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Conversion Factors and Regression Parameters to Backcast and Forecast Strength and Modulus of Cementitious Stabilized Soils in Mississippi

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16. Abstract
The main objectives of this report were to provide minimum and maximum mechanical properties of stabilized soils at 28 days, develop conversion factors between mechanical properties, and evaluate strength regression parameters for forecasting and backcasting mechanical properties based on a 28 day strength. To meet these objectives, nine data sets comprised of approximately 2300 data points were utilized. Evaluation of the data sets showed that approximately 70% of reported strengths were within one standard deviation of the reported average (i.e., approximately 70% of cement stabilized specimens had unconfined compressive strengths within one standard deviation of their average). Conversion factors to relate mechanical properties of cementitiously stabilized soil are also provided. Lastly, regression parameters are developed to forecast and backcast mechanical properties of cementitiously stabilized soil based on a 28 day strength. A set of regression parameters are recommended for use with Mississippi materials to backcast unconfined compressive strength, indirect tensile strength, and elastic modulus. Relationships are also presented for modulus of rupture.

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NOTICE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF SYMBOLS AND ACRONYMS

ANOVA	analysis of variance
avg	average
CSM	cementitious stabilized soil
CSOGB	cement stabilized open graded base
CTAB	cement treated aggregate base
C_w	cement content
DS	data sets
DS1	data set 1
DS2	data set 2
DS3	data set 3
DS4	data set 4
DS5	data set 5
DS6	data set 6
DS7	data set 7
DS8	data set 8
DS9	data set 9
E	elastic modulus
E_{28}	elastic modulus at 28 days
E:UCS	relationship between elastic modulus and unconfined compressive strength
FDR	full depth reclamation
GRG	generalized reduced gradient
h:d	height to diameter ratio
IDT	indirect tensile strength
IDT_{28}	indirect tensile strength at 28 days
IDT:UCS	relationship between indirect tensile strength and unconfined compressive strength
LCFA	lime-cement-fly-ash
LL	liquid limit
L_w	lime content
MDOT	Mississippi Department of Transportation
MEPDG	Mechanistic-Empirical Pavement Design Guide
MH28	28 blows per layer with a modified Proctor hammer
MH56	56 blows per layer with a modified Proctor hammer
MOR	modulus of rupture
MOR:IDT	relationship between modulus of rupture and indirect tensile strength
MOR:UCS	relationship between modulus of rupture and unconfined compressive strength
n	number of specimens
N_{BL}	number of blows per layer in PM Device
NCAT	National Center for Asphalt Technology
p_1	regression parameter
p_2	regression parameter
PI	plasticity index
PL	plastic limit

PM Device	plastic mold compaction device described in AASHTO PP 92
PM3x6	3 by 6 inch specimen compacted with PM Device
PM4x8	4 by 8 inch specimen compacted with PM Device
RMSE	root mean square error
RTO	regression through the origin
SH28	28 blows per layer with a standard Proctor hammer
SS206	State Study 206
SS263	State Study 263
SS276	State Study 276
SS285	State Study 285
t	time
UCS	unconfined compressive strength
UCS(t)	unconfined compressive strength at time, t
UCS_{XX}	unconfined compressive strength at time XX days
w_T	target moisture content
σ	standard deviation

CHAPTER 1 – INTRODUCTION

1.1 General and Background Information

Chemically stabilized soils are an effective method to achieve desired strength and modulus in pavements, especially in states such as Mississippi where quality base aggregates are unavailable (Chenarboni et al., 2021; Liu et al., 2019; Howard et al., 2013; Varner et al., 2011). Capturing these strength and modulus properties in design is important. The Mechanistic-Empirical Pavement Design Guide (MEPDG) has been introduced as a way to interface materials, load-deflection relationships, and other factors into pavement design (AASHTO, 2008); however, it requires user input to determine mechanical property relationships of local materials. Many mechanical property relationships have been proposed in literature and vetted against laboratory and field compacted specimens cured at room temperature and at elevated temperatures (Ayers 2022) as well as against later life core samples from pavements across the Mississippi highway network (Carey et al., n.d.). These relationships can be used within the MEPDG framework as Level 2 inputs for mechanical properties of interest when only one property is experimentally known. However, one facet of the MEPDG that has not been fully studied is assessing the development of mechanical properties over time in a pavement. In design, one usually needs to forecast properties throughout a pavement's life, and to calibrate models, one usually needs to backcast properties of existing pavements to their early life status.

1.2 Objectives and Scope

In this report, a total of 2,301 chemically stabilized soil specimens were used to develop conversion factors and regression parameters to better predict mechanical properties. Mechanical properties including modulus of rupture (MOR), indirect tensile strength (IDT), unconfined compressive strength (UCS), and modulus of elasticity (E) were measured for cementitious stabilized material (CSM) blends typically used on construction projects in Mississippi to develop conversion factors between mechanical properties. Additionally, regression parameters were developed to backcast and forecast measured strength and modulus of CSM materials to 28 day strength values. This research study was funded by the Mississippi Department of Transportation (MDOT) through Project 107595-101000, State Study 285 (SS285). Some data used in this research effort were originally obtained during State Study 206 (SS206) and State Study (SS276).

There are three objective categories in this report: 1) provide minimum and maximum mechanical properties at 28 days, 2) develop conversion factors to relate mechanical properties, and 3) evaluate strength regression parameters for forecasting and backcasting mechanical properties based on a 28 day strength. The majority of this report focuses on the development of regression parameters as the development of conversion factors is thoroughly discussed in Ayers (2022). A condensed summary of the major findings in Ayers (2022) relative to mechanical property conversion factors are presented herein.

SS276 and SS285 have some alignment with each other as performed and agreed upon between MSU and MDOT. SS285 was organized into ten tasks. These ten tasks were in the original notice of award and remained to the end of the project. Some wording, and minor procedural changes within a few of these ten tasks were agreed upon in the spring of 2020.

Given the overall effort, tasks themselves, and project objectives did not change, these adjustments were not further documented beyond the following paragraph, but were the version of the work provided in this report. These tasks are briefly summarized in the remainder of this section and locations within this report where the primary findings were located are also briefly summarized.

Indirect tensile strength (IDT) testing was a primary area where some deviations occurred relative to original plans. Rationale for these deviations is shown in Ayers (2022) and in the State Study 276 report. A table of data is shown therein where Proctor molds, the PM Device, and beam cores were used to produce specimens of a variety of aspect ratios and diameters. The overarching finding from this work was that specimen height to diameter ratios did not affect indirect tensile strength results, thus supporting the deviations made. Procedures utilized in the NCHRP 789 report were considered during this process, and given the desire of MDOT to implement the PM Device, decisions were made accordingly.

Task 1: Soil Sampling, Curing, and Testing: Data was obtained from a variety of other sources including SS206, SS263, and SS276 to allow relationships to be developed between UCS, IDT, E, and MOR, and also to allow mechanical properties to be backcasted. Chapter 3 describes this data.

Task 2: Development of Conversion Factors: Develop factors or relationships between UCS and IDT and between IDT and MOR. The suitability of IDT measurements for pavement design was also to be assessed. Section 4.3 describes the most relevant findings in this regard.

Tasks 3 and 5: Evaluate Strength Regression Parameters: Evaluate relevant equation(s) from NCHRP Report 789 (Wen et al. 2014) to predict mechanical properties at any time based on 28 day properties. The most relevant equation noted was Equation 3-4 of NCHRP Report 789, which for reference is Equation 1 in this report. Section 4.4 describes the most relevant UCS findings in this regard, and Section 4.5 provided the most relevant IDT and E findings in this regard.

Tasks 4 and 6: Maximum and Minimum Mechanical Property Values: Provide highest and lowest 28 day mechanical properties of pertinence from the data sets collected. Section 4.2 provides the most relevant findings in this regard.

Tasks 7 to 10: Project Management, Presentation, Purchasing, and Reporting: These four tasks are related to the overall project oversight and are not directly reflected in this report.

CHAPTER 2 – LITERATURE REVIEW

2.1 Overview of Literature Review

Cementitious stabilized material (CSM), also known as soil-cement can have a wide range of compressive strengths and associated mechanical properties. Although higher cement contents typically produce more strength, they can also contribute to shrinkage cracks in the pavement. This literature review focused on identifying relationships between soil-cement mechanical properties, and how these properties develop.

2.2 Conversion Factors Between Mechanical Properties

Commonly used design guides with respect to pavement design, such as the 1993 AASHTO design guide and the MEPDG, provide little guidance with respect to chemically stabilized soil. With the implementation of the MEPDG, conversion factors can be used as Level 2 inputs to estimate mechanical properties of interest during the design process. Conversion factors between mechanical properties have been researched for several decades as a way to quickly estimate an unknown mechanical property based on a known property (Tables 2.1, 2.2, 2.3, and 2.4). Many of the current design guides utilize UCS as the main design property. Although UCS can be a good indicator of a base's performance, additional mechanical properties such as E, IDT, and MOR can collectively provide a clearer and more representative picture of likely pavement performance. Some commentary is provided for select studies reported in Tables 2.1 to 2.4 in the remainder of this section.

Table 2.1. Summary of E:UCS Relationships from Literature

Reference	Material	Relationship
Reinhold (1955)	Cement Stabilized Soil	E = 1220(UCS) + 160986
AASHTO (1993)	Cement Stabilized Soil	E = 523(UCS) + 400000
AASHTO (2008)	CTAB	$E = 57000(UCS)^{0.5}$
James et al. (2009) & Thompson (1986)	LCFA	E = 1000(500 + UCS)
AASHTO (2008)	Soil Cement	E = 1200(UCS)
Howard et al. (2013)	Soil Cement	E = 2100(UCS)
Sullivan et al. (2015)	Soil Cement	E = 2000(UCS)
Howard and Cox (2016)	FDR	E = 500(UCS)
Sullivan and Howard (2019)	Soil Cement	E = 1967(UCS) + 173033

Note: CTAB - cement treated aggregate base; LCFA - lime-cement-fly-ash; FDR - full depth reclamation; all equations are given in psi

Reinhold (1955) studied the elastic behavior of four blended materials made from fine material with Heppenheim clay. The study suggested that higher cement contents within a mixture produce higher elastic moduli. Three main conclusions were drawn: 1) compressive strength was the defining factor for soil-cement elastic behavior; 2) density, cement content, moisture content, and clay content affected the elastic behavior of soil-cement; and 3) a linear stress-strain relationship can be assumed up to one-third of a specimen's compressive strength.

Thompson (1986) found flexural and split tensile strength of soil-cement to be about 20-25% and 10-15% of the compressive strength, respectively. Thompson (1986) also reported the elastic modulus (E) was 1200 times UCS based on the literature review, thus the relationship should be treated as a generalization with non-specific test conditions.

Table 2.2. Summary of IDT:UCS Relationships from Literature

Reference	Material	Relationship
Kennedy et al. (1971)	Cement Treated Materials	IDT = 0.166(UCS) – 11.38
Kennedy and Moore (1971)	Lime Treated Materials	IDT = 50.6(UCS) + 6.89
Doshi and Guirguis (1983)	Soil Cement	IDT = $0.004529(UCS)^{1.418}$
Hall (1994)	CSOGB	IDT = 0.17(UCS)
Gnanendran et al. (2010)	Slag-Lime Stabilization	IDT = 0.114(UCS)
Scullion et al. (2012)	FDR	IDT = 0.177(UCS) – 9.31
Barišić et al. (2014)	Gravel Slag	IDT = 0.141(UCS)
Solanki and Zaman (2014)	Stabilized Subgrade	IDT = 0.16(UCS)
Wen et al. (2014)	Stabilized Soils	IDT = 0.12(UCS)
Rashidi et al. (2018)	Cement Stabilized Soil	IDT = 0.12(UCS)
Rashidi et al. (2018)	Cement Stabilized Soil	IDT = $7.77(UCS)^{0.38}$
Gonzalo-Orden et al. (2019)	FDR	IDT = 0.10(UCS)

Note: CSOGB – cement stabilized open graded base; FDR – full depth reclamation; all equations are given in psi

Table 2.3. Summary of MOR:UCS Relationships from Literature

Reference	Material	Relationship
Felt and Abrams (1957)	Cement Stabilized Soil	MOR = 0.23(UCS)
Kolias and Williams (1978)	Cement Stabilized Soil	MOR = 0.20(UCS)
Hall (1994)	CSOGB	MOR = 0.20(UCS)
Wen et al. (2014)	Stabilized Soils	MOR = 0.14(UCS)
Solanki and Zaman (2014)	Stabilized Subgrade	MOR = 0.41(UCS)
Hossain et al. (2017)	Cement Stabilized Soil	MOR = 5(UCS) - 190
Gonzalo-Orden et al. (2019)	FDR	MOR = 0.16(UCS)

Note: CSOGB – cement stabilized open graded base; FDR – full depth reclamation; all equations are given in psi

Table 2.4. Summary of MOR:IDT Relationships from Literature

Reference	Material	Relationship
Kolias and Williams (1978)	Cement Stabilized Soil	MOR = 1.40(IDT)
Wen et al. (2014)	Stabilized Soils	MOR = 1.16(IDT)
Gonzalo-Orden et al. (2019)	FDR	MOR = 1.55(IDT)

Note: FDR – full depth reclamation; all equations are given in psi

Kennedy et al. (1971) conducted two experiments to identify correlations between indirect tensile strength and unconfined compressive strength for cemented-treated gravel and crushed limestone mixtures. Specimens were compacted using a Rainhart impact compactor, striking 25 blows per layer with a 10-lb hammer dropping 18 in. The specimens were then cured for 7 days at 75 °F in 100% relative humidity.

