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ACCELERATED CURING AND STRENGTH-MODULUS CORRELATION FOR LIME-STABILIZED SOILS

Michael A. Mooney
Nathan M. Toohey

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Michael A. Mooney, Ph.D., P.E.; Nathan M. Toohey, B.S., E.I.T.

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16. Abstract

This study sought to identify the equivalent 105°F curing duration for lime-stabilized soil (LSS) that will yield the equivalent unconfined compressive strength (UCS) to that resulting from 28-day, 73°F curing. Both 5-day and 7-day 105°F (or 100°F) curing have been used in practice. The study also sought to characterize the relationship between resilient modulus (M_r) and UCS for LSS soils, since the prevailing correlation between M_r and UCS for LSS – based on Thompson (1966) – was not developed from cyclic loading and has been validated with only limited data. The study revealed that the 5-day, 105°F accelerated curing yielded UCS values more representative of 28-day 73°F UCS than did the 7-day, 105°F curing regime. However, there is no universal equivalent accelerated curing duration for LSS; therefore, 5-day 105°F curing can yield erroneous estimates of 28-day 73°F UCS. The study recommends verification of the equivalent 105°F curing duration for each LSS to gage the most representative accelerated curing duration. Based on experimental M_r – UCS data, the relationship M_r (ksi) = 0.124 UCS (psi) + 9.98 was found to be conservative in its prediction of M_r from UCS.

Implementation

Based on the results of the study, the Colorado Department of Transportation (CDOT) will continue using the 5-day, 100°F accelerated curing protocol for LSS, in addition to other approved curing procedures.

The construction process for lime-stabilized soil requires diligent quality control and quality assurance (QC/QA). CDOT should investigate alternative methods of QC/QA that can be conducted in the field instead of the laboratory.

17. Key Words
LSS, accelerated curing, equivalent unconfined compressive strength (UCS), resilient modulus, quality control/quality assurance (QC/QA)

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by

Principal Investigators
Michael A. Mooney, Ph.D., P.E., Associate Professor
Nathan M. Toohey, B.S, E.I.T, Graduate Student

Report No. CDOT-2010-1

Prepared by
Colorado School of Mines
Division of Engineering
1500 Illinois Street
Golden, Colorado 80401

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Colorado Department of Transportation
DTD Applied Research and Innovation Branch
4201 E. Arkansas Ave.
Denver, CO 80222
(303) 757-9506

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EXECUTIVE SUMMARY

This report presents the findings from CDOT Study No. 80.26 entitled "Accelerated Curing and Strength-Modulus Correlation for Lime-Stabilized Soils." The objectives of the study were to identify the most appropriate accelerated curing regime (temperature and duration) for lime-stabilized soil (LSS) specimens that will yield unconfined compressive strength (UCS) values equivalent to UCS of 28-day room temperature 73°F (23°C) cured samples. In addition, the study aimed to characterize the relationship between resilient modulus (M_r) and UCS for LSS soils, since the prevailing correlation between M_r and UCS for LSS is based on limited data.

Lime stabilization of roadway subgrade soils is widely used to reduce soil plasticity, mitigate heave, and increase subgrade stiffness and strength. Lime-stabilized soil performance requires careful construction, and the relatively involved construction process requires diligent quality control (QC) and quality assurance (QA). The need to assess design-related parameters such as 28-day unconfined compressive strength and resilient modulus of LSS during QC/QA conflicts with more rapid pavement construction schedules. Strength and stiffness growth in LSS stems from pozzolanic reactions that continue over months, whereas contractors and construction schedules often desire evaluation of acceptance after days.

As a result, accelerated curing of LSS specimens is commonly employed to estimate 28-day normal (room temperature) unconfined compressive strength (UCS). The National Lime Association (NLA) recommends accelerated curing of LSS specimens at 104°F (40°C) for 7 days. CDOT currently has adopted the 5-day 100°F (38°C) accelerated curing regime recommended by the Metropolitan Government Pavement Engineers Council (MGPEC) Pavement Design Standards of Denver, Colorado.

A thorough review of the literature and a detailed laboratory testing program were performed. Six soils with plasticity indices (PI) ranging from 13-37 were selected from the Denver metropolitan area for laboratory evaluation. Both 4.5 inch tall and 8.0 inch tall specimens (all 4.0 inch diameter) were investigated because Colorado practice is to perform UCS testing on 4.5 inch tall Proctor mold specimens yet M_r testing requires a 2:1 height to diameter ratio. Specimens were subjected to accelerated (2, 4, 6, and 8 day at 105ºF) and normal (28-day 73°F) curing prior to UCS testing. Resilient modulus testing was performed on three of the soils.

Previous studies of accelerated curing documented in the literature suggest that no unique equivalent accelerated curing regime exists. The strength gain of LSS due to time-dependent pozzolanic reactions is a function of soil composition, soil processing, lime content, and temperature. It has been shown that accelerated curing of 7-days at 105°F generally over-estimates UCS determined from samples cured for 28-days at room temperature. In some cases, 28-day strength gain was achieved following 2-days 105°F.

Consistent with the literature, a universal equivalent 105°F curing duration that predicted 28-day 73°F cured UCS was not found. The equivalent 105°F curing durations for soils 1 through 4 (PI = 13, 24, 26 and 37) were found to be 5.4, 4.6, 5.9, and 1.8 days, respectively. The equivalent 105°F curing durations for soils 5 and 6 were less than 1.5 days because the soil was more thoroughly processed. The 7-day, 105°F curing duration overestimated UCS after 28-day 73°F curing by 13 to 256%. The 5-day accelerated curing for UCS testing slightly underestimated 28-

day 73°F cured UCS for soils 1 and 3 (less than 10%) and overestimated 28-day 73°F cured UCS for soil 2 (2%) and 4 (94%).

Thompson's correlation (Thompson 1966) presented in Equation (1) is used by CDOT and recommended by the 2007 Interim Mechanistic-Empirical Pavement Design Guide (MEPDG). Test results from soils 4, 5 and 6 demonstrated that Equation 1 used by CDOT and proposed in the 2007 Interim MEPDG is conservative in its prediction of M_r from UCS of LSS. Equation (1) underestimates measured M_r (σ_c = 2 psi) by 20 – 50% and measured M_r (σ_c = 4 psi) by 50 - 80% for 8.0 in. tall UCS specimens. More appropriately for Colorado practice, the current equation underestimates M_r by 40 – 80% (for σ_c = 2 psi) and 80 - 110% (for σ_c = 4 psi) using UCS from 4.5 in. tall Proctor-molded specimens commonly used in CDOT practice.

$$M_r \text{ (ksi)} = 0.124 \text{ UCS (psi)} + 9.98 \qquad (1)$$

Based on the results of this study, the following recommendations are made for CDOT practice:

1. The study supports the use of 5-day, 100°F curing as a more realistic accelerated curing regime than 7-day, 105°F curing. However, 5-day 100°F curing can yield erroneous estimates of 28-day 73°F UCS. Note that the difference between 100°F and 105°F curing is deemed negligible (the variation in reporting resolution and measurement accuracy is 2-5°F).
2. CDOT should consider requiring verification of the equivalent 100°F curing duration for each LSS. The procedure would be straightforward (e.g., comparison of 4, 6 and 8-day accelerated UCS with 28-day normal temperature UCS) and could be performed during the design or early construction phase.
3. CDOT should consider adopting the M_r – UCS correlation recommended by Little (2004) for LSS. The limited results collected during this study support this relationship. Additional testing should be performed in early adopter projects to validate the use of this correlation. Alternatively, adjust the M_r – UCS correlation per the results presented here combined with further testing.

