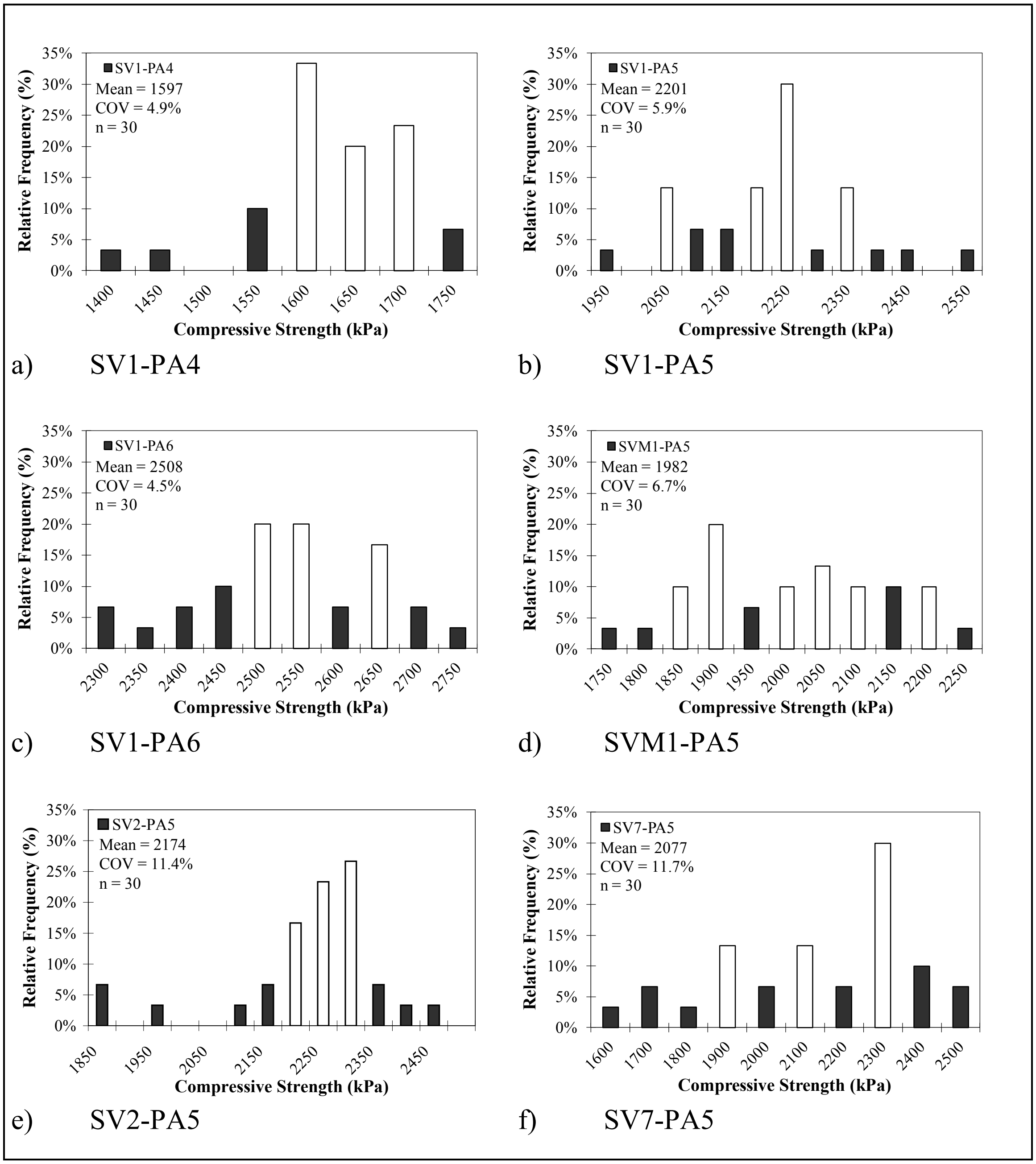


Figure B.1 *Pit A* Compressive Strength Histograms (TH T I/II) – All Data

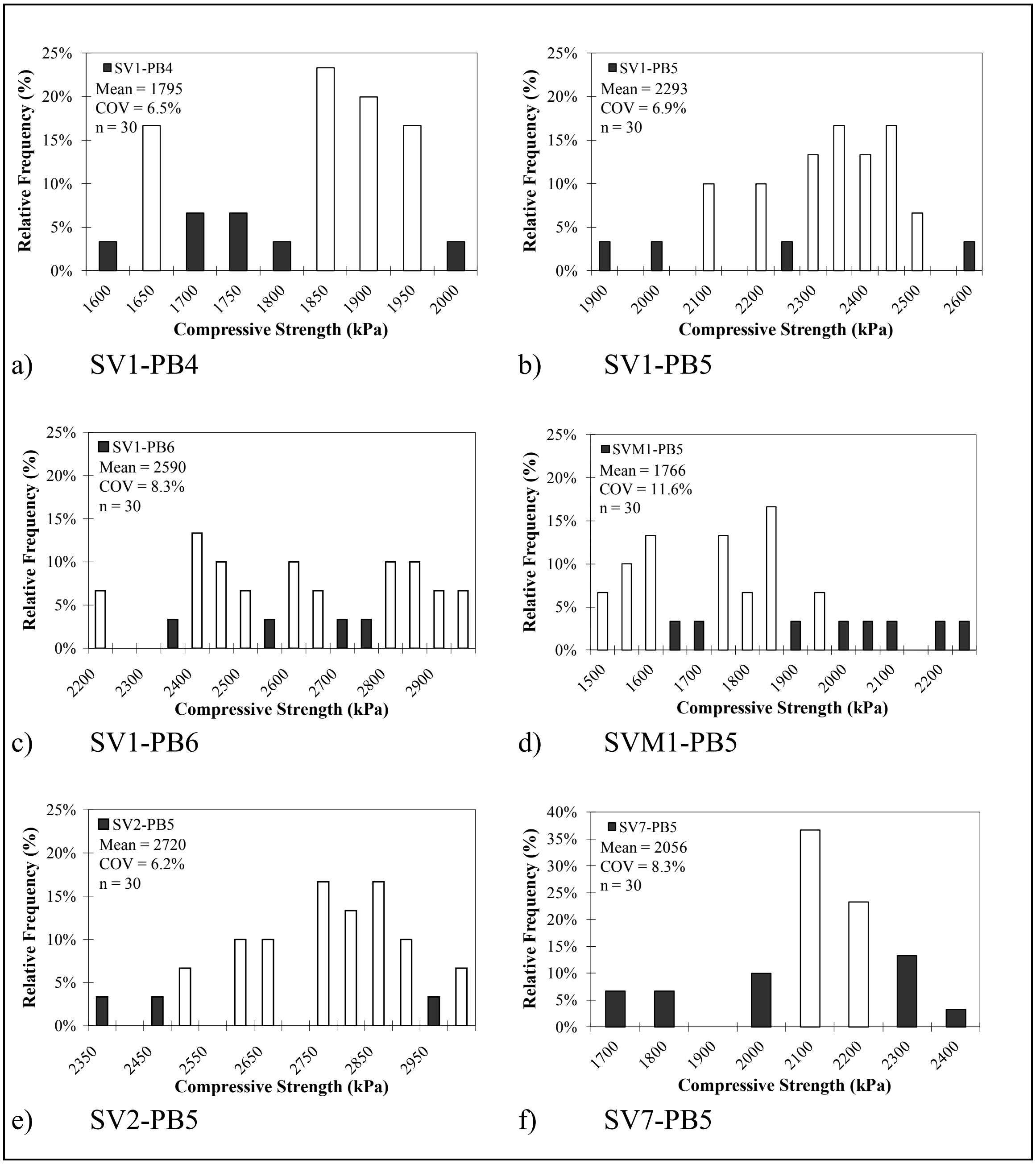


Figure B.2 *Pit B* Compressive Strength Histograms (TH T I/II) – All Data