Doshi and Guirguis (1983) examined correlations between indirect tensile strength, flexural and unconfined compressive strengths of soil-cement and to obtain possible mathematical equations for specific conditions. The authors utilized Type I cement and A-2-4 soil. Five mixtures were analyzed at 2, 5, 7, 9, and 12 % cement by weight of oven-dry soil. Cylindrical specimens for unconfined compression and indirect tensile tests were compacted with AASHTO T 180-74, Method A. Flexural test specimens were prepared with AASHTO T 126-76, where the beam size had a cross-section of 2 in by 2 in and a length of 12 in. The specimens were cured for 2, 7, 14, 21, or 28 days, and then soaked in water at 77 F for 4 hours under atmospheric pressure before loading them to failure.

Wen et al. (2014) addressed material properties and related test methods that can be incorporated in pavement design and analysis procedures to predict pavement performance. Three replicates of soil-cement specimens were tested in accordance with Portland Cement Association methods. Wen et al. (2014) used a range of dosages, additives, and soil types. Specimen strength (UCS, IDT, and MOR) were measured at 3, 7, 28, 90, 180, and 360 days after curing at the conditions of 68°F and 100% relative humidity (RH) in a moist curing room.

Rashidi et al. (2018) studied relationships between resilient modulus, compressive strength, and tensile strength of cement stabilized materials for the analysis and design of pavement structures. Four aggregate sources and four cement contents (2% to 5%) were utilized.

2.3 Mechanical Property Development

Although there have been numerous published relationships to correlate mechanical properties using conversion factors, the development of mechanical properties over time in a pavement is not fully studied. A review of literature shows there are some published relationships that quantify mechanical property development (Table 2.5); however, all of these relationships were derived using specimens cured in a moist room kept at 100% relative humidity and approximately 73°F. Most of these equations require a known strength at 28 days, and then a strength at another time can be estimated. Equation 1 (from Wen et al., 2014) was vetted against nine mixtures based on input from the National Lime Association, Portland Cement Association, and Federal Highway Administration to represent a wide range of soils (clay, silt, sand, gravel) and stabilizing materials (cement, lime, Class F and Class C fly ash). For this reason, Equation 1 could be considered the most robust of the Table 2.5 equations. Some commentary is provided for select studies reported in Table 2.5 in the remainder of this section.

Table 2.5. Equations to Forecast and Backcast Soil-Cement Mechanical Properties

Reference	Eq. No.	Equation	Commentary
Wen et al. (2014)	1	$\mathrm{UCS(t)} = (\mathrm{UCS_{28}})\left[p_1^{\,1-\frac{1}{\left(1+\frac{(t-t_0)}{p_2}\right)}}\right]$	p_1 and p_2 are regression parameters defined as 1.59 and 1.61. t_0 defined as 28/30.5. R^2 of 0.91.
Lim and Zollinger (2003)	2	$\mathrm{UCS(t)} = \mathrm{UCS_{28}}\left[\frac{t}{p_1 + p_2 * t}\right]$	p_1 and p_2 are regression parameters defined as 2.5 and 0.9. Based on ACI 209 model for cement-treated aggregate base.
Linares (2015)	3	$\mathrm{UCS_{28}} = p_1(\mathrm{UCS_7}) + p_2$	p_1 and p_2 are regression parameters defined as 0.695 and 295. Based on relationship of cement stabilized soil. R^2 of 0.73.
Linares-Unamunzaga et al. (2019)	4	$\mathrm{UCS_{90}} = p_1(\mathrm{UCS_7}) + p_2$	p_1 and p_2 are regression parameters defined as 0.763 and 427. Based on relationship of cement stabilized soil. R^2 of 0.73.
Horpibulsuk et al. (2011)	5	$\mathrm{UCS(t)} = p_1(\mathrm{UCS_{28}}) + (p_2)(\mathrm{UCS_{28}})(\ln(t))$	p_1 and p_2 are regression parameters defined as 0.026 and 0.293. Based on relationship between fly ash stabilized clay. R^2 of 0.91.

Note: t - time; UCS(t) - unconfined compressive strength at time, t; $\mathrm{UCS_{XX}}$ - unconfined compressive strength at time XX days; p_1 and p_2 are regression parameters; UCS is reported in psi; regression parameters for Equation 1 are valid when time is in months; regression parameters for Equations 2 and 5 are valid when time is in days.

Lim and Zollinger (2003) investigated the correlation between unconfined compressive strength and modulus of elasticity for a cement-treated aggregate base (CTAB). Two different mixtures: conventional crushed limestone base and recycled concrete, following TxDOT specification Item 276, (Portland Cement Treated Base) were utilized for the testing. 4 by 8 inch specimens were produced at two cement contents, 4% and 8%, and were cured at a controlled temperature of 77 °F and 100% relative humidity for 1, 3, 7 and 28 days. Due to the higher moisture requirements in recycled concrete materials, specimens showed 20 to 30 % lower compressive strength and modulus than conventional aggregate base materials with the same mix proportioning and curing days. It was observed that the development of strength and modulus of CTAB mixtures was mostly governed by cement content.

CHAPTER 3 – EXPERIMENTAL PROGRAM

3.1 Overview of Experimental Program

This chapter describes the seven experimental data sets used to calibrate regression parameters (Section 3.2), an overview of materials (Section 3.3), details on specimen preparation methods (Section 3.4), mechanical testing methods (Section 3.5), and data analysis methods (Section 3.6). As noted in Chapter 1, this work parallels SS276 and some of these experiments were dual purpose.

3.2 Data Sets Summary

Nine data sets are utilized in this report that represent materials commonly used for base and subgrade pavement construction in Mississippi. These data sets have multiple purposes but are used collectively herein for conversion factor development and regression parameter calibration (Table 3.1). Generally speaking, these data sets used three types of specimens: plastic mold (PM) Device compacted specimens (AASHTO PP 92, 2019), field cores, and beams. PM Device specimens were either 3 by 6 inch (PM3x6) or 4 by 8 inch (PM4x8) and tested at ages ranging from 1 to 1095 days. The PM Device was used on field projects as well as in a laboratory setting to compact chemically stabilized soil. Some PM Device specimens were cured at 158°F in a water bath to simulate later age pavement life properties, but the majority were cured in a 73°F moist room that conformed to ASTM C192. Field cores were sampled from pavement sections throughout the MDOT roadway network between 2017 and 2019 and ranged in age from 10 to 54 years. Beams were compacted in a laboratory setting and cured in a 73°F moist room.

The majority of analysis in this report uses data sets (DS) 1, 2, 3, and 4 as these data sets systematically tested soil-cement specimens between 1 and 1095 days. Field cores from DS5 and DS6 as well as accelerated cured specimens in DS7 are used primarily to provide insight into the applicability to relationships from literature to estimate later life mechanical properties of pavements. DS8 and DS9 were used to develop correlations between MOR and other mechanical properties and were not used in efforts to develop regression parameters. During the collection of cores reported in DS5 and DS6, cores stabilized with lime-fly ash were also recorded; however, those cores are not included in this report. Additional details on the lime-fly ash cores can be found in Carey et al. (2022).

Table 3.1 Summary of Data Sets (DS)

Data Set	Specimen Type	Soil Type	Stabilizing Material	Data Set Size [UCS, E, IDT, MOR]	Description
DS1	PM Device	Base	Cement	[368, 262, 269, 0]	Data collected from Interstate 269 corridor construction. Further details can be found in Sullivan and Howard (2019).
DS2	PM Device	Base	Cement	[71, 48, 68, 0]	Data collected from MDOT project at the National Center for Asphalt Technology (NCAT). Further details can be found in Ayers (2022).
DS3	PM Device	Base	Cement	[151, 111, 0, 0]	Data collected to systematically understand range of mechanical properties expected from Mississippi materials at different ages.
DS4	PM Device	Subgrade	Lime	[92, 33, 15, 0]	Data collected from MDOT project at the National Center for Asphalt Technology (NCAT). Further details can be found in Ayers (2022).
DS5	Field Cores	Base	Cement	[24, 0, 28, 0]	Data collected from 10 to 54 year old pavements throughout MDOT's roadway network. Further details can be found in Carey et al. (2022).
DS6	Field Cores	Subgrade	Lime	[58, 22, 74, 0]	Data collected from 10 to 54 year old pavements throughout MDOT's roadway network. Further details can be found in Carey et al. (2022).
DS7	Hot Cured PM Device	Base	Cement	[51, 36, 41, 0]	Data collected to develop laboratory protocols to simulate later age pavement properties. Further details can be found in Ayers (2022).
DS8	Beams	Base	Cement	[107, 107, 107, 108]	Data collected to develop correlations between mechanical properties. Further details can be found in Ayers (2022).
DS9	Beams	Base	Cement	[12, 12, 12, 12]	Data collected to develop correlations between mechanical properties. Further details can be found in Ayers (2022).

3.2.1 Data Set 1

Data set 1 (DS1) is the largest DS used in this effort and is comprised of data collected from Interstate 269 corridor construction. A total of 638 soil-cement specimens are reported in DS1 and a total of 899 tests were conducted (all specimens tested for elastic modulus were also tested for compressive strength). All specimens were compacted with a PM Device in either a field or laboratory setting. Three target cement contents by soil mass (C_W) were used in DS1: 3.6%, 5.1%, and 6.6%. Target moisture contents (w_T) of 12.0% and 11.2% were used. The PM Device number of blows per layer (N_{BL}) was varied between 4, 5, 6, 7, 8, 9, and 11. Testing times varied between 1 and 1095 days. Histograms showing the distribution of these properties are provided in Figure 3.1.

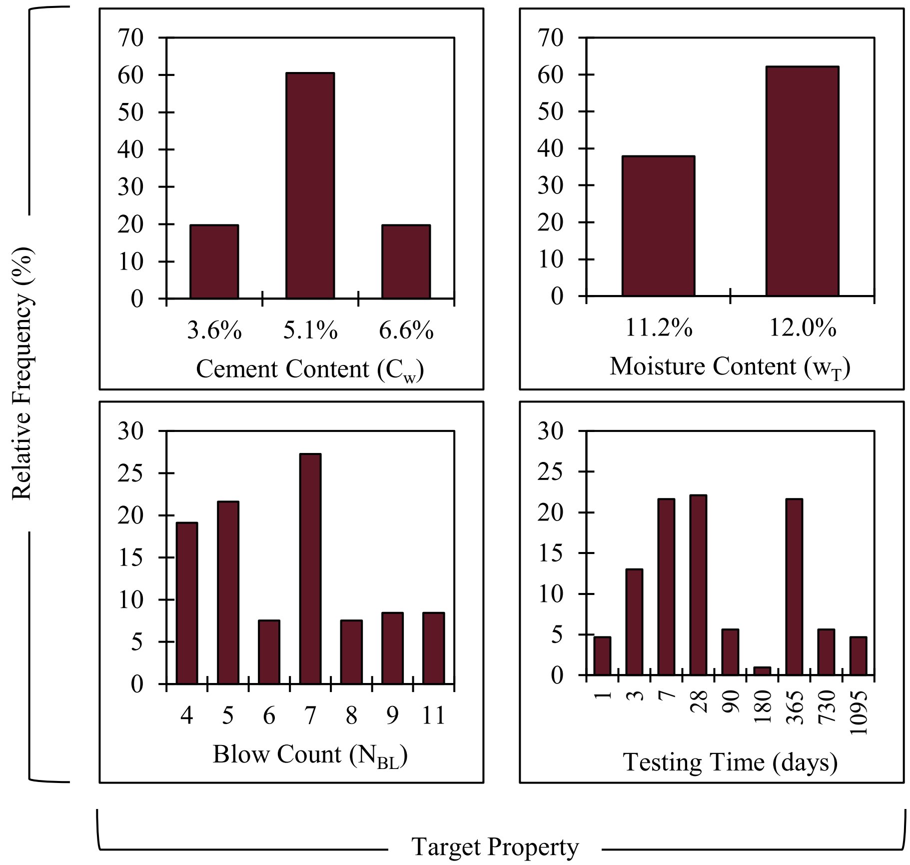


Figure 3.1. Histograms of Target Properties in Data Set 1 (DS1)

3.2.2 Data Set 2

Data set 2 (DS2) is comprised of soil-cement data collected from MDOT's test section at the National Center for Asphalt Technology (NCAT). A total of 139 specimens are encompassed in DS2 and a total of 187 tests are reported. All specimens were produced using the PM Device in both field and laboratory environments. Three target C_w were chosen: 3.6%, 5.1%, and 6.6%. Two target w_T were chosen: 11.3% for laboratory compacted specimens and 13.0% for field compacted specimens. Compaction effort varied between 5 N_{BL} for PM3x6 specimens and 9 N_{BL} for PM4x8 specimens. Testing times varied between 7 and 365 days. Distribution of these target properties for DS2 are shown in Figure 3.2.