A more general recommendation about QC/QA of LSS is provided. The limitations of accelerated curing and M_r – UCS correlation notwithstanding, QC/QA involving *laboratory* compaction, curing, and testing to estimate *field* performance has limitations. Laboratory and field compaction yield different soil structure and fabric. Curing conditions (temperature, confinement) differ in the field and lab. For these reasons, and given the relative complexity of LSS construction, CDOT should consider alternative methods of QC/QA. Sampling could be conducted in the field on LSS that is field compacted and field cured to be representative of the parent material. Performance-related parameters such as modulus and strength could be measured directly, rather than correlated.

TABLE OF CONTENTS

CHAPTER 1: Introduction
1.1 Overview and Objectives....1
1.2 Pavement Design Practice with Lime-Stabilized Soils....2
1.3 Summary of Report....4

CHAPTER 2: Literature Review
2.1 Accelerated Curing Protocols for Lime-Stabilized Soils....5
2.2 Correlation between Resilient Modulus and UCS....13

CHAPTER 3: Test Program and Results
3.1 Test Program....18
3.1.1 Soils and Lime Treatment....18
3.1.2 Specimen Preparation....20
3.1.3 UCS Testing....23
3.1.4 Resilient Modulus Testing....24
3.2 Test Results....26
3.1.1 UCS for Specimens Cured under Normal and Accelerated Conditions....26
3.1.2 Correlation of Resilient Modulus and UCS....34
3.3 Summary of Findings....39

CHAPTER 4: Conclusions and Recommendations
4.1 Equivalent Accelerated Curing Regime....40
4.2 Resilient Modulus-Unconfined Compressive Strength Correlation....41

REFERENCES....44

LIST OF FIGURES

Figure 2-1. Hours of 105°F (40°C) accelerated curing required to match UCS obtained under normal curing temperature 73°F (23°C) (from Biswas 1972)
Figure 2-2. Relationship between 120°F (50°C) and 140°F (60°C) accelerated curing times and curing time at 73°F (23°C) (from Biswas 1972)
Figure 2-3. Comparison of 7-Day 110°F (43°C) UCS with UCS from samples cured at 72°F (22°C) (from Doty & Alexander, 1978)
Figure 2-4. UCS for ML with 3% Lime (after Townsend & Donaghe 1976)
Figure 2-5. UCS for ML with 6% Lime (after Townsend & Donaghe 1976)
Figure 2-6. UCS for CH with 5% Lime (after Townsend & Donaghe 1976)
Figure 2-7. UCS for CH with 8% Lime (after Townsend & Donaghe 1976)
Figure 2-8. Modulus versus unconfined compressive strength relationship (Equation 2) for lime-stabilized soils developed by Thompson (1966)
Figure 2-9. Relationship between unconfined compressive strength and modulus from Thompson's (1966) zero confining stress yields a different relationship than Figure2-8
Figure 2-10. Results of limited testing by CTL/Thompson (1998) corroborate Equation (2). Note that Thompson's correlation is incorrectly referenced in this Figure from CTL/Thompson (1998) as Dallas Little's equation
Figure 2-11. Design M_r vs. UCS relationship for lime-stabilized soil recommended by Little et al. (1994) based on three sets of findings: (a) UCS versus compressive modulus E from Thompson (1966); (b) UCS versus flexural modulus from Thompson & Figueroa (1989); and (c) UCS versus back-calculated FWD modulus from Little et al. (1994)
Figure 3-1. Final field mixing of lime-treated soil 1
Figure 3-2. Laboratory mixing used for lime-treated soils 2 through 6
Figure 3-3. Two specimen geometries used during testing: 4.0 in. diameter × 4.5 in. tall and 4.0 in. diameter × 8.0 in. tall
Figure 3-4. Preparation of 4.0 x 8.0 in. specimens
Figure 3-5. Load frame and data acquisition system at CSM research facility
Figure 3-6. UCS test setup use by Ground Engineering
Figure 3-7. M_r test setup used by Ground Engineering
Figure 3-8. UCS vs. curing time for 4- 4 x 4.5 inch accelerated cure (A4) and normal cure (N4) samples. Individual sample UCS in filled symbols, average UCS in open symbols
Figure 3-9. UCS with time for soils 5 (left) and 6 (right) for 4- 4 x 4.5 inch accelerated cure (A4) and normal cure (N4) samples. Individual sample UCS in filled symbols, average UCS in open symbols
Figure 3-10. Axial stress-strain behavior of soil 1 (top) and soil 2 (bottom) specimens (4 x 4.5 in.). Accelerated cure on left side and normal cure on right.
Figure 3-11. Axial stress-strain behavior of soil 3 (top) and soil 4 (bottom) specimens (4 x 4.5 in.). Accelerated cure on left side and normal cure on right
Figure 3-12. Comparison of 6-day accelerated and 28-day normal curing axial stress-strain behavior for soil 1, 2, 3 and 4, left to right respectively

Figure 3-13. Axial stress-strain behavior of soil 5 (top) and soil 6 (bottom) specimens (4 x 4.5 in.). Accelerated cure on left side and normal cure on right
Figure 3-14. Relationship between M_r (σ_c=2 psi, σ_d=6 psi) and UCS: (a) Individual specimen data for 4.0 x 8.0 in. tall specimens; (b) Average results of 5 specimens for 4.0 x 8.0 in. tall and 4.0 x 4.5 inch tall specimens. Thompson's correlation is shown for comparison
Figure 3-15. Relationship between M_r (σ_c=4 psi, σ_d=6 psi) and UCS: (a) Individual specimen data for 4.0 x 8.0 in. tall specimens; (b) Average results of 5 specimens for 4.0 x 8.0 in. tall and 4.0 x 4.5 inch tall specimens. Thompson's correlation is shown for comparison
Figure 3-16. Average UCS values of 4.5 in. tall and 8 in. tall specimens
Figure 3-17. Comparison of measured data with proposed relationship from Little (1994): (a) σ_c=2 psi, σ_d=6 psi, (b) σ_c=4 psi, σ_d=6 psi. Measured data reflect average results of 5 specimens