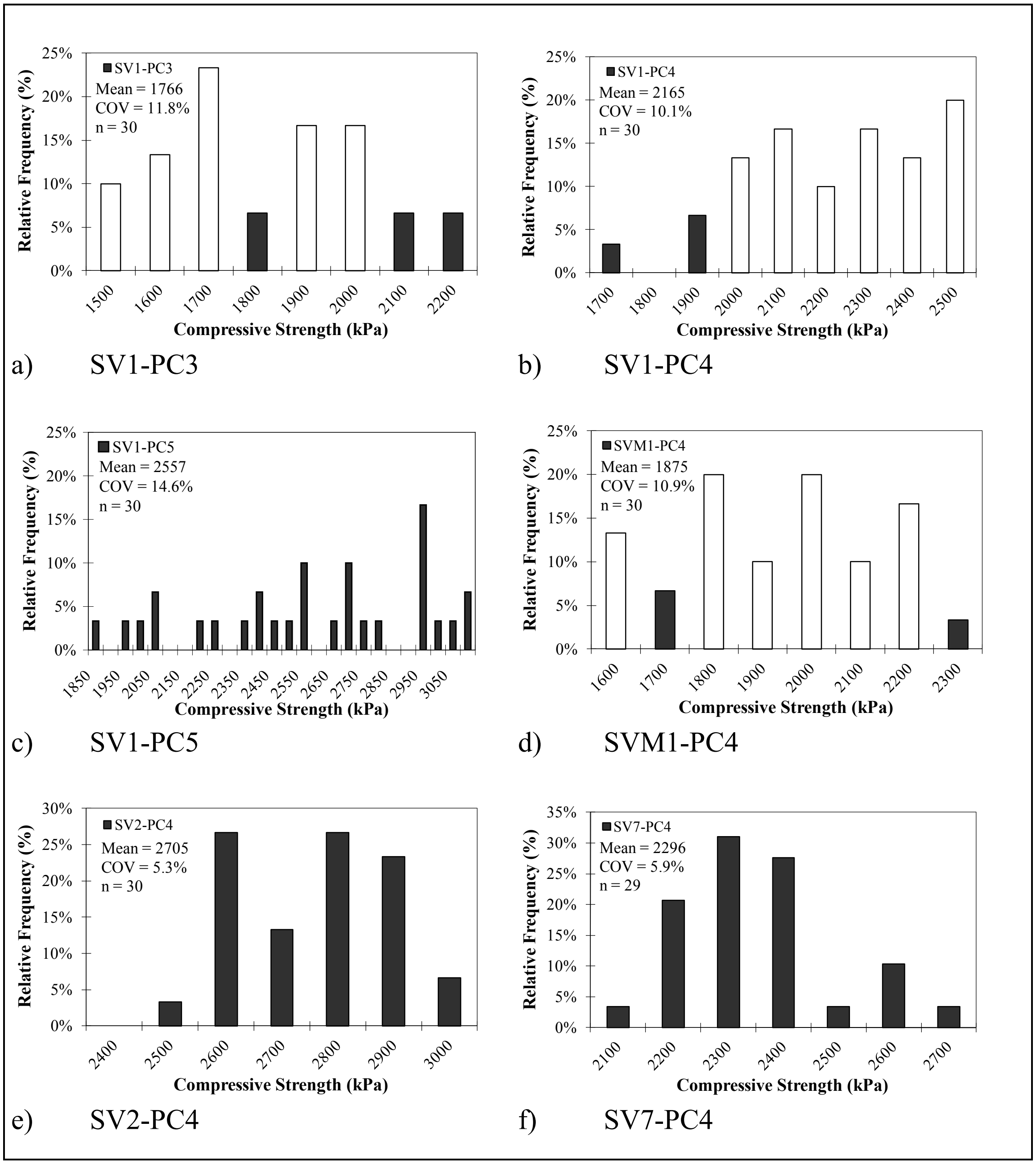


Figure B.3 *Pit C* Compressive Strength Histograms (TH T I/II) – All Data

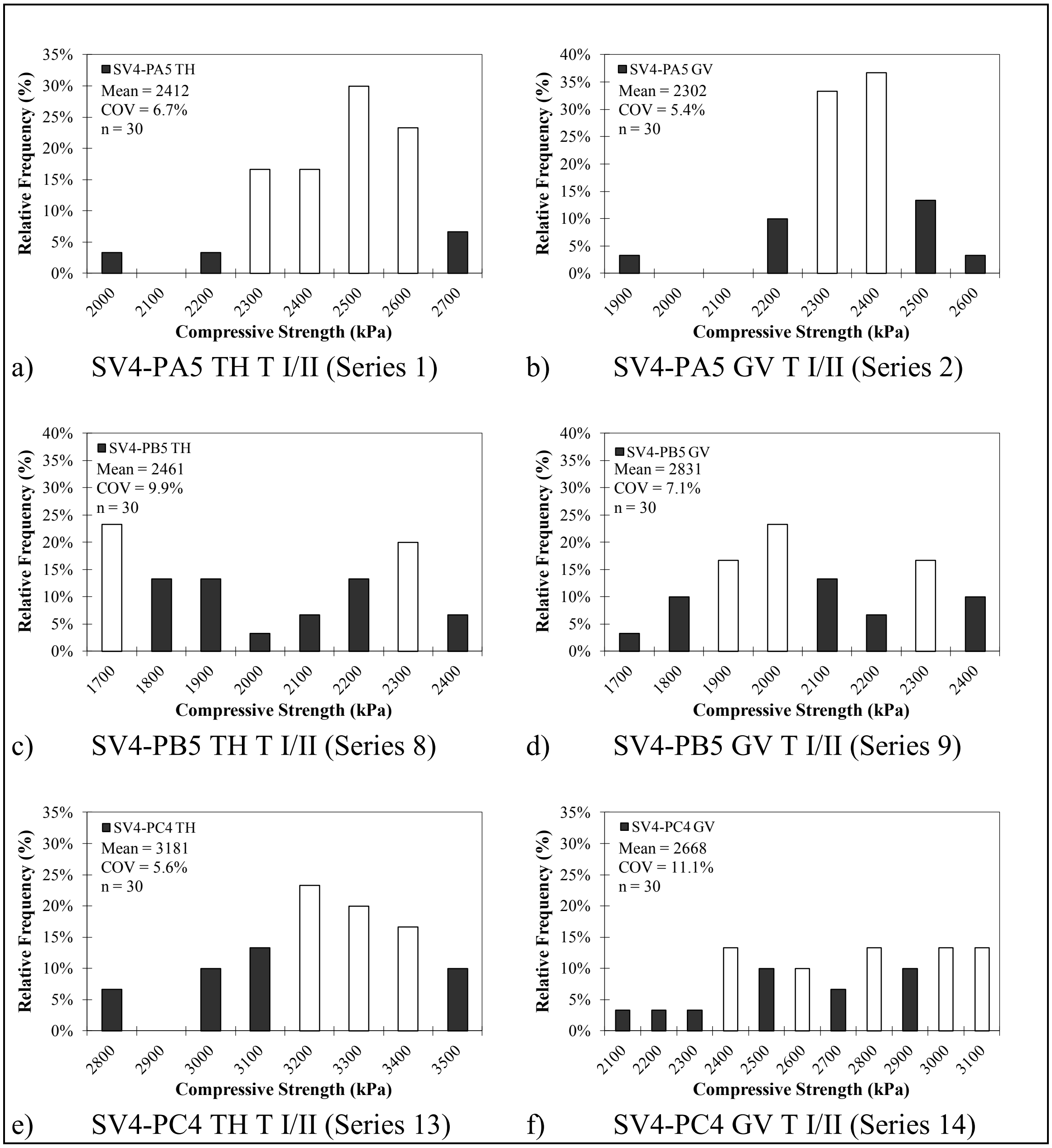


Figure B.4 Specimen Type 4 Compressive Strength Histograms (Series Number from Sullivan 2012) – All Data