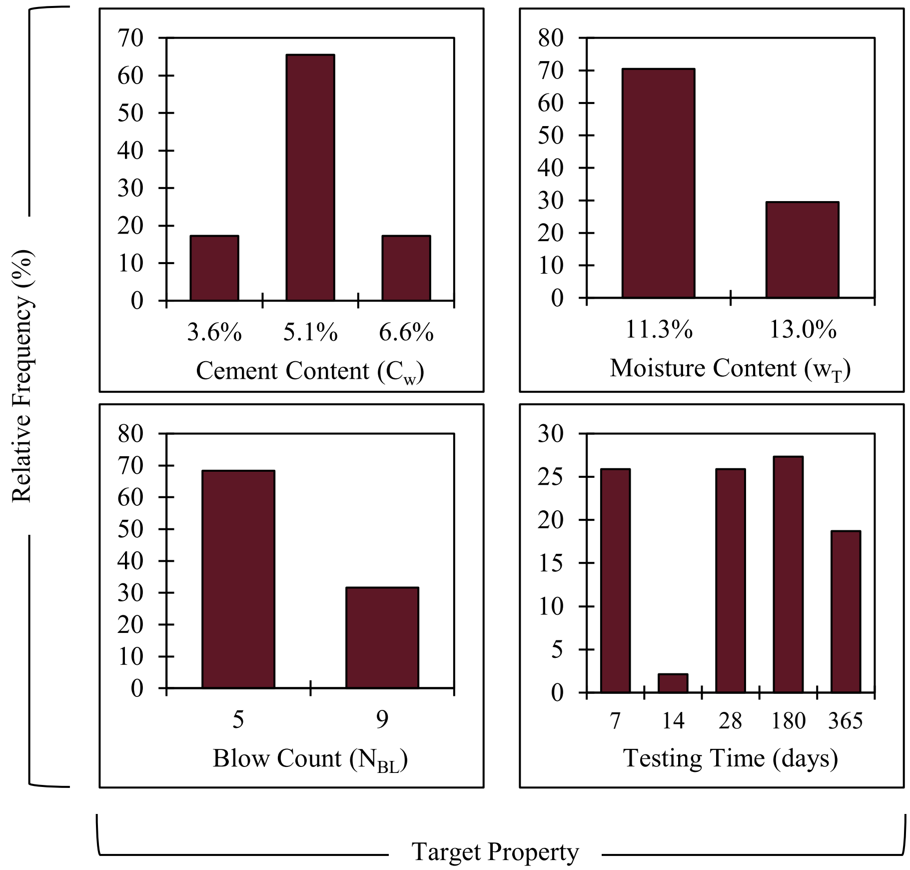


Figure 3.2. Histograms of Target Properties in Data Set 2 (DS2)

3.2.3 Data Set 3

Data set 3 (DS3) is a collection of laboratory compacted PM Device specimens where a large range of materials were used to systematically evaluate the range of mechanical property development in Mississippi materials over time. A total of 151 soil-cement specimens were included in DS3 and a total of 262 test results are included. A wide range of C_w (3.1% to 7.4%) and w_T (10.3% to 15.4%) were evaluated. N_{BL} was varied between 4, 5, and 6 blows per layer. Specimens were systematically tested between 7 and 365 days with the majority of specimens being tested at 28 and 365 days. Distribution of these target properties for DS3 are shown in Figure 3.3.

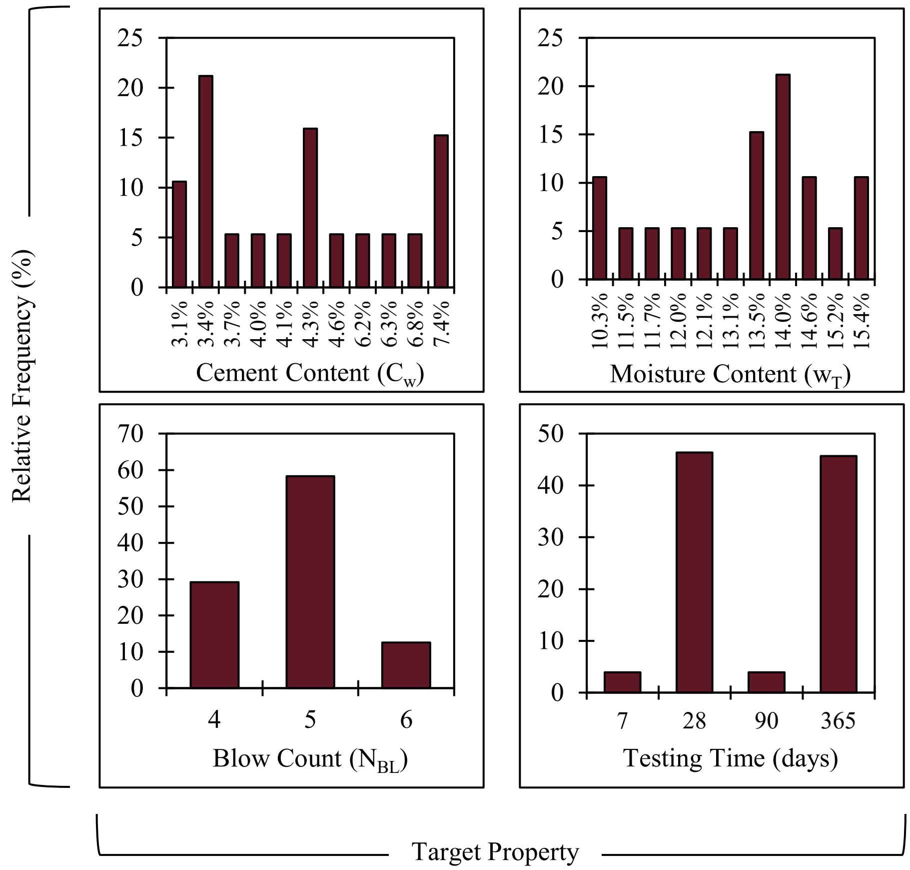


Figure 3.3. Histograms of Target Properties in Data Set 3 (DS3)

3.2.4 Data Set 4

Data set 4 (DS4) is comprised of lime stabilized subgrade data collected from MDOT's test section at the National Center for Asphalt Technology (NCAT). A total of 107 specimens are encompassed in DS4 and a total of 140 tests are reported. All specimens were compacted with the PM Device in either a field or laboratory setting. A target lime content (L_w) of 4% was used in all specimens. The target w_T was 17.3% for all field compacted specimens but varied between 16.6% and 18.6% for laboratory compacted specimens. N_{BL} varied between 4, 5, 7, and 9 blows per layer during compaction. Specimens were tested at 7, 28, and 180 days. Histograms showing the distribution of these target properties are provided in Figure 3.4.

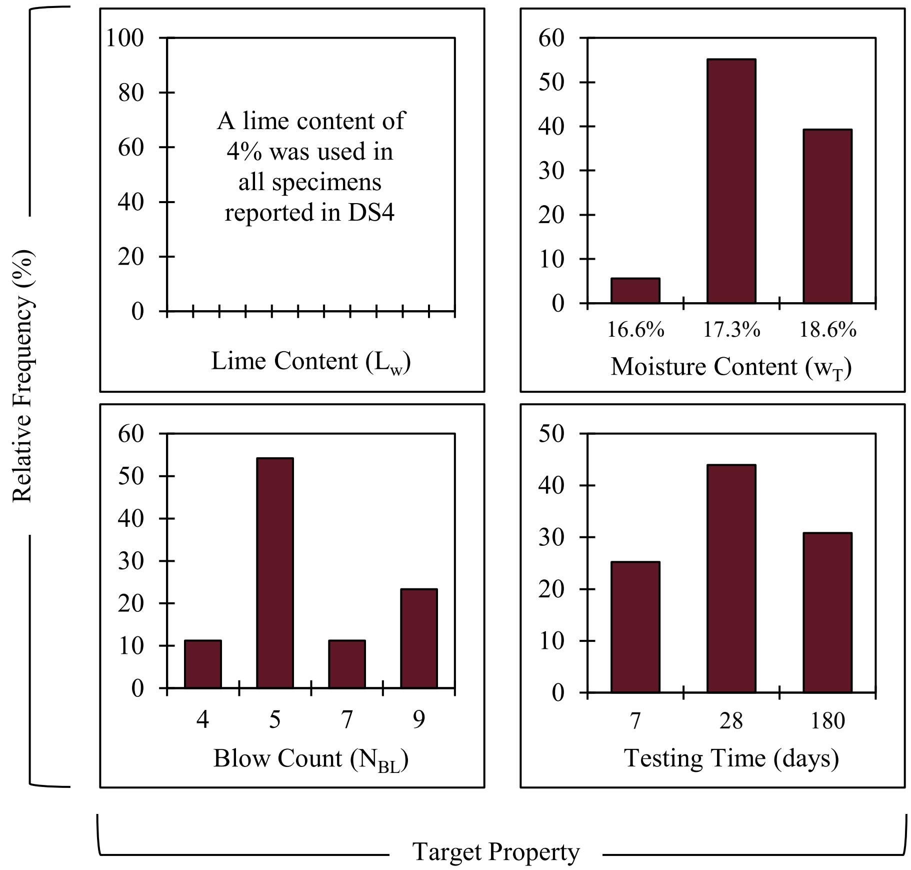


Figure 3.4. Histograms of Target Properties in Data Set 4 (DS4)

3.2.5 Data Set 5

Data set 5 (DS5) is a collection of cement stabilized pavement cores that were obtained from roadways throughout the MDOT highway network. A total of 60 cores are included in this dataset: 14 cores from MDOT District 1 (northeast Mississippi), 26 cores from MDOT District 2 (northwest Mississippi), 12 cores from MDOT District 5 (central Mississippi), and 8 cores from MDOT District 7 (southwest Mississippi). Cores ranged in age from 13 years to 54 years. No information is known regarding target C_W or w_T during construction or the compaction effort/target density. This data set's main objective within this report is to validate the use of calibrated regression parameters for later age pavement properties.

3.2.6 Data Set 6

Data set 6 (DS6) is a collection of lime stabilized subgrade pavement cores that were obtained from roadways throughout the MDOT highway network. A total of 154 cores are included in this dataset: 54 cores were from MDOT District 1 (northeast Mississippi), 77 cores were from MDOT District 2 (northwest Mississippi), 17 cores were from MDOT District 5 (central/east Mississippi), and 6 cores were in MDOT District 6 (southeast Mississippi). Cores ranged from 13 to 54 years old. No information is known regarding target C_W or w_T during construction or the compaction effort/target density. This data set's main objective within this report is to validate the use of calibrated regression parameters for later age pavement properties.

3.2.7 Data Set 7

Data set 7 (DS7) was collected during the development of laboratory protocols to simulate later age pavement properties on laboratory compacted specimens cured in a 158°F water bath (i.e., hot cured). A total of 91 specimens are included in DS7 and a total of 128 tests are reported. All specimens were compacted with the PM Device in a laboratory setting. A target cement content (C_w) of 5% and a target w_T of 12.0% was used in all specimens. The majority of specimens were compacted with 5 N_{BL} but some specimens were compacted with 4 and 7 N_{BL}. Specimens were tested between 2, and 100 days. Histograms showing the distribution of these target properties are provided in Figure 3.5.

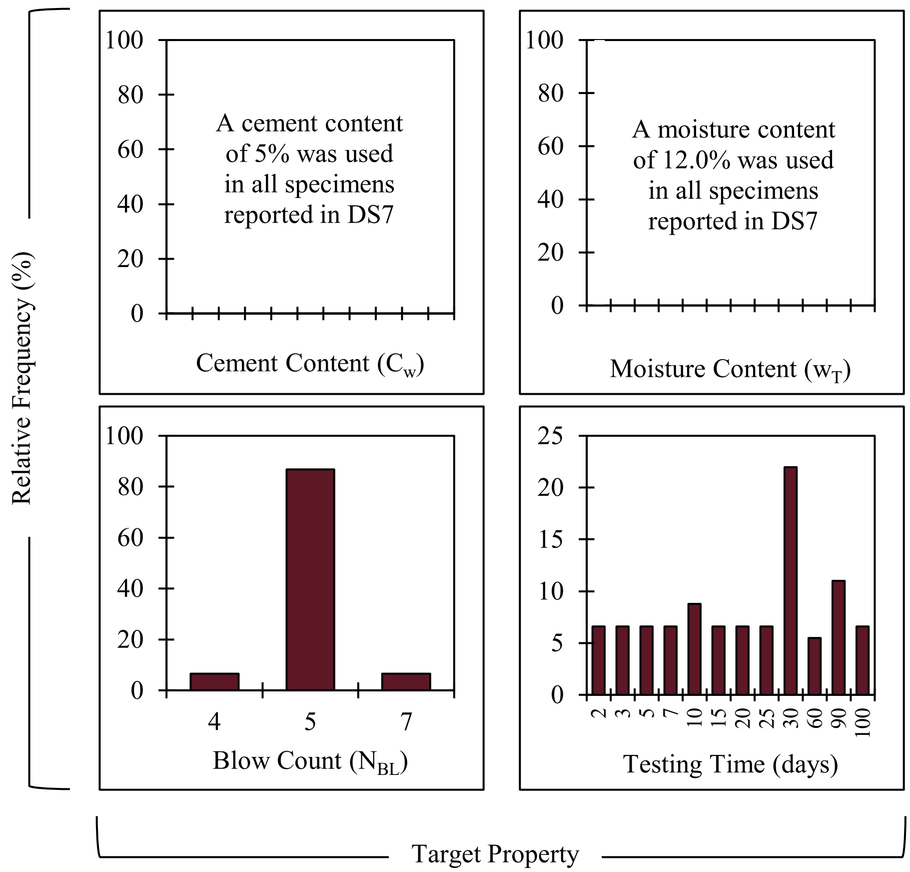


Figure 3.5. Histograms of Target Properties in Data Set 7 (DS7)

3.2.8 Data Set 8

Data set 8 (DS8) is comprised of beam specimens that were used in the development of mechanical property correlations. Beams were produced using the same materials as DS1 specimens. A total of 108 beams are included in DS8 and cores from the tested beam were used to test for UCS, E, and IDT. Target cement content (C_w) varied between 3.6 and 6.6% and target w_T of 12.0% was used in all beams. Beams were compacted with three different N_{BL}

protocols: 28 blows per layer with a standard Proctor hammer (SH28), 28 blows per layer with a modified Proctor hammer (MH28), and 56 blows per layer with a modified Proctor hammer (MH56). Beams were tested at 7, 28, and 365 days. Distributions of these target properties are provided in Figure 3.6.