LIST OF TABLES

Table 2-A. Summary of Biswas (1972) soils tested and accelerated curing times that yield UCS values equivalent to 28-day, 73 °F cured samples
Table 2-B. Summary of the soils investigated by Alexander and Doty (1978)
Table 2-C. Summary of soils tested by Thompson (1966)
Table 2-D. Recommended M_r ratios for LSS and untreated soil (Little 1994)
Table 3-A. Summary of soils investigated
Table 3-B. UCS testing matrix
Table 3-C. Subgrade Soil Testing Sequence (AASHTO T-307)
Table 3-D. Comparison of 6 and 28-day normal and accelerated cured UCS
Table 3-E. Comparison of UCS gain with time for normal and accelerated curing
Table 3-F. Comparison of UCS from 5 and 7-day accelerated cure with 28 day normal cure
Table 3-G. Summary of UCS (N8) and M_r (N8) (σ_c=2 psi, σ_d=6 psi)
Table 3-H. Comparison of measured (N8) and estimated (N8) (Eq. 1) M_r (σ_c=2 psi, σ_d=6 psi)
Table 3-I. Summary of UCS (N8) and M_r (N8) (σ_c=4 psi, σ_d=6 psi)
Table 3-J. Comparison of measured (N8) and estimated (N8) (Eq. 1) M_r (σ_c=4 psi, σ_d=6 psi)
Table 3-K. Summary of UCS (N4) and M_r (N8) (σ_c=2 psi, σ_d=6 psi)
Table 3-L. Comparison of measured M_r (N8) and estimated M_r (N4) (Eq. 1) (σ_c=2 psi, σ_d=6 psi)
Table 3-M. Summary of UCS (N4) and M_r (N8) (σ_c=4 psi, σ_d=6 psi)
Table 3-N. Comparison of measured M_r (N8) and estimated M_r (N4) (Eq. 1) (σ_c=4 psi, σ_d=6 psi)
Table 4-A. Summary of equivalent 105°F curing durations
Table 4-B. Comparison of measured (N8) and estimated (N8) (per Chapter 2, Eq. 1) M_r (σ_c=2 psi, σ_d=6 psi)
Table 4-C. Comparison of measured (N8) and estimated (N8) (per Chapter 2, Eq. 1) M_r (σ_c=4 psi, σ_d=6 psi)
Table 4-D. Comparison of measured (N8) and estimated (N4) (per Chapter 2, Eq. 1) M_r (σ_c=2 psi, σ_d=6 psi)
Table 4-E. Comparison of measured (N8) and estimated (N4) (per Chapter 2, Eq. 1) M_r (σ_c=4 psi, σ_d=6 psi)

CHAPTER 1: INTRODUCTION

1.1 Overview and Objectives

Lime stabilization of roadway subgrade soils is widely used to reduce soil plasticity, mitigate heave, and increase subgrade stiffness and strength. The lime-stabilized soil (LSS) layer becomes a structural component of the pavement system whereby flexural strength and (resilient) modulus are important performance-related and thus design parameters (MEPDG 2007). LSS performance requires careful construction, and the relatively involved construction process, (uniformly blending lime with soil, mellowing, re-mixing, etc.), requires diligent quality control (QC) and quality assurance (QA). The need to assess performance-related parameters (e.g., 28-day unconfined compressive strength, resilient modulus) of LSS during QC/QA conflicts with pavement constructability. Strength and stiffness growth in LSS stems from pozzolanic reactions that continue over months, whereas contractors and construction schedules often desire evaluation of acceptance after days. As a result, the acceptance criteria in current QC/QA specifications of LSS vary throughout the U.S., are only loosely tied to design parameters, and often involved accelerated curing of LSS samples.

For construction expediency, UCS testing is performed after accelerated curing of LSS samples in CDOT practice. ASTM D 5102-96 proposes a curing period of 7 days at room temperature but allows elevated temperatures. The accelerated testing protocol suggested by the National Lime Association (NLA) calls for accelerated 7-day curing at 104°F (40°C). The Metropolitan Government Pavement Engineers Council (MGPEC) Pavement Design Standards of Denver, Colorado recommends 5-day accelerated curing at 100°F (38°C). The latter has become the standard practice of Colorado engineers. Presently, CDOT has adopted the MGPEC 5-day, 100°F (38°C) accelerated testing protocol in its Pavement Design Manual; however, there is significant uncertainty as to its equivalence to 28-day room temperature curing.

The CDOT Pavement Design Manual currently recommends the use of a structural layer coefficient for stabilized subgrade, consistent with the AASHTO 1993 pavement design guide. The coefficient, which cannot be ascertained directly, is determined through correlation to resilient modulus (M_r). CDOT does not currently perform M_r testing; rather, M_r is determined via correlation from unconfined compressive strength (UCS). The 2007 Interim Mechanistic-Emperical Pavement Design Guide (MEPDG) indicates that the design M_r for LSS can be approximated from the results of UCS tests using Equation (1). The MGPEC of Denver also utilizes this relationship for LSS.

$$M_r \text{ (ksi)} = 0.124 \text{ UCS (psi)} + 9.98 \qquad (1)$$

The data upon which Equation (1) was developed appears limited, and a recent study by Little (1994) asserts that Equation (1) is conservative. Further, Equation (1) was derived from samples with 2:1 height to diameter ratios. In Colorado practice, UCS testing is performed on Proctor size samples with 4.0 inch diameter and 4.5 inch height (1.15:1 height to diameter ratio). The influence of Proctor size samples requires clarification.

The objectives of this study are two-fold:

1. Identify the most appropriate accelerated curing regime (temperature and duration) for LSS specimens that will yield UCS values equivalent to UCS of 28-day room temperature 73°F (23°C) cured samples.
2. Investigate the M_r – UCS relationship (Equation 1) recommended for LSS soils.

To meet these objectives, a thorough review of the literature and a detailed laboratory testing program were conducted. Six soils with plasticity indices (PI) ranging from 13 - 37 were selected for laboratory evaluation. Both 4.5 inch tall and 8.0 inch tall specimens (all 4.0 inch diameter) were prepared and subjected to accelerated and normal (28-day 73°F) curing prior to UCS testing. Resilient modulus testing was performed on three of the soils.

1.2 Pavement Design Practice with Lime-Stabilized Soils

In recent years, CDOT pavement design has been aligned with the 1993 AASHTO Pavement Design Guide approach. For unbound untreated subgrade soil, the flexible pavement design input is resilient modulus (M_r). In CDOT practice, M_r is determined via correlation to R-value. The combination of M_r, estimated traffic and design serviceability loss leads to a required structural number (SN) of the subbase-base-asphalt concrete system. The SN is determined per Equation

(2) based on structural layer coefficients (a_i), thickness (D_i) and drainage coefficients (m_i) of the subbase, base and asphalt layers.

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 \qquad (2)$$

Values of base and subbase a_i are determined via empirical correlation to modulus E, M_r, R-value or CBR. Per CDOT practice in Regions 1 and 6, when LSS is used, the stabilized layer typically replaces the subbase and/or base layer and contributes to the SN via Equation (1). The subgrade M_r used in design is then a reflection of the soil beneath the lime-stabilized layer. The determination of a_i for the LSS layer varies across CDOT regions. Region 1 determines a_i based on a correlation to 7-day UCS using Table 3.2 from the CDOT Pavement Design Manual. In tracing the origin of Table 3.2, the 1993 AASHTO pavement design guide has a nomograph with similar values relating 7-day UCS to a_i for cement-treated and bituminous-treated bases. The curing regime (temperature) or sample size for these 7-day UCS tests is not stated in the 2008 CDOT Pavement Design Manual or the 1993 AASHTO Design guide. Region 6 assumes the minimum layer coefficient value per Table 3.2, i.e., $a_i = 0.11$, and does not perform UCS testing. Based on this value, Region 6 requires a minimum field UCS of 160 psi.

In rigid pavement design, a LSS layer beneath a PCC pavement is considered a base course in CDOT design; a base course modulus (E) is used in design. The coefficient of subgrade reaction (k-value) required for design is therefore a reflection of the unbound subgrade beneath the LSS layer. Chapter 4 of the CDOT Pavement Design Guide does not specify a value of E for the base nor does it specifically mention stabilized base materials. Section 4.7 of the CDOT Pavement Design Guide suggests that the resilient modulus M_r of the base course should be determined and used to represent the base course. Table S.11 of the CDOT Pavement Design Guide provides a range of E (or M_r) values from 30-60 ksi for LSS, with a typical value of 45 ksi. For comparison, the 1998 AASHTO pavement design guide supplement suggests a range of E values for LSS bases of 20-70 ksi. The 2007 MEPDG provides a level 3 design E value for LSS of 45 ksi. Regions 1 and 6 use design E = 45 ksi for LSS.