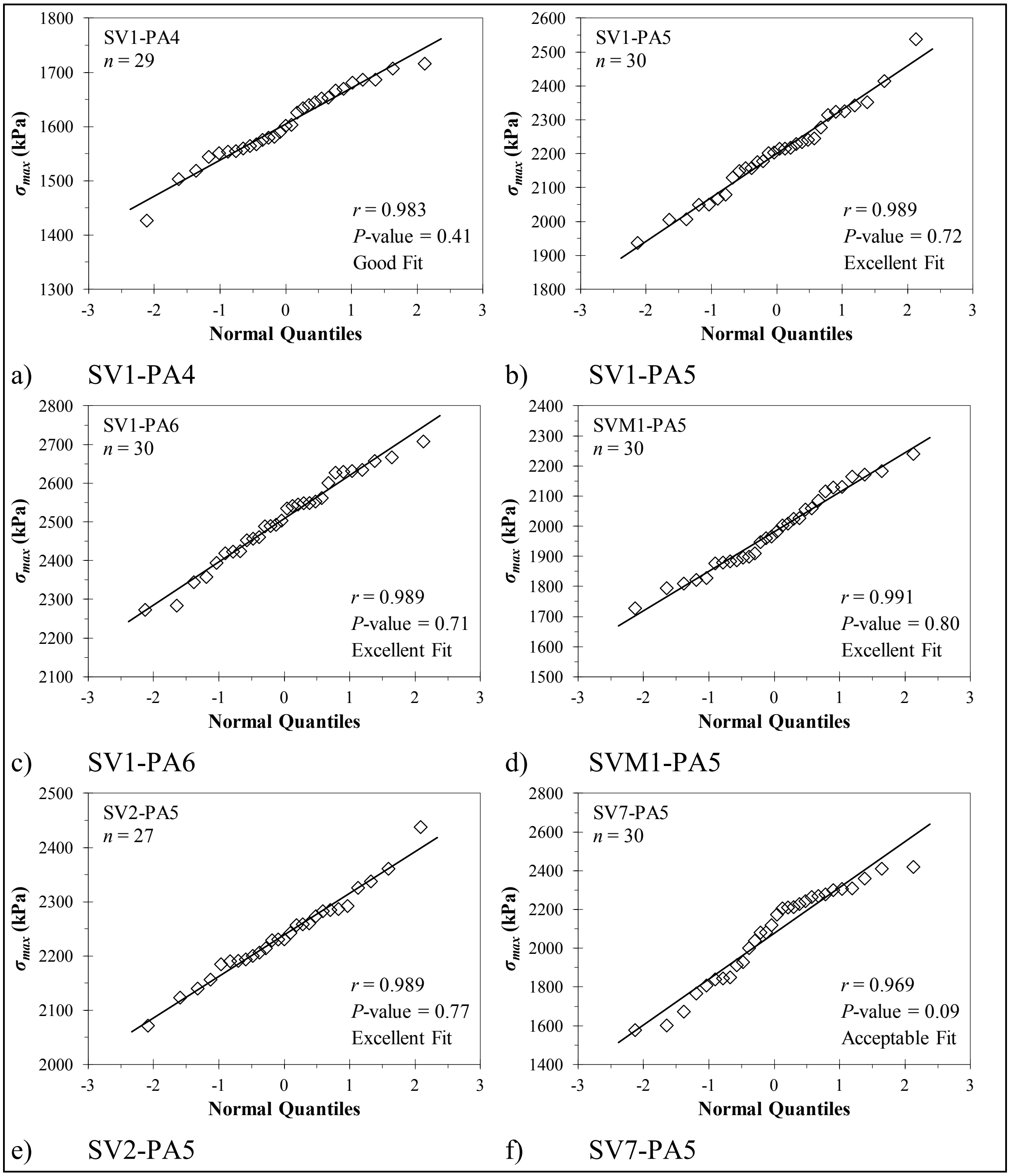


Figure B.5 *Pit A* Compressive Strength Normality Plots (TH T I/II)

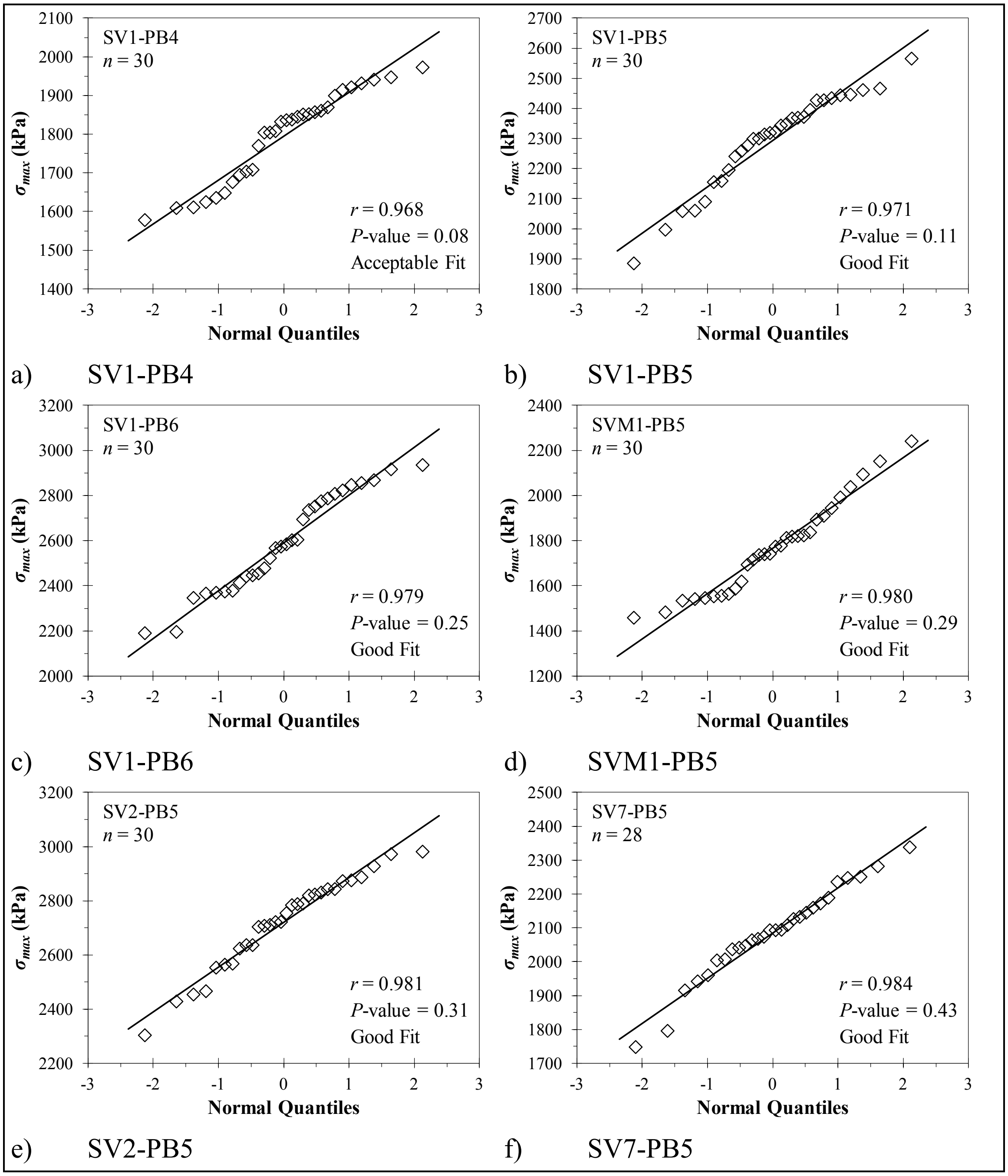


Figure B.6 *Pit B* Compressive Strength Normality Plots (TH T I/II)