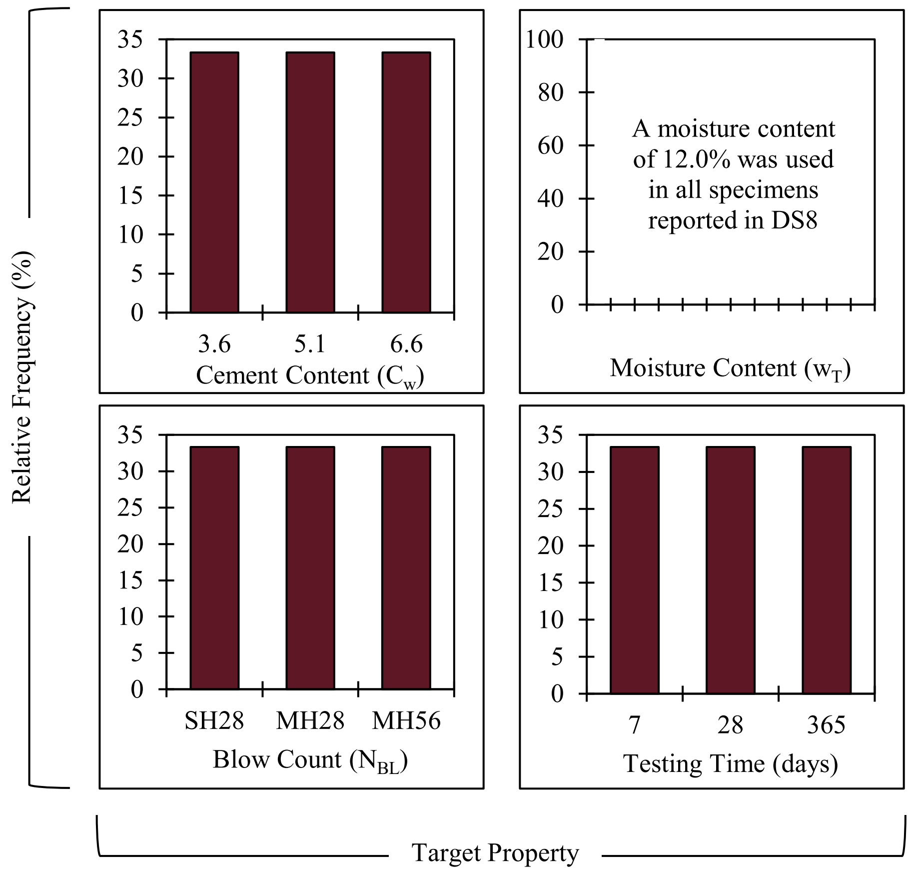


Figure 3.6. Histograms of Target Properties in Data Set 8 (DS8)

3.2.9 Data Set 9

Data set 9 (DS9) is comprised of beam specimens that were used in the development of mechanical property correlations. Beams were produced with the same materials as DS2 specimens. A total of 12 beams are included in DS9 and cores from the tested beams were used to test for UCS, E, and IDT. A target cement content (C_w) of 5.1% and target w_T of 11.3% were used in all beams. Beams were compacted using 28 blows per layer with a modified Proctor hammer (MH28). Beams were tested at 7, 28, 180, and 365 days. Distributions of these target properties are provided in Figure 3.7.

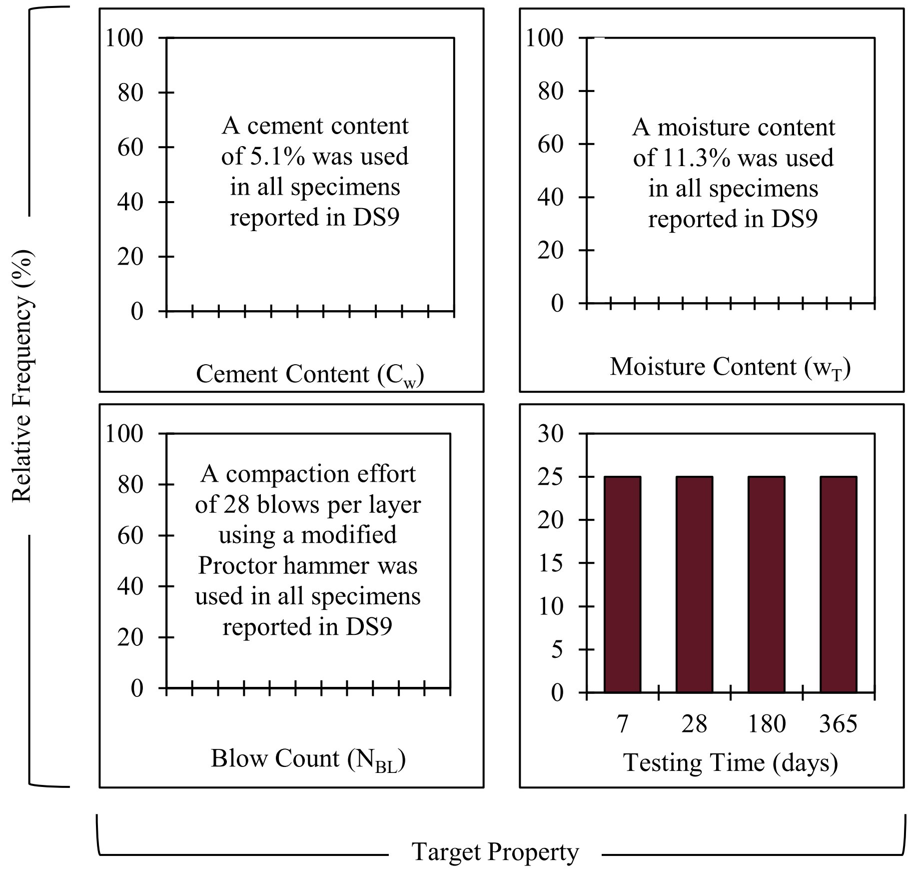


Figure 3.7. Histograms of Target Properties in Data Set 9 (DS9)

3.3 Materials

3.3.1 Soil

PM Device compacted specimens in DS1, DS2, DS3, DS4, and DS7 used 14 different soils (S1 to S14). The majority of these soils were AASHTO A2-4 soils with no plasticity. Soils 9 through 14 varied in soil classification and all had associated plasticity index (PI) values. Fundamental properties of these 14 soils including Atterberg Limits, gradation, AASHTO T88 test results, AASHTO 99 test results, AASHTO T134 test results, and soil classification are provided in Table 3.2.

Table 3.2. Fundamental Soil Properties

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
Att. Limit	LL	---	---	---	---	---	---	---	---	---	29	25	25	30	39
	PL	NP	NP	NP	NP	NP	NP	NP	NP	NP	14	13	17	20	18
	PI	NP	NP	NP	NP	NP	NP	NP	NP	NP	15	12	8	10	21
Percent Passing (%)	1/2"	100	100	100	100	100	100	100	100	82	99	---	100	100	100
	3/8”	95	100	100	100	100	100	100	100	82	99	90	100	100	100
	No. 4	92	100	100	100	100	98	100	83	66	87	82	100	100	99
	No. 10	88	99	99	100	99	93	100	73	58	74	77	100	100	98
	No. 40	71	91	80	95	91	91	87	54	38	69	76	96	98	98
	No. 60	33	72	60	63	56	69	44	22	27	66	39	87	95	97
	No. 200	17	16	20	22	27	13	19	15	19	44	24	45	93	93
T88	Silt (%)	4	7	8	7	8	5	7	3	13	22	7	11	70	68
	Clay (%)	12	8	12	18	20	7	12	8	5	22	11	17	22	24
T99	γ_d (pcf)	114.5	110.0	116.1	114.5	121.5	107.7	117.3	121.4	114.8	113.3	124.6	114.3	111.3	107.8
	OMC (%)	13.6	13.0	11.6	13.8	11.0	13.7	12.1	11.2	14.3	15.0	9.9	14.0	14.5	16.2
T134	γ_d (pcf)	117.4	114.1	119.8	113.1	120.8	111.5	121.0	124.8	113.2	111.2	125.6	114.8	112.3	101.2
	OMC (%)	13.5	13.0	11.8	14.0	11.4	13.1	11.7	10.3	15.5	14.0	10.3	14.6	15.2	17.3
Soil Class	USCS	SMd	SMd	SM	SM	SM	SP-SM	SMd	SP-SM	SP-SM	SC	SC	SC	CL	CL
	AASHTO	A2-4	A2-4	A2-4	A2-4	A2-4	A2-4	A2-4	A2-4	A1	A6	A2-6	A4	A4	---
	MDOT	9B	9B	9C	9C	9C	9B	9C	---	---	---	---	---	---	---
	SS285 DS	1,7,8	2,9	3	3	3	3	3	3	3	3	3	3	3	4

Notes: Att. Limit – Atterberg Limits; LL – liquid limit; PL – plastic limit; PI – plasticity index; T88 – AASHTO T88; T99 – AASHTO T99; γ_d – dry density; OMC – optimum moisture content; T134 – AASHTO T134; SS285 DS – data set referenced in this report; NP – not plastic; --- indicates data not known.

3.3.2 Cementitious Materials

Four cements and one hydrated lime were used as stabilizing materials in this report. Material properties of three of these cements are reported in Table 3.3. Properties of the cement used in DS2/DS9 and lime used in DS4 (i.e. stabilizing materials used at the NCAT test section) were evaluated in accordance with ASTM C150 and ASTM C977, respectively, but individual properties were not recorded. As discussed in Section 3.2, varying stabilization contents were utilized in this report.

Table 3.3. Cementitious Material Properties

Property	C1	C2	C3
SiO_2 (%)	19.9	19.4	19.9
Al_2O_3 (%)	4.8	4.8	4.7
Fe_2O_3 (%)	3.4	3.3	3.4
CaO (%)	64.1	64.5	64.5
MgO (%)	1.1	1.0	1.2
SO_3 (%)	3.3	3.2	3.7
C_3S (%)	60.4	64	60
C_2S (%)	11.3	6	11
C_3A (%)	6.8	7	7
C_4AF (%)	10.4	10	10
Limestone (%)	1.7	4.2	2.5
LOI (%)	1.7	2.4	2.2
Blaine (m^2/kg)	405	420	379
Initial Vicat (min)	90	107	101
1-day strength (psi)	2,408	---	2,321
3-day strength (psi)	4,148	4,351	3,771
7-day strength (psi)	5,105	5,482	4,786
Plant of Origin	Holcim; Theodore, AL	Holcim; Theodore, AL	Holcim; Theodore, AL
Sample Date	2012	2018	2010
SS285 DS Allocation	1,3,8	7	3

Note: 1, 3, and 7 day compressive strengths were recorded according to ASTM C109; properties of cement and lime used at NCAT test section were not recorded.

3.4 Specimen Preparation and Production

Specimens were either field compacted using a PM Device, laboratory compacted using a PM Device, cored from pavements, or laboratory compacted beams. Details on each specimen preparation method are below.

3.4.1 Field Compacted PM Device Specimens

Field compacted PM Device specimens were included in DS1, DS2, and DS4 (Figure 3.8). Sampling of these specimens varied slightly depending on if they were cement stabilized soil specimens or lime stabilized subgrade specimens. Soil-cement specimens were sampled after the final mixing pass and then immediately compacted. Subgrade-lime specimens were sampled after the final mixing pass but allowed to mellow for 1 day prior to compaction. All specimens were compacted with the PM Device and followed protocols outlined in AASHTO PP 92. Both 3 by 6 inch (PM3x6) and 4 by 8 inch (PM4x8) specimens were made during field compaction. PM3x6 specimens were compacted in 3 lifts while PM4x8 specimens were compacted in 4 lifts; the number of blows per layer varied. Between compaction layers, the surface was scarified to avoid delamination. Once compacted, specimens were topped with a plastic cap and transported in an air conditioned van back to MSU for testing.

Figure 3.8. Field Compacted PM Device Specimen Overview

3.4.2 Laboratory Compacted PM Device Specimens

Laboratory compacted PM Device specimens were included in DS1, DS2, DS3, DS4, and DS7 (Figure 3.9). Materials were mechanically mixed and then either compacted immediately after mixing (base materials) or allowed to mellow for one day (subgrade materials). All specimens were compacted using the PM Device and followed protocols outlined in AASHTO PP 92. PM3x6 specimens were compacted in 3 lifts while PM4x8 specimens were compacted in 4 lifts; the number of blows per layer varied. Between compaction layers, the surface was scarified to avoid delamination. Once compacted specimens from DS1, DS2, DS3, and DS4 were topped with a plastic cap and then cured in a moist curing room kept at 73.5 ± 3.5°F and 100% relative humidity. After approximately 1 day specimens were removed from plastic molds and placed back into the moist curing room until mechanical testing.

Specimens cured in DS7 were cured in a hot water bath kept at 158°F and required additional specimen preparation prior to curing. Once compacted, plastic lids were taped with electrical tape at the top and bottom of each specimen to provide water proofing. Specimens were then placed in two large plastic bags and then submerged in a room temperature water bath. Specimens were kept in the room temperature water for 1 day and then the bath was turned on and heated to 158°F over 3 hours. Specimens were removed from the hot water bath approximately 6 hours prior to testing to allow time to return to room temperature.