As CDOT transitions to mechanistic-empirical design, a synopsis of recommended practice reflected in the 2007 Interim MEPDG is warranted. CDOT LSS design practice is consistent with the 2007 Interim MEPDG in that LSS is considered as a separate structural layer. Under this case, a LSS layer can be considered as a material that is insensitive to moisture and the resilient modulus or stiffness can be held constant over time. Both resilient modulus and flexural strength are important for LSS layer performance. The 2007 AASHTO Interim MEPDG recommends the following design inputs for LSS, both for flexible and rigid pavement. Recall that AASHTO uses the level system.

Level one (laboratory determined values):
- M_r determined via AASHTO T307
- Flexural strength (AC only) determined via levels two or three

Level two (correlation to UCS):
- M_r (ksi) = 0.124 UCS (psi) + 9.98
- Flexural strength (AC only) = 0.2 UCS (from lab samples or cores)

Level three (default values)
- M_r = 45 ksi
- Flexural strength (AC only) = 0.2(UCS) where UCS = 250 psi for subbase, select or subgrade under flexible, or 750 psi for base layer.

1.3 Summary of Report

Chapter 1 introduces the study, explains the objectives, and summarizes pavement design using LSS. In Chapter 2, a detailed review of the literature on accelerated curing of LSS and on the correlation between UCS and M_r is provided. The laboratory testing program and results are presented in Chapter 3. Conclusions and recommendations are provided in Chapter 4.

CHAPTER 2: LITERATURE REVIEW

2.1 Accelerated Curing Protocols for Lime-Stabilized Soils

This section summarizes the literature on accelerated curing protocols and their relationship to producing UCS values that are equivalent to UCS from 28-day room temperature cured samples. ASTM 5102-04 recommends curing at 73±4°F (23±2°C) and indicates that any curing period may be specified (7, 28 and 90 day are listed as most common). ASTM 5102 notes that if accelerated curing conditions are necessary, temperatures higher than 120°F (49°C) should be avoided. ASTM 5102 also notes that a curing temperature of 105°F (40°C) does not introduce additional pozzolanic reactive products that significantly differ than field conditions.

Of specific interest to CDOT practice is the nature and efficacy of the 5-day 100°F curing regime recommended in the MGPEC pavement design manual and the 7-day 105°F (40°C) curing regime recommended by the AASHTO 2007 interim MEPDG. The only documented source for the 5-day 100°F curing regime is Little (1999), where it is recommended without support from data, analysis or reference. Dr. Little does not recall the origin of the 5-day curing recommendation (Little, personal communication, March 2008). Conversations with a number of Colorado area geotechnical engineers suggest that the 5-day 100°F (38°C) curing came from the LSS construction at Denver International Airport (DIA) in the early 1990s. Unfortunately, there is no documentation or available data to support this approach. The 7-day 105°F (40°C) regime recommended in the 2007 MEPDG can be traced to a National Lime Association (NLA) recommendation per Little (2000). Dr. Little based this recommendation on a survey of the accelerated curing literature (Little, personal communication, March 2008). The NLA also recommends that samples should be sealed in plastic bags for the 7-day 105°F (40°C) curing period, and that curing should be followed by a 24-hour capillary soak prior to UCS testing.

Biswas (1972) conducted an investigation with five A-7-6 soils mixed with optimal lime concentration determined via Eades and Grim pH test (ASTM D 6276) to explore the effect of time and temperature on UCS (summary of soils in Table 2-A). UCS testing was performed on 2.0 in. diameter by 4.0 in. tall samples prepared with equivalent standard Proctor compaction energy. Three accelerated curing temperatures were investigated: 105°F (40°C), 122°F (50°C) and 140°F (60°C). The results from Biswas' testing are shown in Figures 2-1 and 2-2 where the hours of accelerated temperature curing required to achieve normal temperature 73°F (23°C) curing UCS values are presented. For 105°F accelerated curing, the time required to reach 28-day 73°F UCS ranged from 2-4 days for the five soils tested (see Fig. 2-1 and Table 2-A). Biswas did not conduct 5-day or 7-day UCS testing at 105°F; however, UCS values at these time periods would have significantly overestimated 28-day 73°F UCS.

Per regression analysis, Biswas (1972) concluded that, on average, accelerated curing at 105°F for 69 hrs (approx. 3 days) produced UCS values equivalent to those obtained after 28-day 73°F curing. The results of testing at 120°F and 140°F are shown in Figure 2-2. Biswas concluded that 120°F curing for 32 hrs (approx. 1.3 days) or 140°F curing for 12 hrs produced UCS values equivalent to those obtained after 28-day 73°F curing. It was subsequently found that curing at temperatures of 120°F (50°C) and higher induced pozzolanic reactions that do not occur at temperatures in the field (Townsend & Donaghe 1976). In light of this, accelerated curing at temperatures of 120°F (50°C) and higher should not be used (ASTM 5102).

Table 2-A. Summary of Biswas (1972) soils tested and accelerated curing times that yield UCS values equivalent to 28-day, 73 °F cured samples

Soil	AASHTO Classif.	USCS Classif	LL	PI	Lime (%)	Time (hours) to reach 28-day 73°F (23°C) UCS		
						105°F (40°C)	122°F (50°C)	140°F (60°C)
Dyess	A-7-6	CL	44	23	4.0	58	22	7
Altus Subgrade	A-7-6	CL	49	20	5.0	70	36	15
Houma	A-7-6	CH	64	41	5.0	52	25	8
Perrin B	A-7-6	CH	65	42	5.5	68	34	12
Perrin A	A-7-6	CH	72	40	6.5	97	40	20

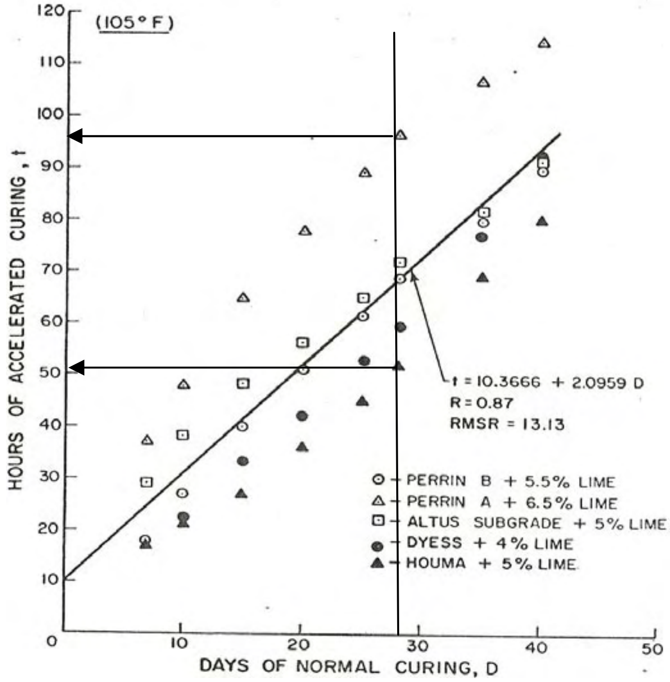

Figure 2-1. Hours of 105°F (40°C) accelerated curing required to match UCS obtained under normal curing temperature 73°F (23°C) (from Biswas 1972)