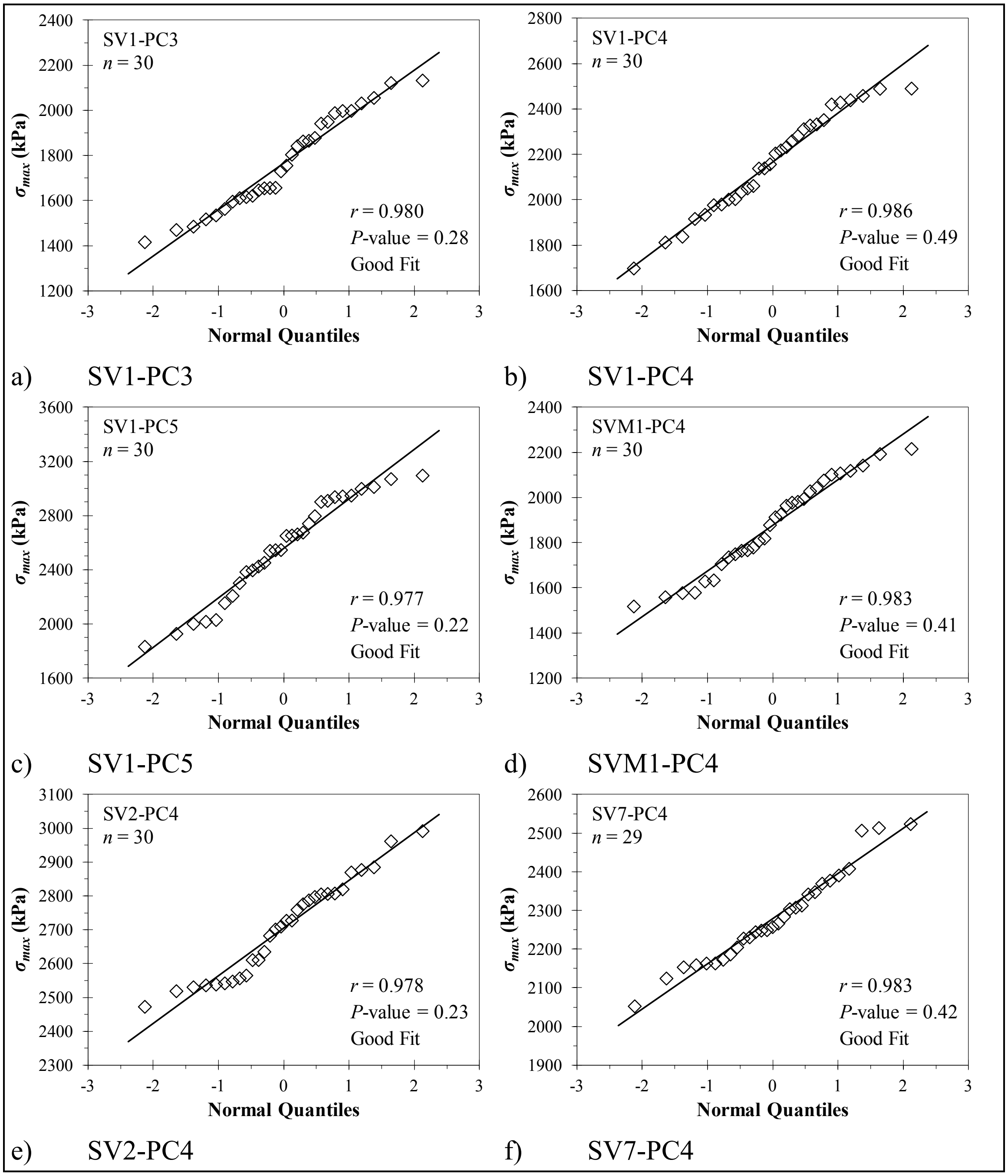
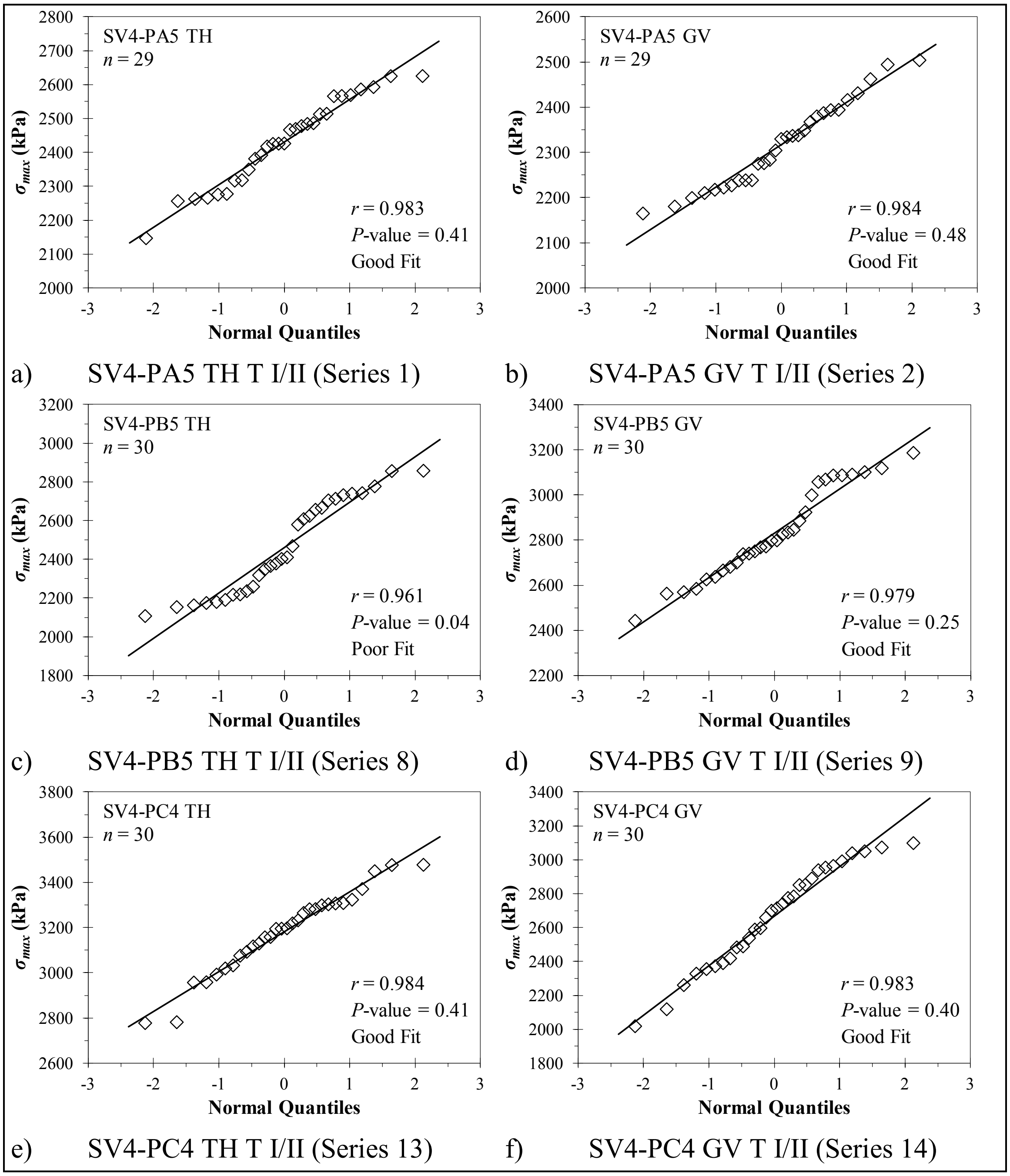