Figure 3.9. Laboratory Compacted PM Device Specimen Overview

3.4.3 Field Cores

Field cores were sampled from 45 pavement sections dispersed throughout MDOT's roadway network between 2017 and 2019 as part of MDOT SS263 and made available for this study. Three to five locations were cored within each pavement section. A tractor mounted coring rig with a 6 inch bit was used to obtain cores. The original test plan intended for 3 cores to be sampled from each pavement section location, but it was often difficult to get 3 intact CSM cores due to pavement structure depth which often led to deviation from the test plan. In some cases, only 1 or 2 cores were sampled from a given pavement section. Core had height to diameter (h:d) ratios ranging from 1.1:1 to 2.2:1. Once sampled, cores were placed in plastic bags to control moisture and transported to a laboratory for mechanical testing.

Research by Ayers (2022) showed there were no significant relationship between height to diameter ratio and mechanical properties. Cement stabilized specimens compacted with the PM Device were cut to h:d ratios of 2:1, 1.7:1, 1.4:1, and 1.15:1 and average unconfined compressive strengths of each h:d ratio was not significantly different from one another (Table 6.9 in Ayers, 2022). A similar trend was also seen for PM Device specimens tested in indirect tension as a weak correlation of R^2 = 0.04 was reported for the correlation between indirect tensile strength and h:d ratio (Figure 6.10b in Ayers, 2022).

3.4.4 Laboratory Compacted Beams

Beams for DS8 and DS9 were compacted in a 4 inch by 4 inch by 16 inch metal concrete beam molds (Figure 3.10). During compaction, one mold was placed in a wooden frame and a second beam mold with no base plate was attached upside down and secured with clamps to act as a "collar" during compaction (similar to the collar used in the PM Device). Beams were compacted in 3 lifts and scarified between layers. Compaction was performed in a 14 blow grid pattern to standardize compaction efforts. Once compaction was complete, the "collar" was removed and leveled with a straight edge. Specimens were then covered with dampened towels and saran wrap to prevent moisture loss and cured in a 73°F moist curing room.

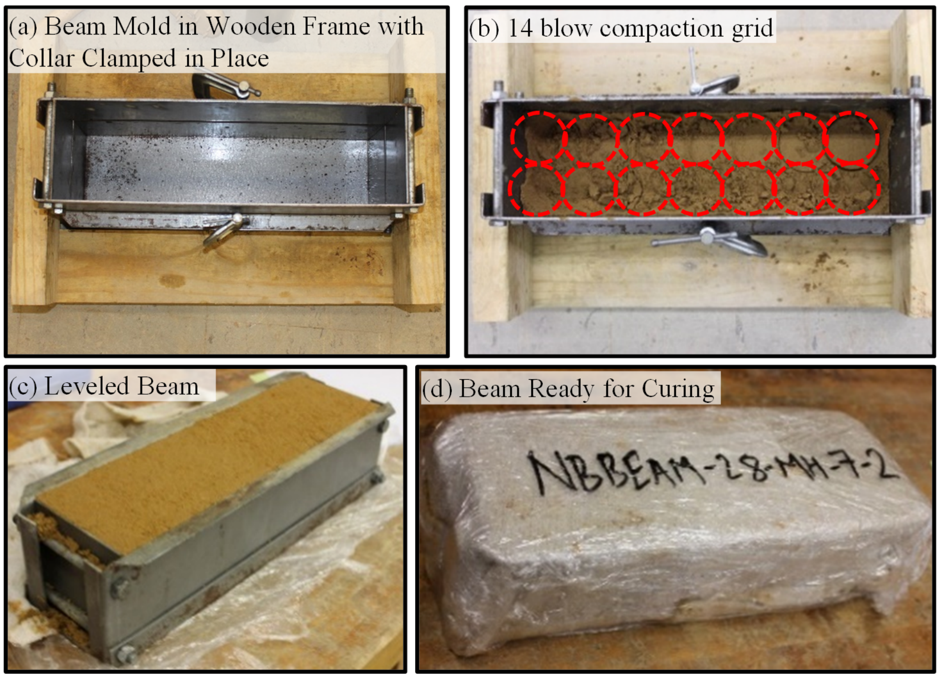


Figure 3.10. Laboratory Compacted Beams Overview

3.5 Mechanical Testing Methods

Four mechanical properties were recorded: unconfined compressive strength (UCS), modulus of elasticity (E), indirect tensile strength (IDT), and modulus of rupture (MOR) (Figure 3.11). UCS was conducted in accordance with ASTM D1633 with no soaking period. Specimens were loaded at a rate of 0.05 in/min. Load measurements were taken every 10 seconds until failure. The UCS value was then calculated by converting the highest recorded load reading to a stress measurement.

E testing utilized a modulus collar to measure vertical deflection during loading as outlined in ASTM C469. Specimens were loaded at a rate of 0.05 in/min. Deflection readings were taken every 5 to 10 seconds and then converted to strain so that a stress-strain relationship could be developed. Minor modifications were made from ASTM C469 based on specimen availability. Typically, UCS values used to determine the 40% loading are based on two UCS values, but in this work only 1 UCS value was used to determine the 40% loading capacity. Additionally, due to machine limitations specimens were not unloaded at a constant load rate.

IDT was measured in accordance with ASTM C496. Wooden bearing strips were placed on the top and bottom of the specimen. Specimens were loaded at a rate of 105 psi/min. A preload of 250 lbs was used as the machine operated on a closed feedback loop and the machine would stop testing if no load was detected.

MOR was measured in accordance with ASTM D1635. A third point loading head with load points 4 inches apart from one another was used with a base plate with loading points 12 inches apart. The beam was tested at a load rate of 105 psi/min with a preload of 250 lbs similar to IDT testing. Once the beam had broken, the two beam halves were cored to obtain two additional specimens to test IDT and UCS/E. Cores were then trimmed to produce level ends and then tested for mechanical properties identically to PM device specimens.

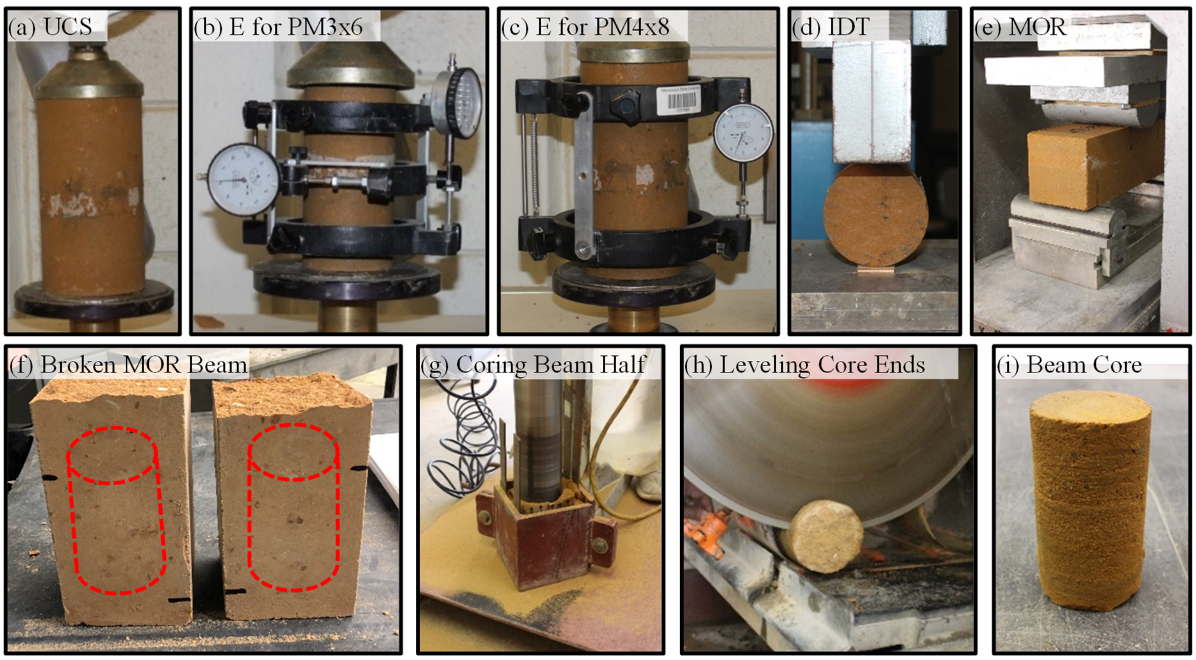


Figure 3.11. Mechanical Testing Methods

3.6 Data Analysis Methods to Optimize Regression Parameters

Optimization calculations used to determine regression parameters to forecast and backcast properties were performed in Excel where experimental data was used with equations from literature. All initial prediction calculations were performed using the published regression parameters from each reference (e.g., for Equation 1, p_1 and p_2 were initially set to 1.59 and 1.61, respectively). From this, an error term (calculated as predicted minus actual strength) was calculated for each specimen, and each error term was squared and summed to determine the root mean square error (RMSE), shown in Equation 6. RMSE was chosen as the error metric for this effort to minimize large errors as much as possible while not weighting small errors heavily (Chai and Draxler, 2014). RMSE is commonly used for various property prediction efforts of construction materials including concrete (Ashrafian et al., 2018; Ly et al., 2021) and asphalt (Hosseini et al., 2021; Omranian et al., 2021).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{predicted} - \mathrm{actual})^2} \quad (6)$$

Regression parameters in each of these equations were then optimized to the data set using Excel solver with the generalized reduced gradient (GRG) method where the objective was to minimize the RMSE of the data set. This iterative method looks at the gradient of the objective function (in this case minimizing RMSE) and changes the variables (i.e. strength equation constants) to reach an optimal solution where the partial derivatives equal zero (Lasdon et al., 1974; Smith and Lasdon, 1992). Solver usually converged to a solution within five to ten iterations. GRG optimization is commonly used in optimization procedures and has been used to calibrate MEPDG constants for local materials in Tennessee, Kansas, Iowa, Nevada, and Canada (Gong, 2018; Sufian, 2016; Ceylan et al., 2013; Nabham, 2015; Esfandiarpour and Shalaby, 2017).

CHAPTER 4 – RESULTS AND DISCUSSION

4.1 Overview of Results

This section outlines relevant results based on analysis of the nine data sets discussed in this report. The majority of this results section centers on the analysis of regression parameters to forecast and backcast mechanical properties. A detailed analysis of mechanical property correlations is provided in Ayers (2022) and a condensed overview is provided herein for brevity.

4.2 Expected Range of Mechanical Properties at 28 Days

Mechanical properties of cement stabilized base soil and lime stabilized subgrade were analyzed to determine an expected range of mechanical properties at 28 days (UCS_{28}, E_{28}, and IDT_{28}). DS1, DS2, and DS3 were used for cement stabilized base while DS4 was used for lime stabilized subgrade. On average for cement stabilized soil, UCS_{28} values were 308 psi, E_{28} values were 822 ksi, and IDT_{28} values were 43 psi; however, for lime stabilized subgrade, UCS_{28} values were 73 psi, E_{28} values were 93 ksi, and IDT_{28} values were 17 psi. The distribution of these properties can be seen in Figure 4.1 along with the number of specimens considered (n), average strength (avg), and standard deviation (σ). When looking at UCS_{28} values, 70% of cement stabilized soil fell within one σ of the average while for lime stabilized soil 74% of recorded UCS_{28} values fell within one σ. For E_{28}, 75% of recorded values for cement stabilized soil and 69% of recorded values for lime stabilized soil fell within one σ of their respective averages. For IDT_{28}, 61% of cement stabilized soil and 89% of lime stabilized soil fell within one σ of their respective averages.

When evaluating extreme strength values of cement stabilized soil, the lowest recorded UCS_{28} strength was 123 psi while the highest recorded UCS_{28} was 622 psi. The lowest recorded E_{28} strength for cement stabilized soil was 235 ksi while highest recorded E_{28} was 2639 ksi. As seen in Figure 4.1, the maximum E_{28} appeared to be an outlier as there is a meaningful gap between this value and the next highest E_{28} value of 1552 ksi. The lowest recorded IDT_{28} for cement stabilized soil was 20 psi while the highest recorded IDT_{28} was 100 psi.

When evaluating the extreme strength values of lime stabilized subgrade, the lowest recorded UCS_{28} was 38 psi while the highest recorded UCS_{28} was 140 psi. The lowest recorded E_{28} was 30 ksi while the highest recorded E_{28} was 182 ksi. The lowest recorded IDT_{28} was 12 psi while the highest recorded IDT_{28} was 30 psi. It is important to note that all lime stabilized subgrade evaluated from DS4 mellowed for one day prior to compaction.