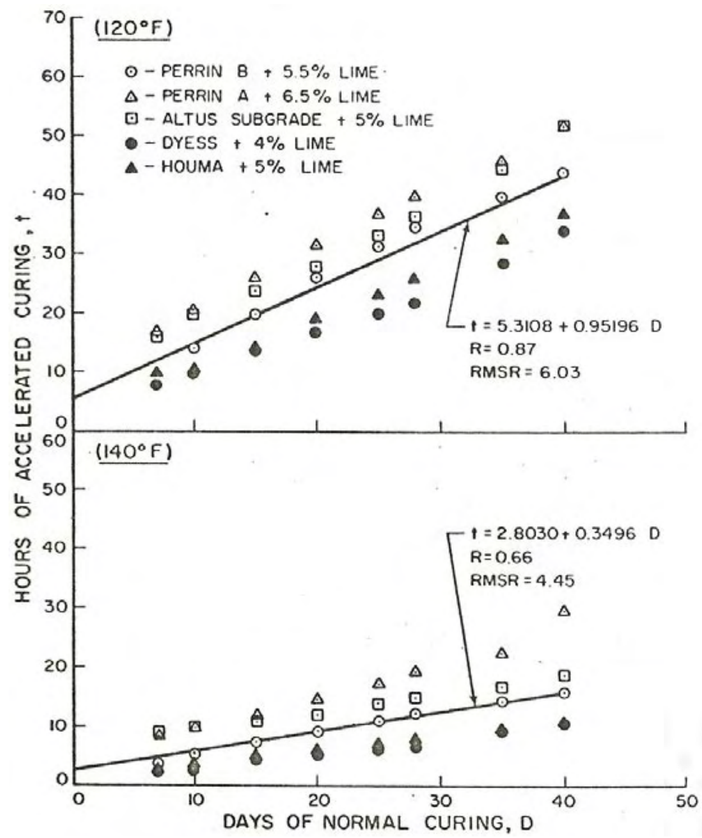

Figure 2-2. Relationship between 120°F (50°C) and 140°F (60°C) accelerated curing times and curing time at 73°F (23°C) (from Biswas 1972)

Alexander and Doty (1978) performed a study to compare UCS from samples cured at 110°F (43°C) for 7 days with UCS from samples cured for 28-360 days at 72°F (22°C). Twelve soil types ranging from A-2-4 to A-7-5 were investigated (see Table 2-B). Each soil was mixed with 3, 5 and 7% hydrated lime. 4 inch diameter by 4 inch tall samples were prepared and tested. The results presented in Figure 2-3 show that UCS determined after 7-day 110°F are greater than 28-day 72°F UCS for all soils (and both lime percentages). Upon closer inspection of the 7% lime-soil results, 7-day 110°F UCS values are 1.5-2 times greater than 28-day 72°F values. Alexander and Doty (1978) concluded that 7-day 110°F UCS values are more representative of 90 days of normal temperature curing.

Table 2-B. Summary of the soils investigated by Alexander and Doty (1978)

Soil	AASHTO Classification	Group Index	LL	PI
1	A-6	10	34	14
2	A-6	10	36	11
3	A-7-5	31	56	30
4	A-2-4	1	16	NP
5	A-7-6	33	52	30
6	A-7-5	13	51	15
7	A-4	5	24	7
8	A-6	7	33	14
9	A-4	1	31	7
10	A-7-5	22	41	22
11	A-4	2	25	10
12	A-7-5	24	50	22

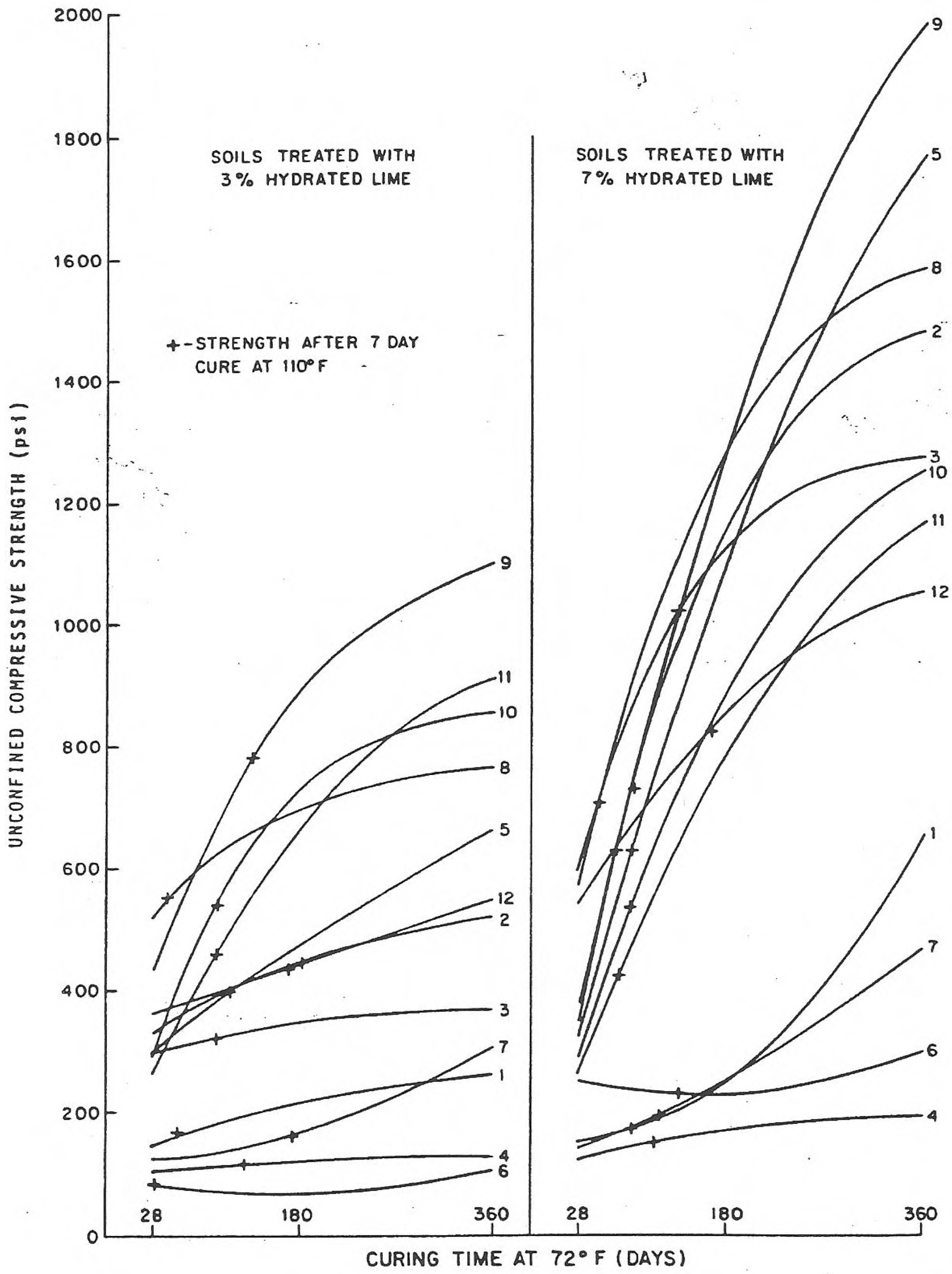

Figure 2-3. Comparison of 7-Day 110°F (43°C) UCS with UCS from samples cured at 72°F (22°C) (from Doty & Alexander, 1978)

Townsend and Donaghe (1976) investigated the effects of accelerated curing on UCS for two soils: (1) silty clay (ML, LL=58, PI=35, optimal lime per Eades & Grim = 3%) and (2) high plasticity clay (CH, LL=27, PI=5, optimal lime per Eades & Grim = 5%). Optimal lime and optimal lime + 3% were investigated for each soil type. Samples with 2 inch diameter and 4 inch height were prepared at standard Proctor optimum moisture and maximum dry density. The curing temperatures investigated included 50°F (10°C), 72°F (22°C), 90°F (32°C), 105°F (40°C) and 120°F (49°C). Their UCS data vs. degree-days is presented in Figures 2-4 through 2-7.