Figure B.7 *Pit C* Compressive Strength Normality Plots (TH T I/II)



a) SV4-PA5 TH T I/II (Series 1)

b) SV4-PA5 GV T I/II (Series 2)

c) SV4-PB5 TH T I/II (Series 8)

d) SV4-PB5 GV T I/II (Series 9)

e) SV4-PC4 TH T I/II (Series 13)

f) SV4-PC4 GV T I/II (Series 14)

Figure B.8 Specimen Type 4 Compressive Strength Normality Plots (Series Number from Sullivan 2012)

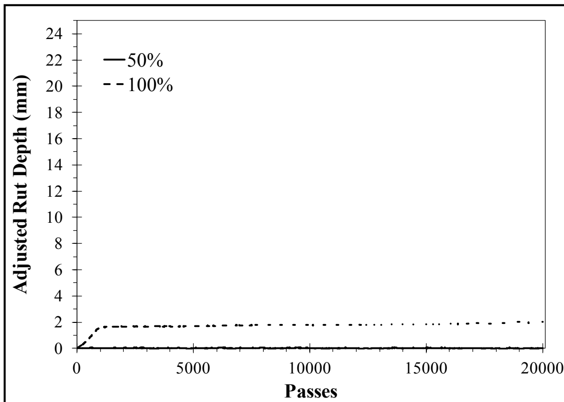
APPENDIX C

WHEEL TRACKING RAW DATA

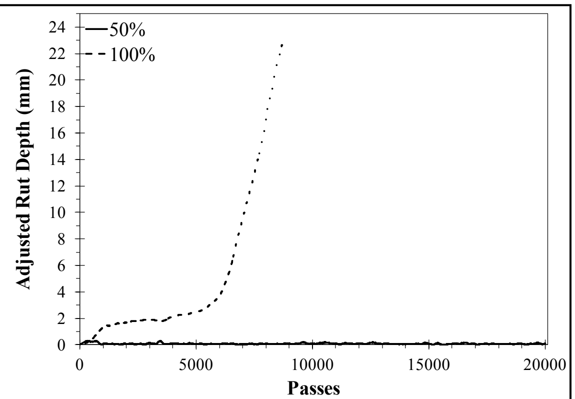
Table C.1. PURWheel Test Results for PW5-PA5-01

Dry Test (Test 098) γ = 2.217 g/cm³				**Submerged Test (Test 099) γ = 2.217 g/cm³**			
50% Load		**100% Load**		**50% Load**		**100% Load**	
Pass	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***
250	0.0	250	0.3	250	0.3	250	0.1
500	0.0	500	0.7	500	0.2	500	0.4
1000	0.0	1000	1.6	1000	0.1	1000	1.3
2000	0.0	2000	1.7	2000	0.1	2000	1.7
4000	0.0	4000	1.7	4000	0.1	4000	2.1
8000	0.1	8000	1.8	8000	0.1	8000	17.1
12000	0.0	12000	1.8	12000	0.1	8774	23.1
16000	0.0	16000	1.9	16000	0.1	---	---
20008	0.0	19998	2.0	20000	0.1	---	---

Wheel Load: 50% = 86.4 kg   *Test Temperature: 64 C*   ** Rut in mm*
Wheel Load: 100% = 176 kg   *Tire Pressure: 862 kPa*



a) Dry Test



b) Submerged Test

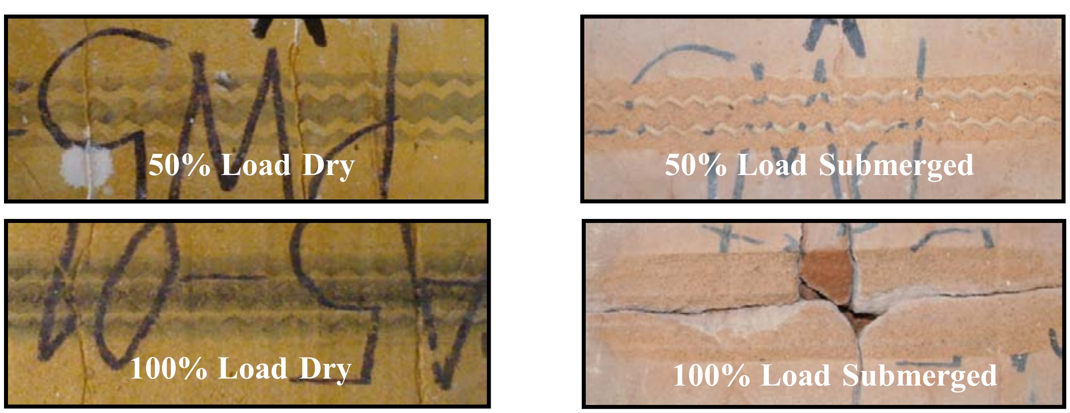


Figure C.1 PURWheel Test Results for PW5-PA5-01

Table C.2. PURWheel Test Results for PW5-PB5-01

Dry Test (Test 096) γ = 2.163 g/cm^3				Submerged Test (Test 097) γ = 2.163 g/cm^3			
50% Load		**100% Load**		**50% Load**		**100% Load**	
Pass	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***
250	-0.1	250	0.2	250	0.1	250	0.2
500	0.0	500	0.7	500	0.1	500	1.0
1000	0.0	1000	1.5	1000	0.1	1000	3.2
2000	0.1	2000	1.6	2000	0.2	2000	4.8
4000	0.0	4000	1.7	4000	1.0	4000	6.4
8000	0.0	8000	1.8	8000	2.4	6356	23.0
12000	0.0	12000	1.8	12000	2.6	---	---
16000	0.1	16000	1.9	16000	2.5	---	---
20000	0.0	20000	2.0	20000	2.6	---	---

Wheel Load: 50% = 86.4 kg *Test Temperature: 64 C* ** Rut in mm*
Wheel Load: 100% = 176 kg *Tire Pressure: 862 kPa*