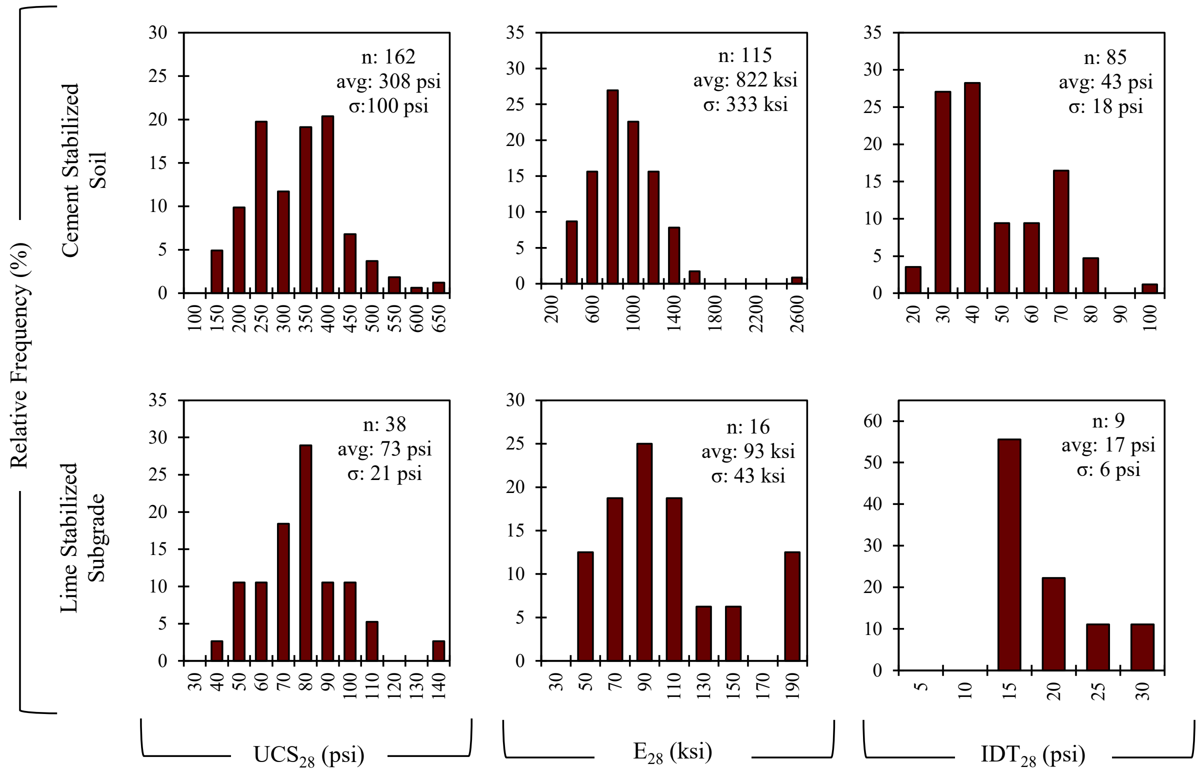


Figure 4.1. Distribution of 28 Day Mechanical Properties for Cement Stabilized Soil and Lime Stabilized Subgrade

4.3 Conversion Factors between Mechanical Properties

Several conversion factors were developed between mechanical properties of PM Device specimens and beams/cores from beams. A full description of these conversion factors can be found in Ayers (2022); however, a condensed overview of those findings are presented herein for brevity. Mechanical property relationships evaluated by Ayers (2022) included: elastic modulus to unconfined compressive strength (E:UCS), indirect tensile strength to unconfined compressive strength (IDT:UCS), modulus of rupture to unconfined compressive strength (MOR:UCS) and modulus of rupture to indirect tensile strength (MOR:IDT).

Generally speaking, the E:UCS ratio of 1200:1 recommended by the MEPDG is a conservative estimate for cement stabilized specimens less than 5 years old. A more realistic E:UCS relationship to use as a Level 2 input within the MEPDG framework is 2500:1 for cement stabilized specimens. An E:UCS ratio of 1200:1 provided a reasonable correlation for lime stabilized subgrade.

An IDT:UCS relationship of 0.15:1 produced a strong correlation and was within the expected ranges given in literature. Relationships between MOR:IDT and MOR:UCS were developed from beams and subsequent cores from beam halves. The most realistic MOR:IDT relationship was determined to be a logarithmic trend where MOR = 74*ln(IDT) – 183 and both terms are in psi units. This relationship produced an R^2 value of 0.74 and was determined using data with range of compaction efforts, stabilizing material percentages, and curing conditions. The most realistic MOR:UCS relationship was determined to be a logarithmic trend where MOR = 69*ln(UCS) – 297 and both terms are in psi units. This relationship also produced an R^2 value of 0.74 and was determined using data with range of compaction efforts and stabilizing material percentages.

In pavement design, use of an IDT:UCS ratio of 0.15 where UCS is measured, and IDT is estimated is suggested. If MOR is desired, obtaining this value from UCS is suggested by way of the equation in the previous paragraph. UCS and E are suggested for measurement in pavement design, and any need for IDT or MOR calculated from the relationships presented in the previous paragraph. In some cases, measurement of UCS and calculation of E is also suggested depending on the size and importance of a given design.

4.4 Evaluation of Equations from Literature to Predict UCS

Table 2.5's equations were compared to DS1, DS2, DS3, and DS4 using regression parameters published in literature. For Equations 1, 2, and 5, strengths at ages ranging from 1 to 1095 days were estimated based on a 28 day strength. For Equations 3 and 4, 28 and 90 day strengths were estimated based on a 7 day strength. To assess the accuracy of predicted strengths, an equality plot with a linear regression through the origin (RTO) was used to determine whether, on average, strengths were over predicted (RTO slope greater than 1) or under predicted (RTO slope less than 1). Equality plots were made for each equation to assess published regression constants to Mississippi materials (Figure 4.2).

Equation 1 yielded the most accurate predictions for cement stabilized base (DS1, DS2, and DS3) on average ranging from 8% less than actual UCS values to 7% greater than actual UCS values. Equation 2 (originally calibrated for cement treated aggregate base) noticeably underpredicted UCS for cement stabilized soil while Equations 3 and 4 noticeably overpredicted UCS and predicted values were approximately 45% greater than actual values. UCS data to use in Equation 4 was limited due to a small amount of 90 day UCS values in these data sets. Equation 5 reasonably predicted UCS overall, and was notably more accurate than Equations 2, 3, and 4. In the case of lime stabilized subgrade Equations 1, 2, and 5 meaningfully under predicted UCS values; however, Equation 3 significantly over predicted UCS values. With the exception of Equation 1, which was developed using nine different soil mixtures, Equations 2 to 5 were calibrated for use with cement stabilized material and not lime stabilized material. This could account for the decrease in prediction accuracy for DS4.

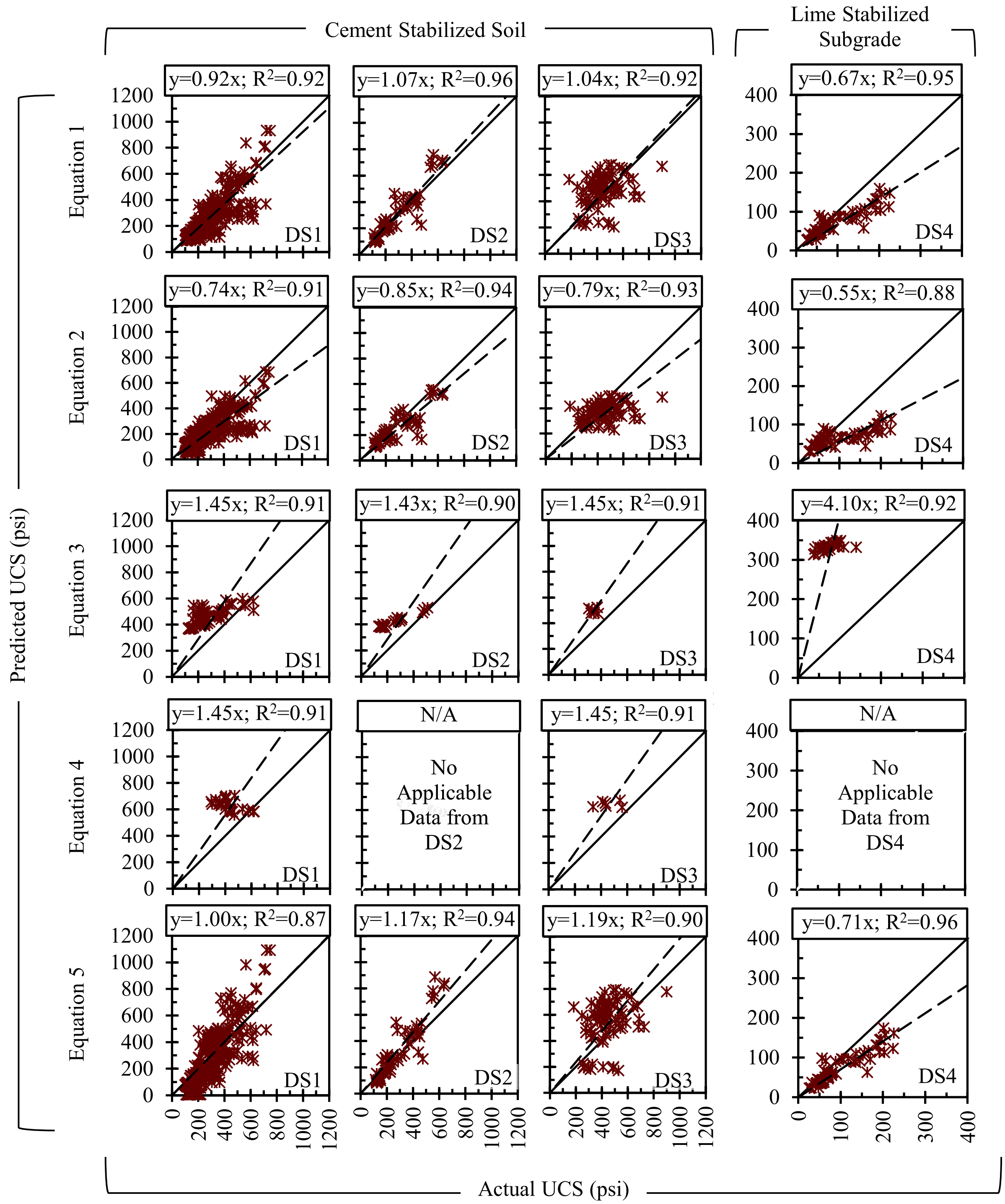


Figure 4.2 Comparison of Strength Prediction of Table 2.5 Equations with Published Regression Parameters to Experimental Data Sets

For each of these equations, regression parameters were then optimized to best fit the data sets using the data analysis techniques discussed in Section 3.6. Table 4.1 compares the prediction accuracy of equations with regression parameters published in literature and optimized regression parameters. In almost all cases optimizing regression parameters improved prediction accuracy. RTO slopes of optimized data sets were less than 1 indicating that on average, predictions were conservative. Additionally, RMSE meaningfully decreased when regression parameters were optimized, especially for Equations 3 and 4 which were linear regressions. This emphasizes the importance of using appropriate regression parameters (i.e., local calibration is valuable for the MEPDG) for forecasting and backcasting calculations.

Table 4.1. Original and Optimized Regression Parameters to Predict UCS

Data Set	Regression Parameters		Table 2.5 Equation 1	2	3	4	5
DS1	Original (Table 2.5)	p_1	1.59	2.50	0.695	0.763	0.026
		p_2	1.61	0.90	295	427	0.293
		RTO Slope	0.92	0.74	1.45	1.45	1.00
		RMSE	93	114	198	231	128
	Optimized	p_1	1.47	0.10	0.93	0	1.04
		p_2	1.59	0.69	61.4	429	0.16
		RTO Slope	0.89	0.92	0.93	0.96	0.93
		RMSE	92	94	84	87	91
DS2	Original (Table 2.5)	p_1	1.59	2.50	0.695	---	0.026
		p_2	1.61	0.90	295	---	0.293
		RTO Slope	1.07	0.85	1.43	---	1.17
		RMSE	76	83	182	---	105
	Optimized	p_1	1.37	0.17	1.43	---	0.93
		p_2	1.27	0.75	0	---	0.17
		RTO Slope	0.96	0.96	0.99	---	0.95
		RMSE	67	68	32	---	66
DS3	Original (Table 2.5)	p_1	1.59	2.50	0.695	0.763	0.026
		p_2	1.61	0.90	295	427	0.293
		RTO Slope	1.04	0.79	1.45	1.45	1.19
		RMSE	143	138	158	208	197
	Optimized	p_1	1.44	0.04	0	0.50	1.17
		p_2	4.84	0.77	341	307	0.05
		RTO Slope	0.91	0.93	0.99	0.97	0.93
		RMSE	121	118	26	75	119
DS4	Original (Table 2.5)	p_1	1.59	2.50	0.695	---	0.026
		p_2	1.61	0.90	295	---	0.293
		RTO Slope	0.67	0.55	4.10	---	0.71
		RMSE	44	58	260	---	39
	Optimized	p_1	3.99	0.20	1.03	---	1.38
		p_2	4.21	0.44	17.7	---	0.42
		RTO Slope	0.96	0.96	0.94	---	0.96
		RMSE	24	24	19	---	24

Notes: Original p_1 and p_2 from literature are in Table 2.5; Optimized p_1 and p_2 found using data analysis techniques discussed herein and are all for time in months; RMSE calculated using Equation 6; --- indicates no data available

4.5 Evaluation of Equations from Literature to Predict E and IDT

With the exception of Equation 1, Table 2.5 equations are only intended to forecast and backcast UCS; however, their applicability to other mechanical properties is unknown. Regression parameters in Table 2.5 equations were optimized to forecast and backcast E and IDT strength development (Table 4.2). When regression parameters were optimized, equations were able to reasonably predict E and IDT. For elastic modulus, predictions were generally conservative and on average ranged from 86% to 99% of experimentally reported E. IDT strength predictions were also relatively conservative; however, predicted values on average ranged from 85% to 106% of experimentally reported IDT values. RMSE values for linear trends (Equations 3 and 4) were lower in some cases, but these equations used smaller subsets of data compared to Equations 1, 2, and 5 and, if not calibrated correctly, can produce poor predictions. As a result, linear trends were not analyzed going forward.

In previous research (Wen et al., 2014) it was found that UCS and IDT strength development could be modeled using the same equation and regression parameters. When comparing predicted IDT values based on regression parameters from Wen et al. (2014), original parameters generally produced higher RMSE values compared to optimized regression parameters. For most cement stabilized soils, there were not meaningful differences between original and optimized parameters; however, for lime stabilized subgrade there was a noticeable difference in prediction accuracy when optimized regression parameters were used.