For the ML soil, UCS values after 3-day 105°F curing and 7-day 90°F curing were less than 50% of the 28-day 72°F UCS values for both 3% and 6% lime concentrations. Unfortunately, Townsend and Donaghe did not extend 90°F and 105°F curing times until UCS values equaled those determined at 28-day 72°F. For the CH soil, the 28-day 72°F UCS was reached after approximately 2 days at 90°F and 105°F curing.

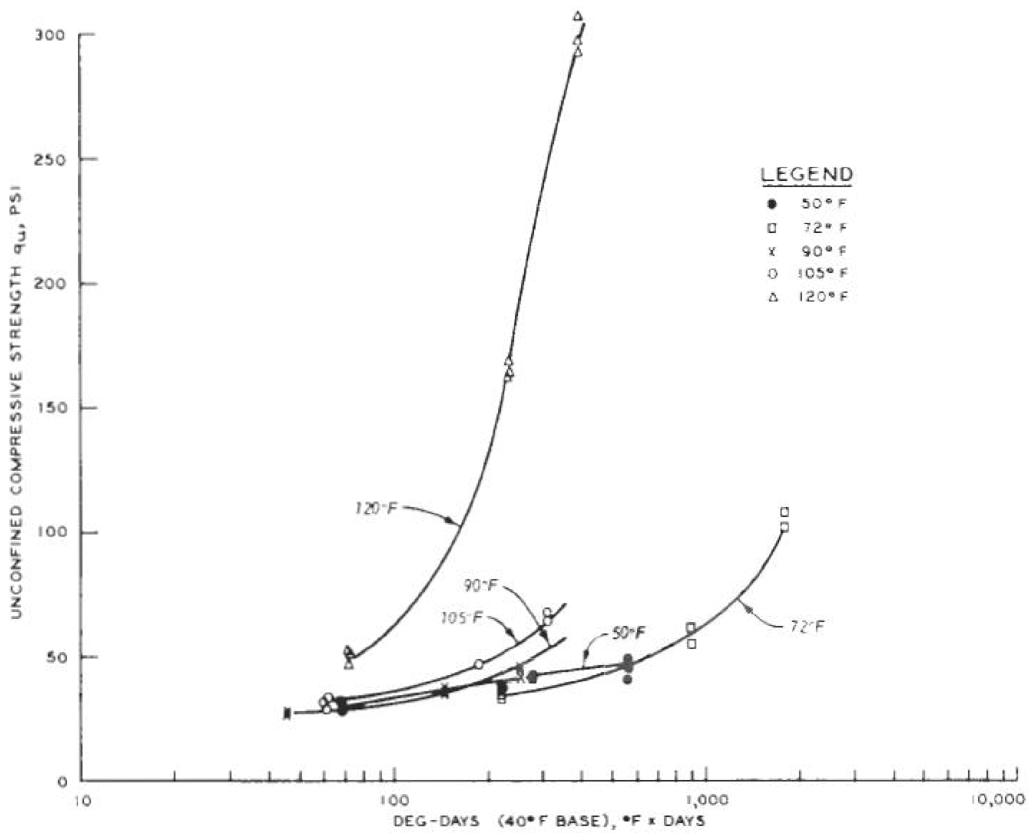

Figure 2-4. UCS for ML with 3% Lime (after Townsend & Donaghe 1976)

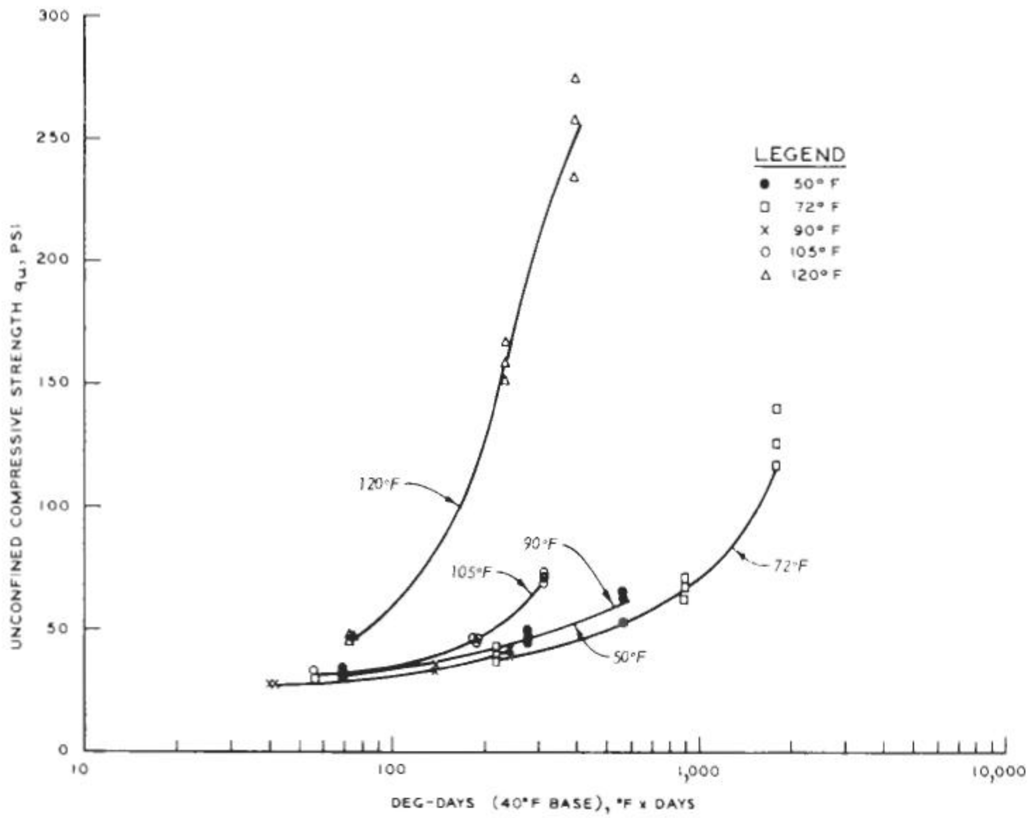

Figure 2-5. UCS for ML with 6% Lime (after Townsend & Donaghe 1976)