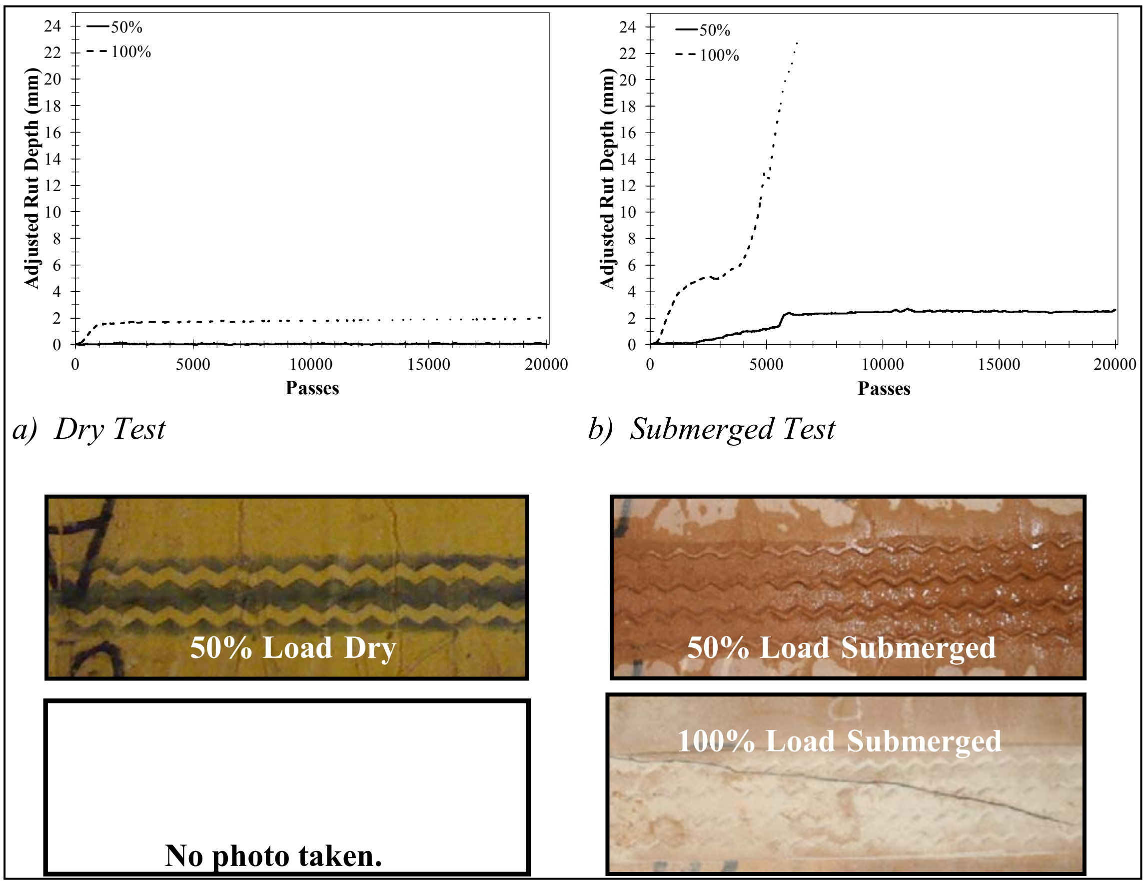


Figure C.2 PURWheel Test Results for PW5-PB5-01

Table C.3. PURWheel Test Results for PW5-PB5-02

Dry Test (Test 159) $\gamma = 2.182$ g/cm^3				**Submerged Test (Test 160) $\gamma = 2.182$ g/cm^3**			
65% Load		**80% Load**		**65% Load**		**80% Load**	
Pass	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***
250	0.0	250	0.1	250	0.1	250	1.1
500	0.0	500	0.1	500	0.1	500	1.1
1000	0.0	1000	0.3	1000	0.1	1000	0.7
2000	0.0	2000	0.4	2000	0.1	2000	0.4
4000	0.0	4000	0.8	4000	0.1	4000	0.1
8000	0.1	8000	0.9	8000	1.0	8000	0.9
12000	0.1	12000	0.9	12000	5.4	12000	3.3
16000	0.0	16000	1.0	16000	9.1	16000	15.4
20000	0.0	20000	0.8	20000	11.2	16938	19.7

Wheel Load: 65% = 111 kg *Test Temperature: 64 C* ** Rut in mm*
Wheel Load: 85% = 139 kg *Tire Pressure: 862 kPa*

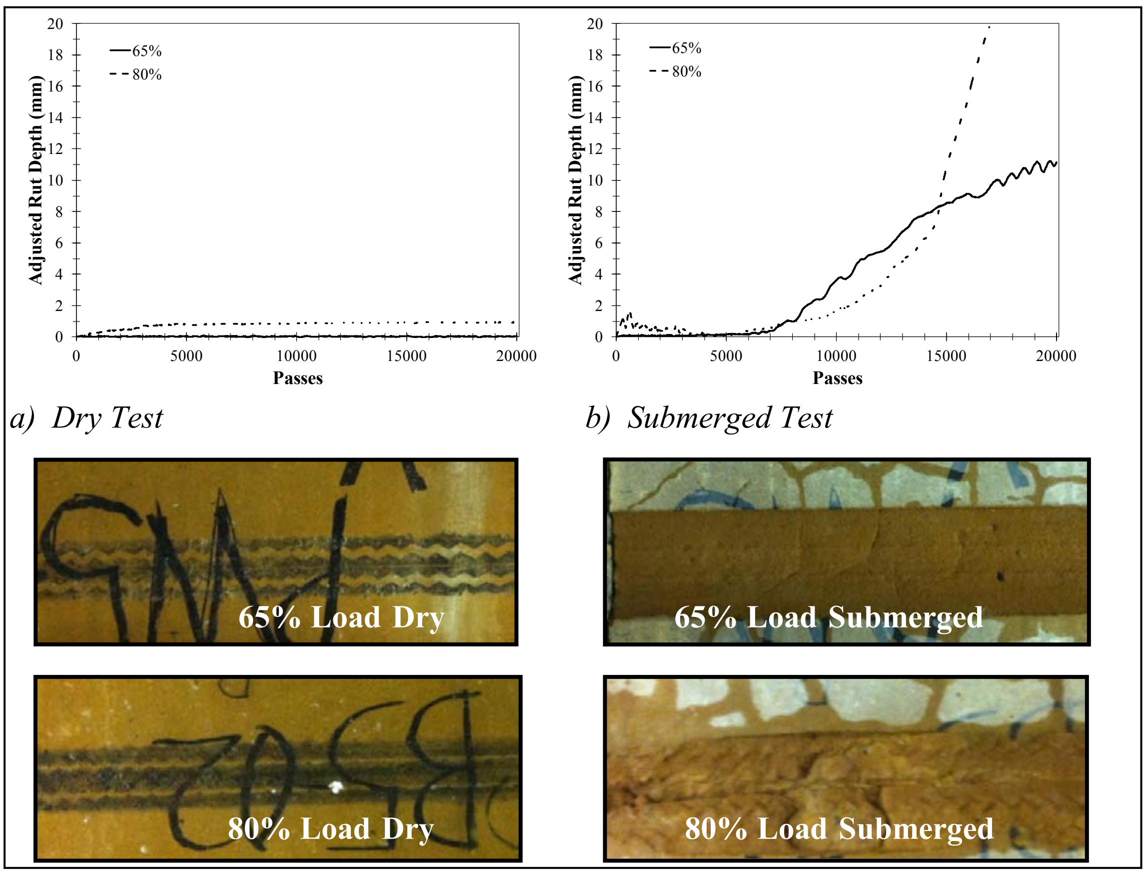


Figure C.3 PURWheel Test Results for PW5-PB5-02

Table C.4. PURWheel Test Results for PW5-PB5-04

Dry Test (Test 170) $\gamma = 2.171$ g/cm^3				**Soaked Test (Test 171) $\gamma = 2.171$ g/cm^3**			
50% Load		**100% Load**		**50% Load**		**100% Load**	
Pass	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***
250	0.0	250	-0.1	250	0.1	250	0.0
500	0.0	500	-0.1	500	0.2	500	-1.2
1000	-0.1	1000	-0.4	1000	0.2	1000	-1.2
2000	0.1	2000	0.1	2000	0.2	2000	-1.3
4000	0.2	4000	-0.3	4000	0.2	4000	-1.4
8000	0.3	8000	-0.3	8000	0.2	8000	-1.4
12000	0.3	12000	-0.2	12000	0.3	12000	-1.2
16000	0.4	16000	0.3	16000	0.4	16000	-1.3
20000	0.4	20000	-0.3	20000	0.4	20000	-1.5

Wheel Load: 50% = 86.4 kg *Test Temperature: 64 C* ** Rut in mm*
Wheel Load: 100% = 176 kg *Tire Pressure: 862 kPa*