Table 4.2. Optimization of Regression Parameters to Predict E and IDT

Mechanical Property	Data Set	Regression Parameters	Table 2.5 Equation				
			1	2	3	4	5
E (ksi)	DS1	p_1	1.30	0.08	0.71	0	0.93
		p_2	1.32	0.81	310	1170	0.11
		RTO Slope	0.91	0.90	0.94	0.90	0.89
		RMSE	250	248	179	384	258
	DS2	p_1	1.40	0.19	1.42	---	0.92
		p_2	1.24	0.73	2.54	---	0.19
		RTO Slope	0.91	0.90	0.93	---	0.90
		RMSE	250	251	176	---	244
	DS3	p_1	1.16	0.07	0.37	0	0.99
		p_2	1.20	0.87	573	1101	0.06
		RTO Slope	0.92	0.92	0.99	0.99	0.91
		RMSE	344	343	43	134	345
	DS4	p_1	5.47	0.41	0	---	1.71
		p_2	2.36	0.25	119	---	0.82
		RTO Slope	0.87	0.86	0.95	---	0.87
		RMSE	112	112	28	---	112
IDT (psi)	DS1	p_1	1.36	0.11	1.11	0	0.96
		p_2	1.39	0.75	5.02	67	0.14
		RTO Slope	0.90	0.91	0.96	0.97	0.91
		RMSE	16	16	10	13	15
	DS2	p_1	26661	0.16	1.32	---	1.01
		p_2	209	0.68	0	---	0.20
		RTO Slope	1.02	0.95	0.98	---	0.96
		RMSE	10	11	5		10
	DS3	p_1	---	---	---	---	---
		p_2	---	---	---	---	---
		RTO Slope	---	---	---	---	---
		RMSE	---	---	---	---	---
	DS4	p_1	2.58	0.16	---	---	1.63
		p_2	1.50	0.46	---	---	0.25
		RTO Slope	0.99	0.96	---	---	0.97
		RMSE	6	6	---	---	6

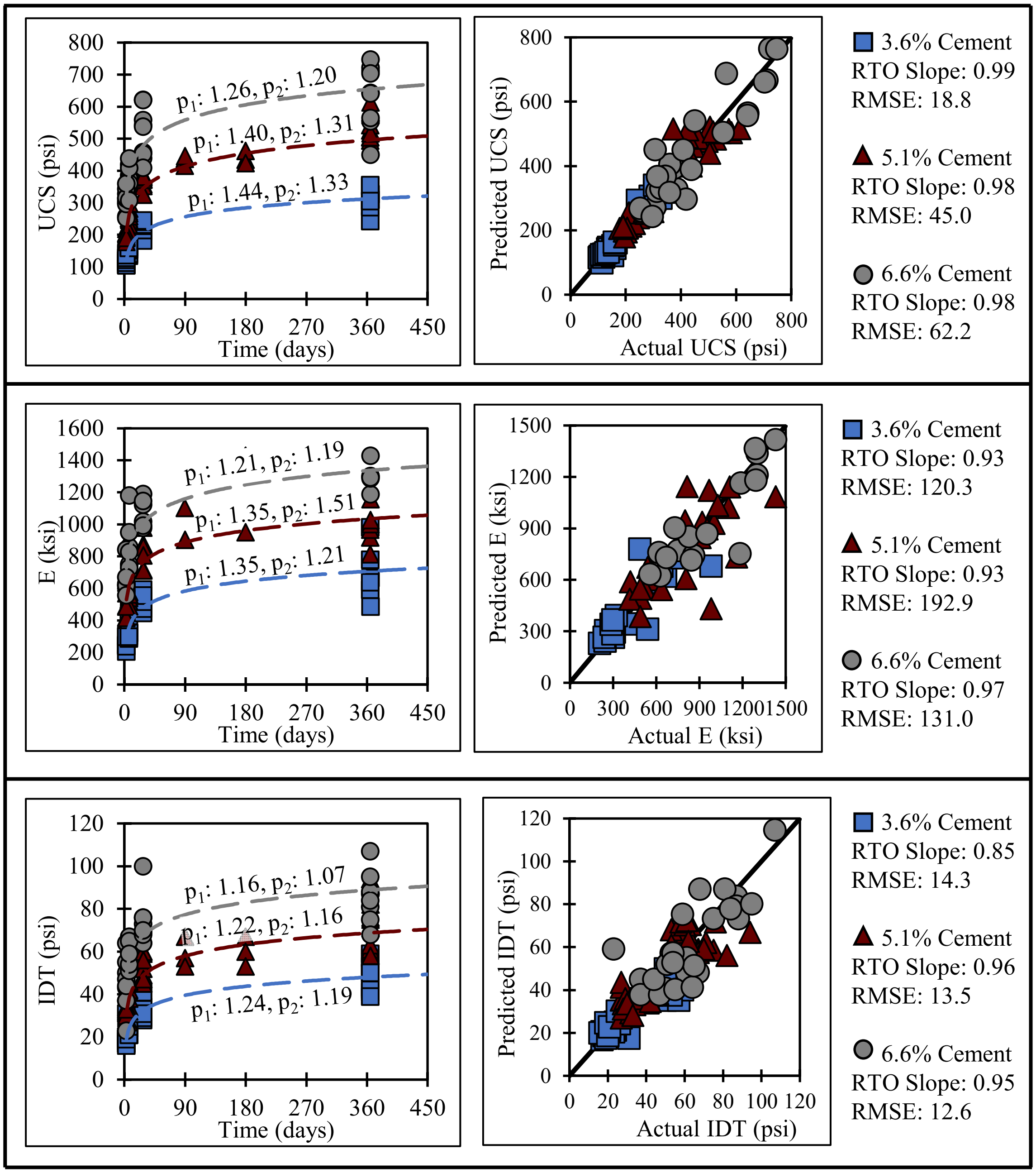
Notes: Optimized p_1 and p_2 found using data analysis techniques discussed herein; --- indicates no data available

If a user desires to predict or backcast/forecast MOR based on IDT, an equation was presented in Section 4.3 to convert IDT to MOR. A user could elect to use the IDT backcast/forecast equations, and then convert to MOR in this manner. If this occurs based on IDT, the Table 4.2 coefficients are suggested for use. As stated in Section 4.3, UCS is the most recommended measurement, and an equation is presented to convert UCS to MOR. A user could elect to use the UCS backcast/forecast equations, and then convert to MOR in this manner. If this occurs, the Table 4.1 optimized coefficients are suggested for use.

4.6 Effects of Blow Count and Cement Content on Regression Parameters

DS1 had multiple groups of data where the number of blows per layer (N_{BL}) and cement content (C_w) were varied to determine their effects on mechanical property development over time. Equation 1 was used to determine the statistical effects of N_{BL} and C_w on regression parameters. Analysis of variance (ANOVA) tests at a 0.05 significance level were used to determine statistically significant variables. 242 PM3x6 specimens were produced and tested for mechanical properties at 1, 3, 7, 28, 90, 365, 730, and 1095 days where the only variable was N_{BL} (4, 5, 6, 7, and 8). ANOVA tests revealed that N_{BL} did not significantly affect UCS (*p*-value: 0.27), E (*p*-value: 0.80), or IDT (*p*-value: 0.99). As a result, N_{BL} did not meaningfully affect regression parameters used to backcast or forecast strength. This finding is encouraging from a DOT operations standpoint as the parameters are rugged enough to manage expected deviations in compaction effort from project to project.

Additional PM3x6 and PM4x8 data groups from DS1 were used to evaluate the effects of cement content (C_w) on regression parameters. As cement content increased from 3.6 to 6.6%, the overall logarithmic strength gain trend also increased but optimized constants for these data sets generally decreased for all mechanical properties (Figures 4.3 and 4.4). When predicted values found using optimized regression parameters (for each cement content) were plotted against actual recorded values, slopes were slightly conservative (i.e., less than 1). To determine the statistical significance of C_w on regression parameters, a set of optimized parameters was found for each specimen tested that predicted an exact match for each specimen. These individually optimized parameters were then used as inputs for ANOVA analysis. There were no consistent statistical trends when evaluating the effects of C_w on regression parameters on PM3x6 or PM4x8. In some cases, C_w significantly affected both p_1 and p_2 while in other cases it made no difference. Although statistical trends were not consistent, general trends shown in Figures 4.3 and 4.4 show that C_w did visually influence regression parameters. As long as regression parameters are developed using a wide array of cement contents that are representative of the materials used, there should be manageable effects on the accuracy of predictions. Consideration for developing regression constants based on cement content would need additional research and validation.



Note: All predicted strength values were calculated using optimized regression parameters shown on logarithmic curve for each cement content and mechanical property.

Figure 4.3. Effects of Cement Content (C_w) on Regression Parameters – PM3x6

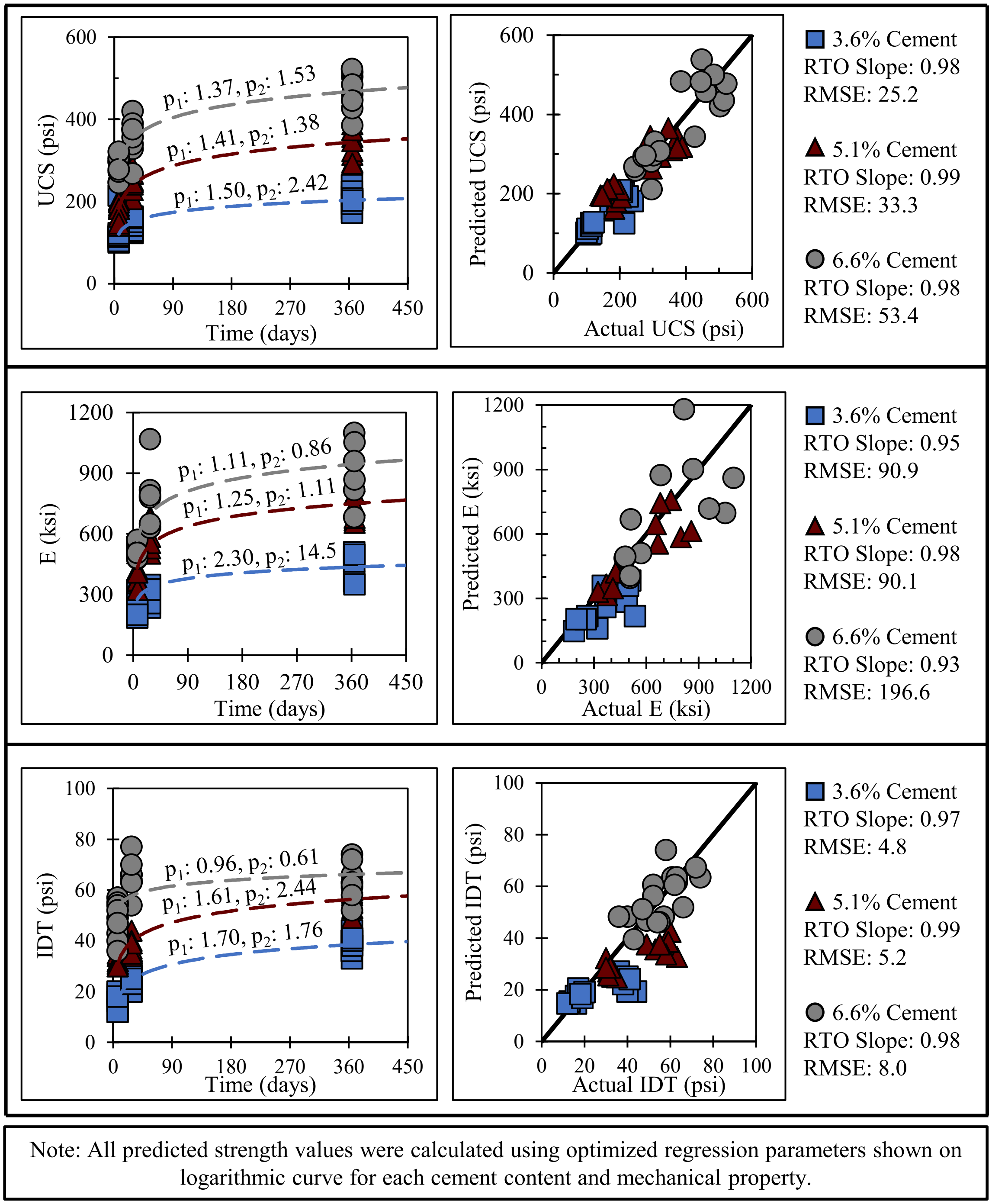


Figure 4.4. Effects of Cement Content (C_w) on Regression Parameters – PM4x8

4.7 Comparison of Equations to Accelerated Cured Laboratory and Field Core Data

Table 2.5 equations from literature are envisioned to interface with MEPDG principles to provide design inputs; however, these constants are derived from specimens cured at room temperature and 100% relative humidity and their applicability to replicate later life pavement properties is uncertain. DS5 and DS6 are comprised of late age cores (10 years or more) from the Mississippi highway network while DS7 is comprised of hot water cured specimens to replicate later life pavement properties. Laboratory cured specimens from DS1 and accelerated cured specimens from DS7 were compared to the range of properties recorded from cores to determine their applicability to determine later life mechanical properties. Specimens from DS1 and DS7 used in this analysis had identical cement contents, blows per layer, and target water contents; the only variation was method of curing.