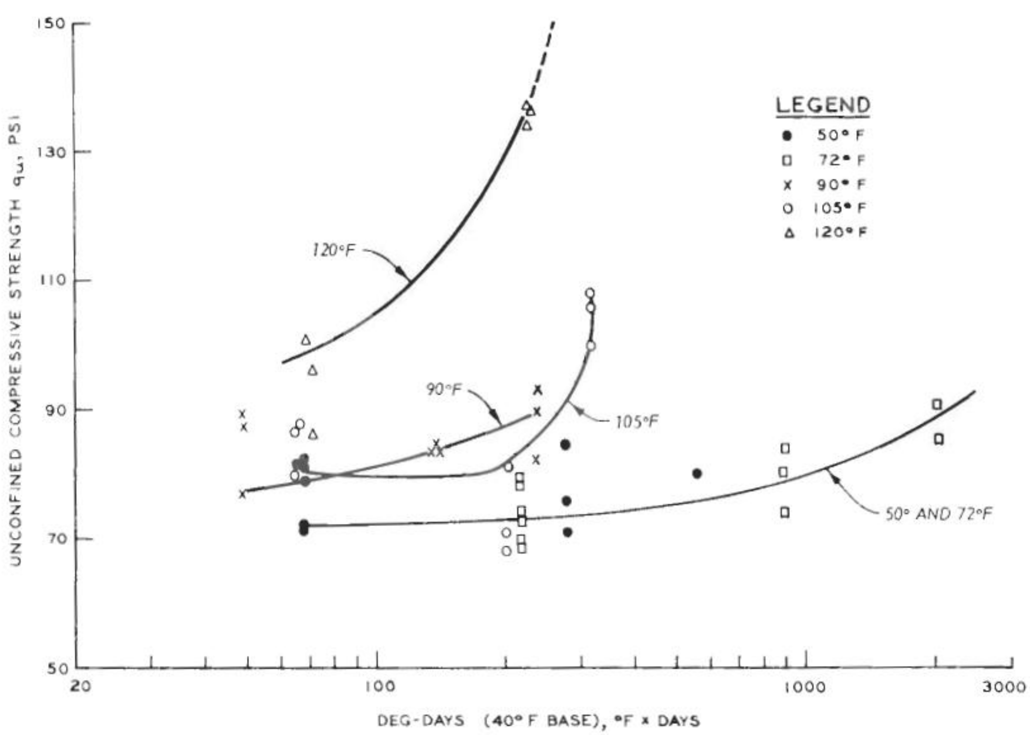

Figure 2-6. UCS for CH with 5% Lime (after Townsend & Donaghe 1976)

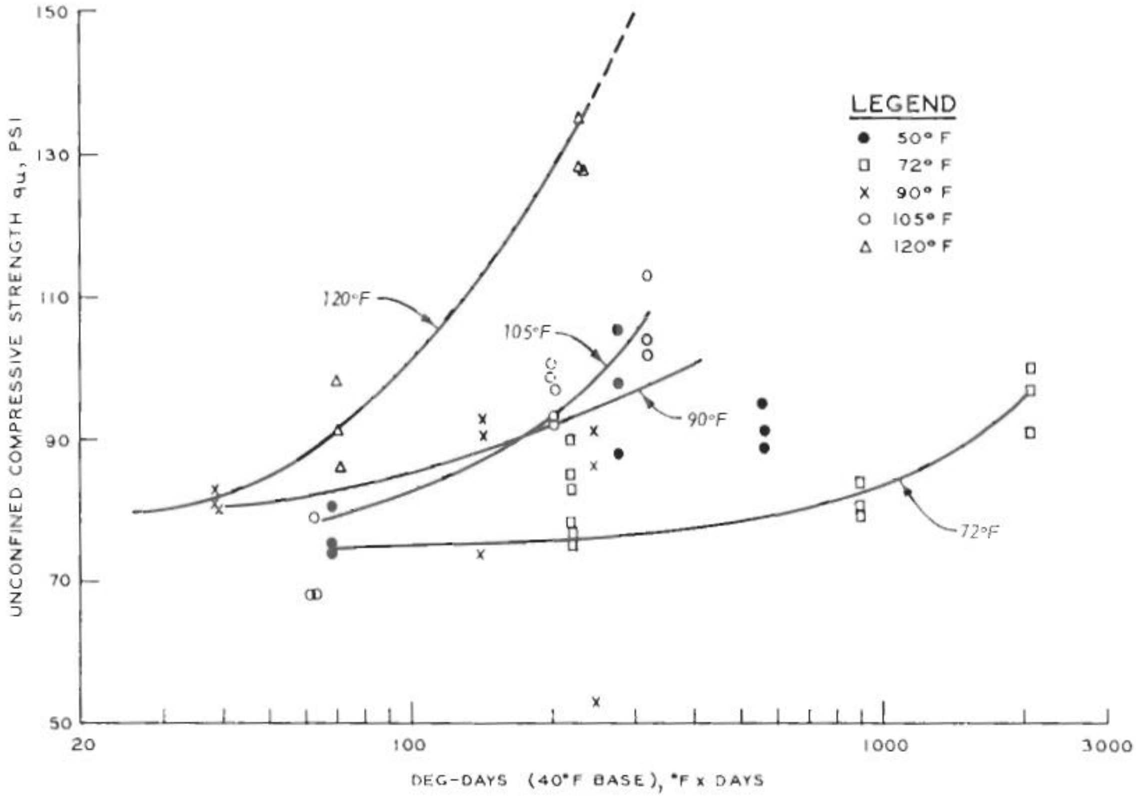

Figure 2-7. UCS for CH with 8% Lime (after Townsend & Donaghe 1976)

Yusuf et al. (2001) performed a study to compare UCS after 7-day 105°F (40°C) curing with UCS after 30-day 77°F (25°C) curing. Four natural Mississippi soils were selected. The only information provided about these soils was PI: 29, 32, 28 and 17. For each soil, 3 samples with 2.5 inch diameter and 5.0 inch height were prepared using equivalent modified Proctor energy. After curing in plastic bags, the samples were subjected to a 24-hour capillary soak prior to UC testing. The 7-day 105°F UCS values were found to be 15-35% greater than the 30-day 77°F UCS values.

As evidenced by the literature, there is no unique accelerated curing regime (time and temperature) that will yield 28-day room temperature UCS values for all soils. The development and rate of pozzolanic reactions in LSS is a function of soil composition, lime content and temperature. Per the data in the literature, 7-day 105°F (40°C) curing yields UCS values greater than UCS determined from samples cured for 28-days at room temperature. Some studies show that 28-day room temperature strengths are achieved after 2 days at 105°F (40°C).

2.2 Correlation between Resilient Modulus and UCS

The 2007 Interim M-E Pavement Design Guide (Table 25, p. 122) and Mallela et al. (2004) indicate that the design M_r for lime-stabilized subgrade can be approximated from the results of UCS tests using Equation (1).

$$M_r \text{ (ksi)} = 0.124 \text{ UCS (psi)} + 9.98 \qquad \text{[(1) re-stated]}$$

Mallela et al. (2004) cites Thompson (1966) as the source of Equation (1) and indicates that the design M_r and UCS values should be based on testing of 28-day room temperature cured strengths in accordance with ASTM D5102. Mallela et al. (2004) states that 7-day, 104°F (40°C) curing can be used and is representative of the 28-day curing at "room temperature."

Equation (1) was developed by Thompson (1966) from unconsolidated undrained triaxial compression testing of 2.0 inch diameter by 4.0 inch tall remolded LSS samples. Samples from four different soil types (see Table 2-C) were compacted into 2.0 inch diameter molds using an equivalent standard Proctor energy (3 layers, 20 blows/layer of 4.0 lbf hammer). Samples were cured at 120°F (49°C) within sealed metal cans for periods of 1, 2, 4 and 6 days. Regarding the curing regime, Thompson refers to Anday (1963) and states "these curing conditions produce strengths that are comparable to those developed under field curing conditions." Confinement was applied (0, 5, 15 or 35 psi) and the samples were axially compressed at a rate of 0.05 in/min.