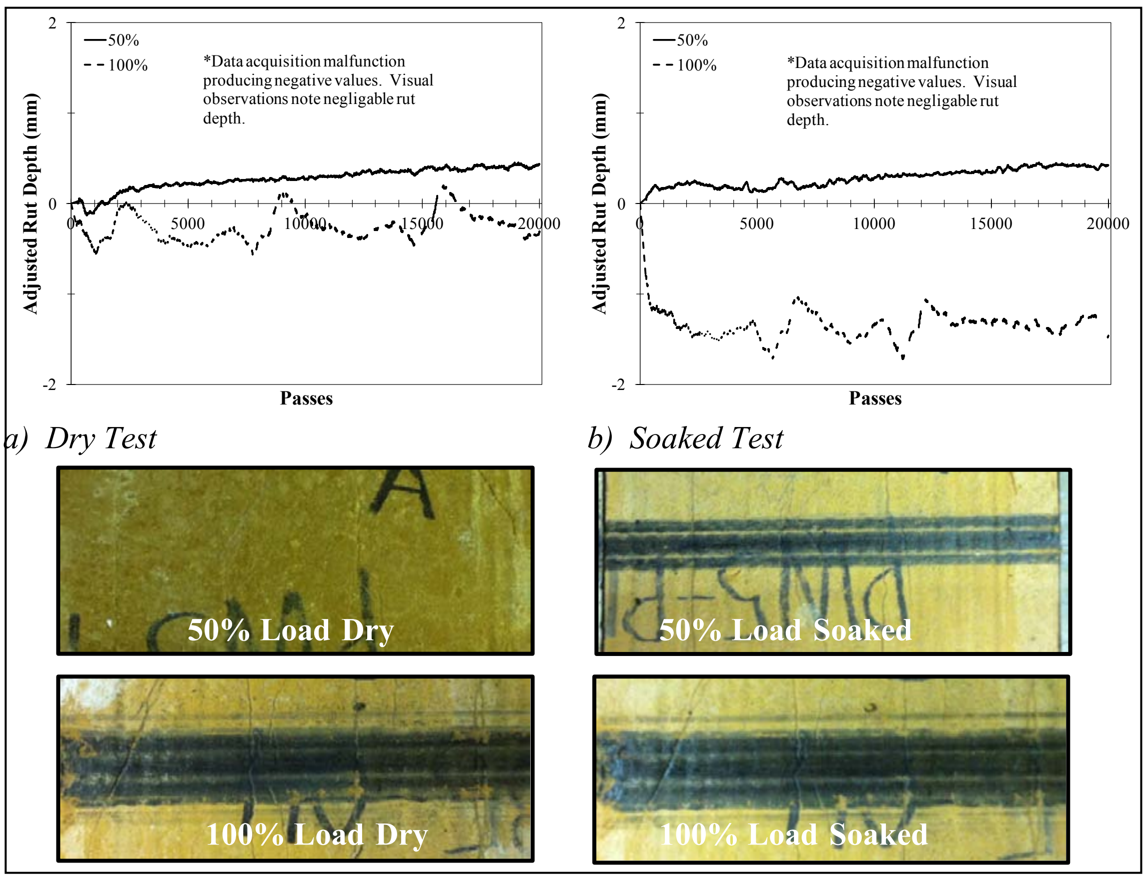


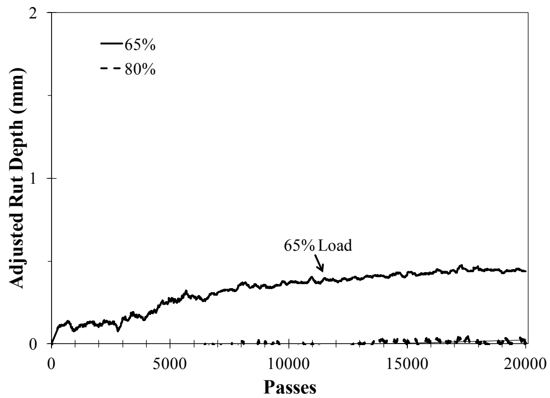
Figure C.4 PURWheel Test Results for PW5-PB5-04

Table C.5. PURWheel Test Results for PW5-PB5-03

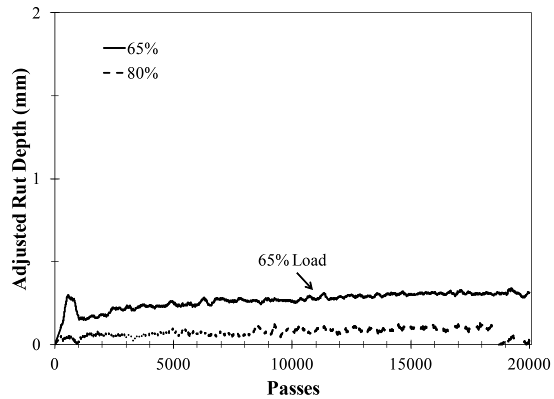
Dry Test (Test 161) $\gamma = 2.187\ g/cm^3$				Soaked Test (Test 162) $\gamma = 2.187\ g/cm^3$			
65% Load		**80% Load**		**65% Load**		**80% Load**	
Pass	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***
250	0.1	250	-0.1	250	0.1	250	0.0
500	0.1	500	-0.1	500	0.3	500	0.0
1000	0.1	1000	0.0	1000	0.2	1000	0.0
2000	0.1	2000	-0.1	2000	0.2	2000	0.1
4000	0.2	4000	0.0	4000	0.2	4000	0.1
8000	0.4	8000	0.0	8000	0.3	8000	0.1
12000	0.4	12000	0.0	12000	0.3	12000	0.1
16000	0.4	16000	0.0	16000	0.3	16000	0.1
20000	0.4	20000	0.0	20000	0.3	20000	0.0

Wheel Load: 65% = 111 kg   *Test Temperature: 64 C*   ** Rut in mm*

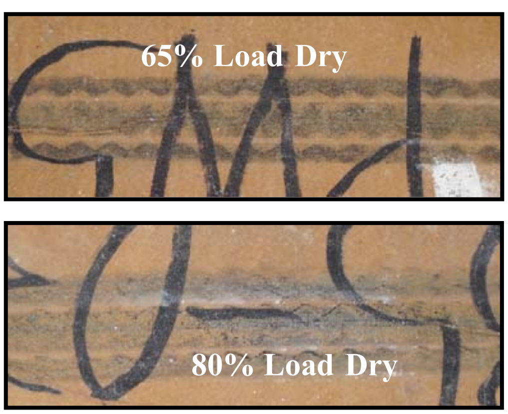
Wheel Load: 85% = 139 kg   *Tire Pressure: 862 kPa*



a) *Dry Test*



b) *Soaked Test*



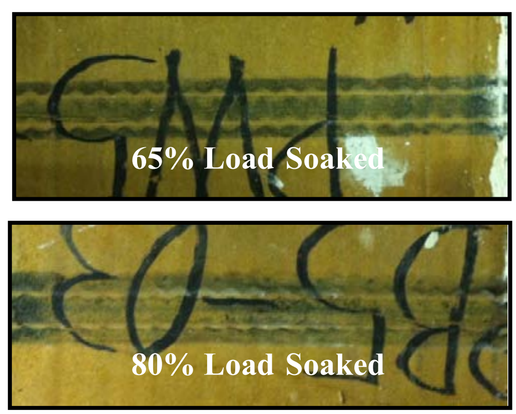


Figure C.5 PURWheel Test Results for PW5-PB5-03

Table C.6. PURWheel Test Results for PW5-PC4-01

Dry Test (Test 094) γ = 2.211 g/cm³				Submerged Test (Test 095) γ = 2.211 g/cm³			
50% Load		**100% Load**		**50% Load**		**100% Load**	
Pass	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***	**Pass**	**Adj. Rut ***
250	0.1	250	0.1	250	0.0	250	0.0
500	0.1	500	0.1	500	0.2	500	0.2
1000	0.1	1000	0.2	1000	0.1	1000	0.5
2000	0.1	2000	0.2	2000	0.1	2000	0.6
4000	0.2	4000	0.2	4000	0.2	4000	0.7
8000	0.2	8000	0.2	8000	0.2	8000	0.8
12000	0.2	12000	0.2	12000	0.2	12000	0.8
16000	0.2	16000	0.3	16000	0.3	16000	0.9
20000	0.2	20000	0.3	20000	0.3	20000	3.4