As seen in Figure 4.5, for UCS and IDT, laboratory cured specimens are well below the average properties recorded by later life cores; however, accelerated cure specimens produced strengths that were comparable of later life cores after only 7 to 10 days of hot water curing for UCS and 25 to 30 days of hot water curing for IDT. For E, both laboratory and accelerated curing methods met the average recorded in field cores. Laboratory curing took approximately 6 months to achieve this strength while accelerated curing only took 5 to 7 days. Figure 4.5 validates that accelerated curing of chemically stabilized soil can replicate later life mechanical properties of pavements as well as that laboratory curing does not always reach these strengths, and if it does, it takes a meaningful amount of time (Ayers 2022). After 30 days of accelerated curing, UCS, E, and IDT of laboratory compacted specimens were equivalent to those of pavement cores between 10 and 54 years old. This could be an alternative to an empirical equation if mechanical properties at intermediate timeframes are not of interest.

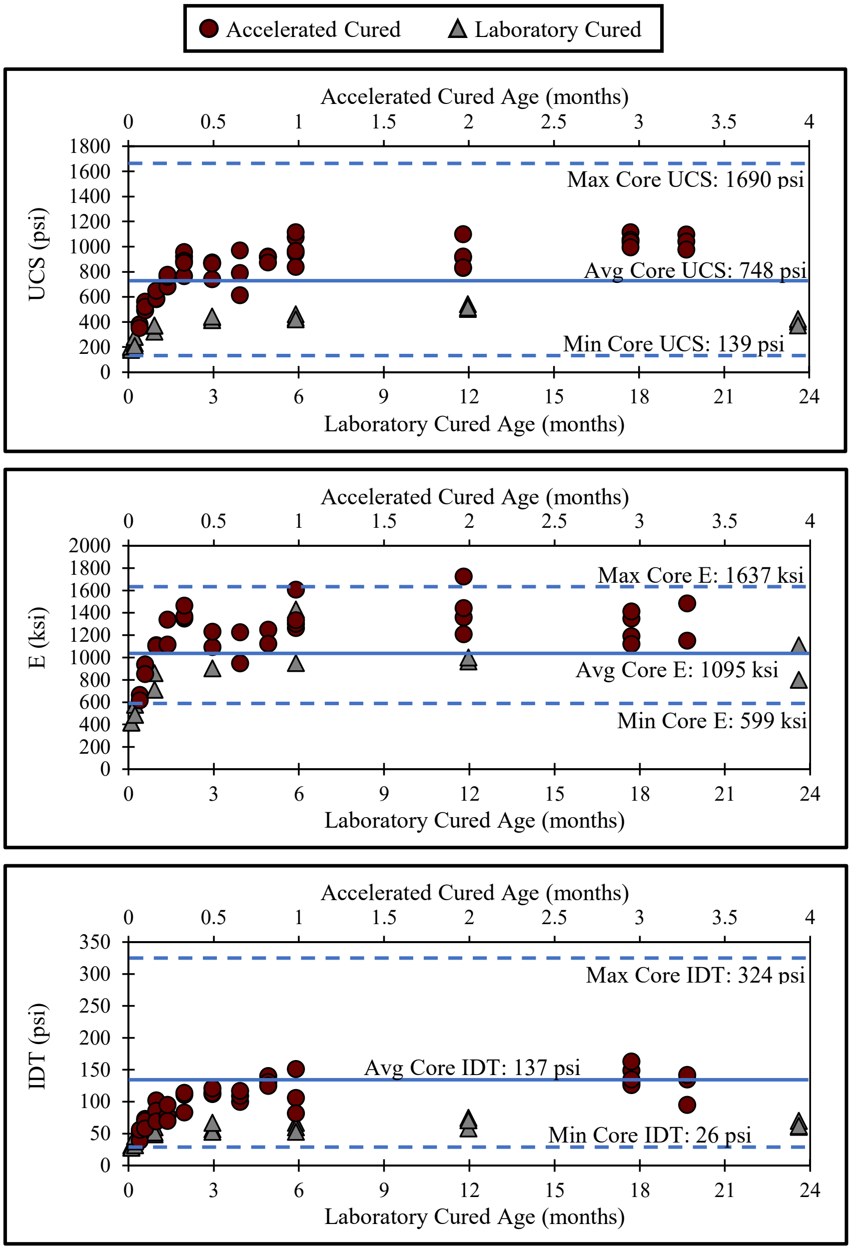


Figure 4.5. Comparison of Laboratory Cured Specimens (DS1), Accelerated Cured Specimens (DS7), and Field Cores (DS5)

Field cores were compared to equations from literature with regression parameters optimized for laboratory cured cement stabilized specimens from DS1 and lime stabilized specimens from DS4. Comparison of accelerated cure and laboratory cure cement stabilized specimens from DS1 showed that 28 day laboratory cure specimens and 2 day accelerated cured specimens produced roughly equivalent mechanical properties; therefore, mechanical properties from both curing methods were used as input into literature equations when predicting mechanical property development. For both curing protocols a t_0 value of 28/30.5 months was used. Figure 4.6 shows that regardless of whether 28 day laboratory cure or 2 day accelerated cure mechanical properties were used as equation inputs, Table 2.5 equations that used optimized regression parameters from Tables 4.1 and 4.2 predicted mechanical properties within the range of cement and lime stabilized core strengths. Table 2.5 equations generally predicted strengths that were average or lower bound strengths for both cement stabilized base and lime stabilized subgrade. Field cores had a wide range of variability which can be attributed to a number of factors including varying stabilizer dosage rates, varying target densities, etc. Despite this large variability, Table 2.5 equations were able to predict strengths within the range of strengths found in 10 to 54 year old cores indicating that these regression parameters can be used to reasonably estimate material strength for pavements that are decades old. Indirect tensile strength testing specifics are available in the State Study 276 report.

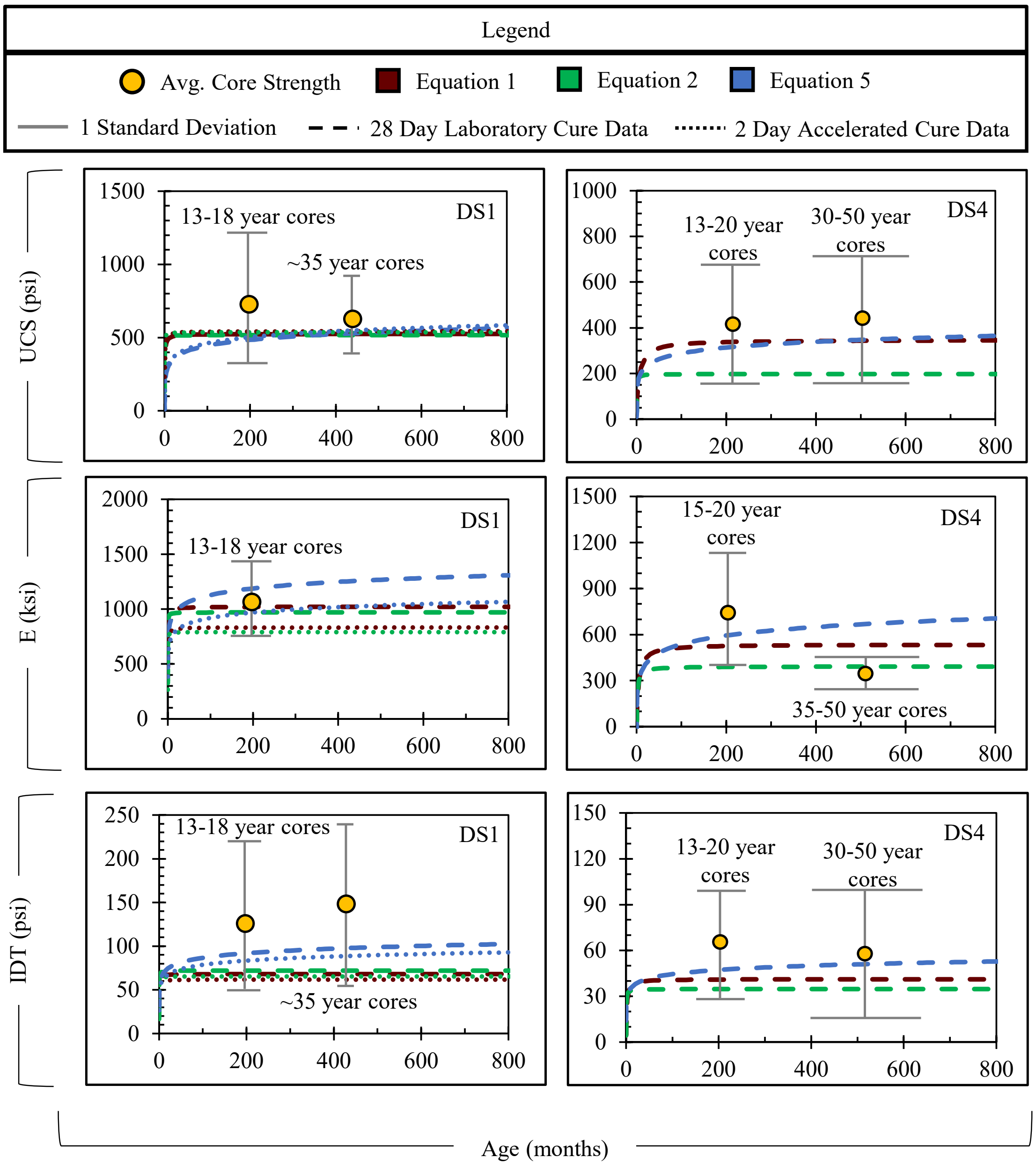


Figure 4.6. Comparison of Table 2.5 Equations with DS1 and DS4 Optimized Parameters to Field Core Data (DS5 and DS6)

CHAPTER 5 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

Nine data sets collectively encompassing approximately 2300 data points were used to complete three categories of objectives: 1) determine minimum and maximum mechanical properties at 28 days, 2) develop conversion factors between mechanical properties, and 3) evaluate strength regression parameters for forecasting and backcasting mechanical properties. Chapter 2 provided a brief literature review summarizing published mechanical property correlations as well as equations to predict mechanical property development over time. Chapter 3 summarized the nine data sets included in this study and described how specimens in each data set were produced and tested. Chapter 4 reported the results of this study with respect to the three objectives and also provided relevant discussion.

5.2 Conclusions

The following conclusions were drawn based on the analysis presented in this report. Conclusions are divided by report objective for reader convenience.

5.2.1 Range of Mechanical Properties at 28 Days

- For cement stabilized soil, minimum 28 day strength values were 123 psi for UCS, 235 ksi for E, and 20 psi for IDT while maximum 28 day strength values were 622 psi for UCS, 2639 ksi for E, and 100 psi for IDT.

- For lime stabilized subgrade, minimum 28 day strength values were 38 psi for UCS, 30 ksi for E, and 12 psi for IDT while maximum 28 day strength values were 140 psi for UCS, 182 ksi for E, and 30 psi for IDT.

5.2.2 Conversion Factors between Mechanical Properties

- The generally used E:UCS relationship of 1200:1 provided in the MEPDG is a conservative estimate. An E:UCS relationship of 2500:1 for cement stabilized soil and 1200:1 for lime stabilized subgrade were shown to accurately model the E:UCS relationship of specimens less than 5 years old.

- An IDT:UCS relationship of 0.15:1 was calculated using data with different soils, stabilizing agents, compaction effort, and curing conditions. This trend also matched many IDT:UCS trends reported in literature.

- A MOR:IDT relationship was determined to be a logarithmic trend where $MOR = 74*\ln(IDT) - 183$.

- A MOR:UCS relationship was determined to be a logarithmic trend where $MOR = 69*\ln(UCS) - 297$.

5.2.3 Regression Parameters to Forecast and Backcast Strength

- Published regression parameters underpredicted UCS; however, when regression parameters were optimized to the data sets herein, predictions were, on average, within 89 to 99% of actual UCS values.

- Strength development equations for UCS were also shown to provide reasonable predictions for elastic modulus and indirect tensile strength when regression parameters were optimized.

- Although compaction level did not statistically influence regression parameter, cement content did statistically influence regression parameters in some cases.

- Accelerated curing can produce specimens with mechanical properties similar to later life pavement cores after 30 days of curing in a 158°F water bath.

5.3 Recommendations

This work has shown that equations in Table 2.5 effectively forecast and backcast mechanical properties of chemically stabilized soils commonly used in Mississippi. Additionally, Table 2.5 equations were validated to reasonably estimate later life pavement properties using field cores and accelerated cured specimens when using optimized parameters. Recommended regression parameters are provided for use with Mississippi materials with Equations 1, 2, and 5 (Table 5.1). These recommended regression parameters were developed using all available data from DS1 through DS9 and data analysis techniques from Section 3.6.

Table 5.1 Recommended Regression Parameters to Use with Mississippi Materials

Table 2.5 Equation	Material	UCS (psi)		E (ksi)		IDT (psi)	
		p_1	p_2	p_1	p_2	p_1	p_2
Eq. 1	Cement Stabilized Base	1.40	1.54	1.21	1.15	1.40	1.45
	Lime Stabilized Subgrade	3.99	4.21	5.47	2.36	2.58	1.50
Eq. 2	Cement Stabilized Base	0.10	0.73	0.08	0.83	0.12	0.74
	Lime Stabilized Subgrade	0.20	0.44	0.41	0.25	0.16	0.46
Eq. 5	Cement Stabilized Base	1.01	0.14	0.92	0.11	0.98	0.15
	Lime Stabilized Subgrade	1.38	0.42	1.71	0.82	1.63	0.25

Note: Parameters are calibrated for time (t) in months; either a laboratory cure 28 day strength or accelerated cure 2 day specimen can be used as input into equations for cement stabilized base.

Based on these findings, the authors recommend using Equation 1 with optimized constants from Table 5.1 when forecasting or backcasting properties of pavements with AASHTO A2-4 soils or similar with 3 to 7% stabilizing material.

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