Wheel Load: 50% = 86.4 kg *Test Temperature: 64 C* ** Rut in mm*
Wheel Load: 100% = 176 kg *Tire Pressure: 862 kPa*

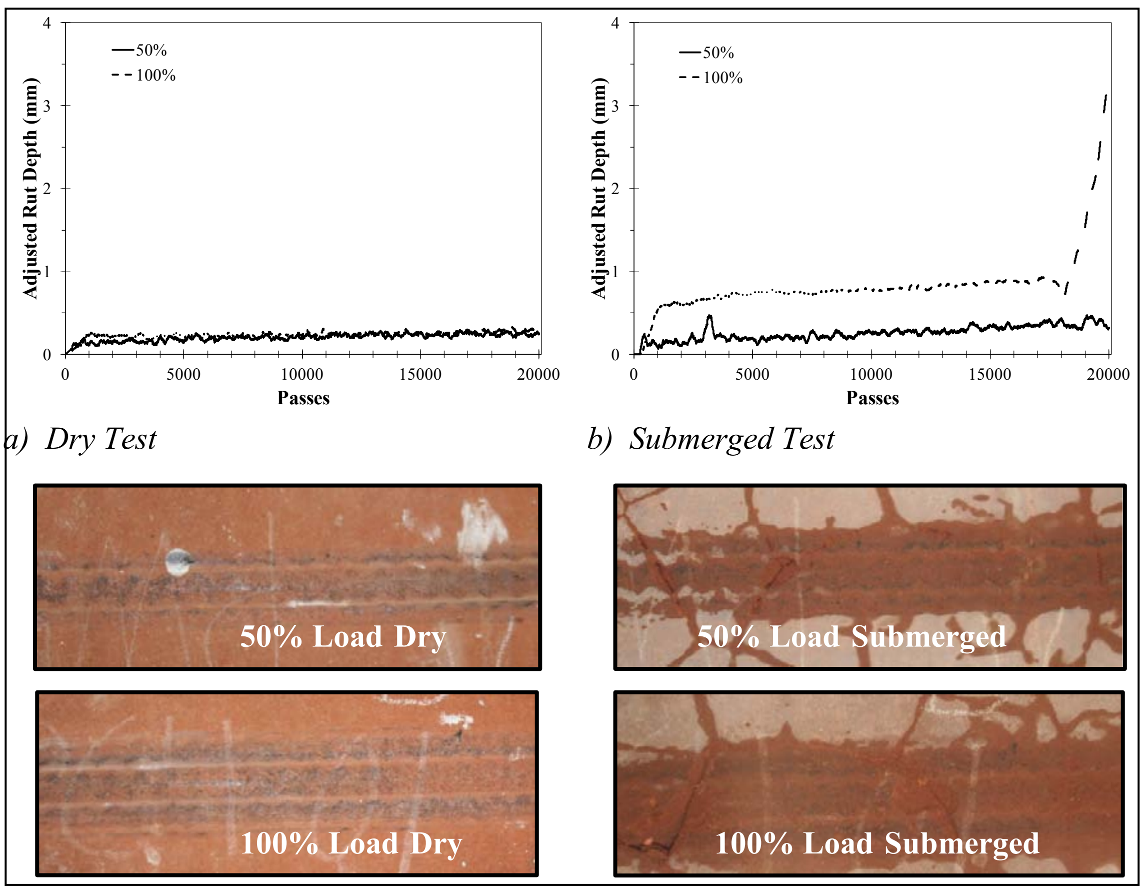


Figure C.6 PURWheel Test Results for PW5-PC4-01

APPENDIX D

STATE DOT SOIL CEMENT SURVEY

Chemically Stabilized Pavement Layer Survey - The purpose of this survey is to determine the extent and nature of chemically stabilized soil (e.g. soil-cement) use in DOT projects.

General Information and Use of Survey Data - The primary purpose of this survey is for use within Mississippi DOT research project: *State Study 206: Performance Specification for Chemically Stabilized Pavement Layers* (Principal Investigator is Isaac L. Howard 662-325-7193 ilhoward@cee.msstate.edu). This information will be included within the State Study 206 research report (a publically available document) and may also be used in thesis/dissertations, journal articles, conference proceedings, or presentations at technical venues. Responses will be identified by state and employer type information in the following section (no identifying information for any individual will be included).

Identification Information

State _____________ (please fill out one survey per state where you have feedback)

Employer (please mark with an X)

_____ Department of Transportation (___________ please list division within DOT)
_____ Federal Highway Administration (___________ please list division within FHWA)
_____ US Army Corps of Engineers (___________ please list division within USACE)
_____ Consultant
_____ Contractor/Construction Company
_____ Material Supplier
_____ Researcher/Academia
_____ Other (_________________ please specify)

Timeline and Submission information

- Responses received after December 31, 2012 may not be included.
- Please submit in manner that is most convenient (e.g. handwritten, scanned, typed….)
- An electronic version of this document is available at XYZ@cee.msstate.edu
- Completed surveys can be returned via any of the approaches listed below.
  - Fax: 662-325-7189 (please put to attn: State Study 206-Isaac L. Howard)
  - email: ilhoward@cee.msstate.edu (note the first letters are i l h)
  - mail: Attn: Isaac L. Howard (Mail Stop 9546)
    Civil and Environmental Engineering
    Mississippi State University
    501 Hardy Road-235 Walker Hall
    Mississippi State, MS 39762

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1) Does your state utilize chemically stabilized (i.e. portland cement, fly ash, lime, slag cement, etc) pavement layers for roadway construction?

Yes ___ (If yes, please list stabilizing materials used and estimate how often chemical stabilization occurs within the state; e.g. very frequently, frequently, infrequently)
No ___ (If no, please provide any reasons why chemical stabilization is not used)

2) How is the design stabilizer (e.g. portland cement) content determined? Please list any test types (e.g. unconfined compression), specimen sizes (e.g. 3 in by 6 in), and test requirements (e.g. 200 psi after 7 day cure) that are used to determine the design stabilizer content.

3) Once determined, how is the design stabilizer content referenced? Examples might include percent of dry soil mass, by volume…..

4) What compaction method(s) are used to make specimens for Question 2?

5) Is there any replication of the tests performed in Question 2? For example, are three replicate unconfined compression tests averaged to compare to the design strength requirement?

6) Is there a maximum time allowed between mixing the chemical stabilizer, soil, and water until compaction must be completed?

Yes ___; _______________minutes
No ___

7) Briefly describe any quality control measures that are taken with regard to chemically stabilized pavement layers in your state. Of particular interest is whether design and construction are interfaced in any way (i.e. is the laboratory design ever verified and if so how?). Examples might include field proctor tests, measuring cement content after mixing, verifying cement spread rates, compacting specimens in the field for laboratory strength testing….

8) Please list any problems or concerns with chemically stabilized pavement layers, their design, or their quality control. Also provide any feedback on areas of needed improvement in design or quality control.