The data used to derive Equation (1) are shown in Figure 2-8(a). These data show the UCS values (from samples tested at 0 psi confining stress) plotted against elastic modulus (E) values from samples tested at 15 psi confining stress. E values were determined as the secant modulus at approximately 0.7-0.8 of the UCS. A confining stress = 15 psi is considerably higher than the 2, 4 and 6 psi used in AASHTO T307 for subgrade soils. For posterity, the UCS vs. E relationship from 0 psi confining stress is shown in Figure 3.8b. The relationship is mildly different and indicates that for these LSS, confining stress had little effect on the sample stiffness.

Table 2-C. Summary of soils tested by Thompson (1966)

Soil	LL	PI	% clay	Lime %
A-7-6 (18)	53	29	52	5.0
A-6 (6)	26	11	14	3.0
A-6 (8)	32	10	21	5.0
A-4 (8)	24	8	18	3.0

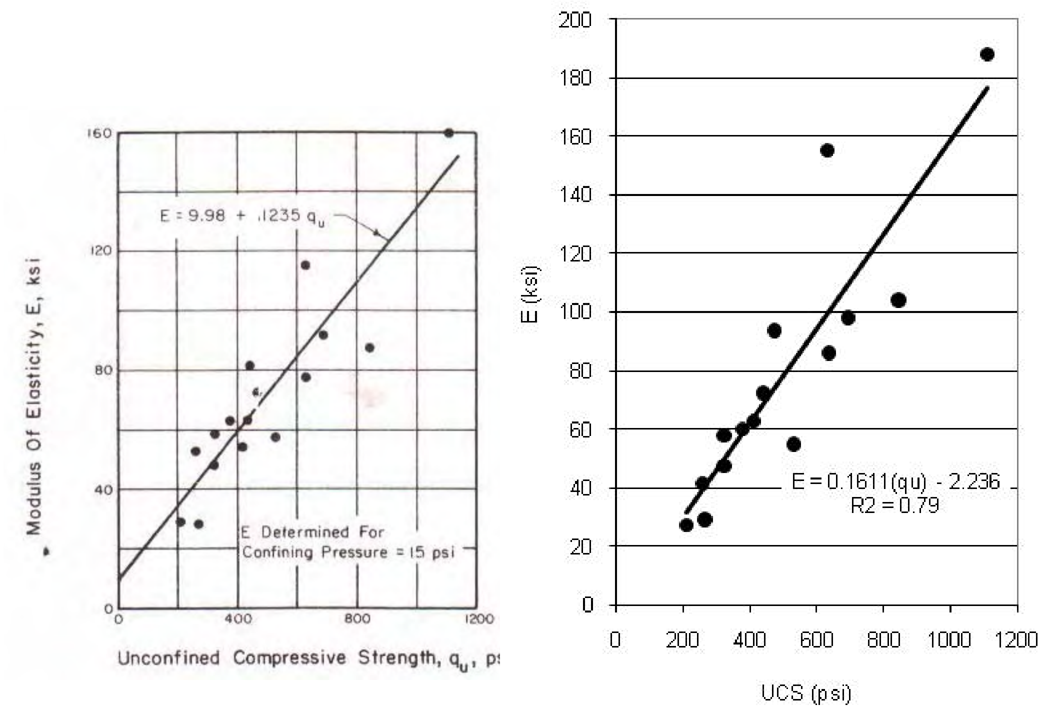

Figure 2-8. Elastic Secant Modulus (E) versus UCS relationship by Thompson (1966): (a) E measured at 15 psi confining stress (from Thompson 1966); (b) E measured at 0 psi confining stress (plot re-created from Thompson 1966 data)

Thompson's relationship (Equation 1) was derived based on samples with height to diameter ratios of 2 to 1. Per ASTM D 5102, height to diameter ratios of 2 to 1 provide the standard measure of compressive strength. UCS testing is permitted on traditional Proctor mold samples (4 inch diameter by 4.5 inch tall) per ASTM D 5102 Method B; however, Proctor mold UCS values may be different than those from 2:1 height to diameter ratio samples, and should not necessarily be used interchangeably.

In addition, Equation (1) was developed based on the results of static triaxial tests. Resilient modulus testing is dynamic, and the M_r values are dynamic moduli. Research has shown that M_r values can be 5-10 times greater than statically determined E values. Finally, M_r is the ratio of deviator stress to resilient or recoverable strain. The E values used to derive Equation (1) were determined from an initial secant modulus using a stress level at 0.7-0.8 peak strength. Stress-strain plots from UCS tests tend to become nonlinear at stress levels above 0.5 UCS (Yusuf et al. 2001), with some strains being non-recoverable.

CTL/Thompson (1998) performed 3 UCS and M_r tests (per AASHTO T294) on one A-7-6 soil mixed with 6% quicklime. These samples were prepared according to AASHTO T294 which requires 2:1 height to diameter ratios. No information was provided about the curing conditions. The results (identified as "duplicate" sets of 3 samples in the referenced report) are shown in Figure 2-9 and generally agree with Thompson's (1966) correlation for the values of UCS tested. Note that Thompson's correlation is not based on any UCS data less than 200 psi.

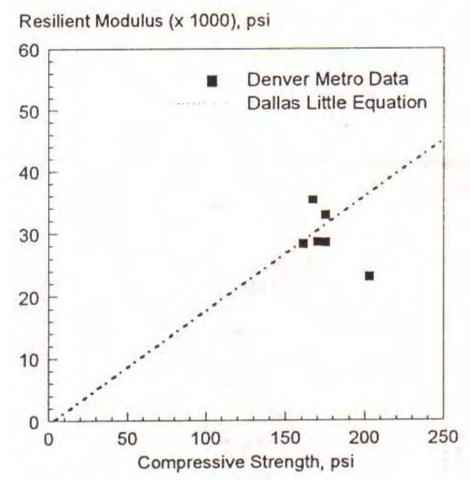

Figure 2-9. Results of limited testing by CTL/Thompson (1998) corroborate Equation (1). Note that Thompson's correlation is incorrectly referenced in this Figure from CTL/Thompson (1998) as Dallas Little's equation

Little et al. (1994) proposed a relationship between M_r and UCS based on a comparison of Thompson's 1966 correlation (Equation 1), UCS versus flexural modulus data from Thompson and Figueroa (1989), and UCS versus modulus back-calculated from FWD results. Figure 2-10 shows the three relationships. Little and co-workers conclude that Equation (1) is conservative, and recommends a "realistic and conservative approximate modulus for the lime-stabilized layer" shown by the dashed line in Figure 2-10. This design relationship produces much greater M_r values than Equation (1), e.g., 2 times greater at UCS = 200 psi and 2.5 times greater at UCS = 300 psi. Little et al. (1994) recommends that the approximate design M_r be determined from Figure 2-11 using 28-day, 25°C cured UCS values. As shown in Table 2-D, Little also recommends that the ratio of lime-stabilized design M_r to modulus of underlying untreated soil should not exceed 17 for subgrade moduli equal to or less than 18 ksi, 10 for subgrade moduli between 18 and 70 ksi, or 5 for subgrade moduli equal to or above 70 ksi.

Table 2-D. Recommended M_r ratios for LSS and untreated soil (Little 1994)

Subgrade M_r (ksi)	M_r (LSS)/ M_r (untreated soil)
≤ 18	≤ 17
18 < M_r < 70	≤ 10
≥ 70	≤ 5

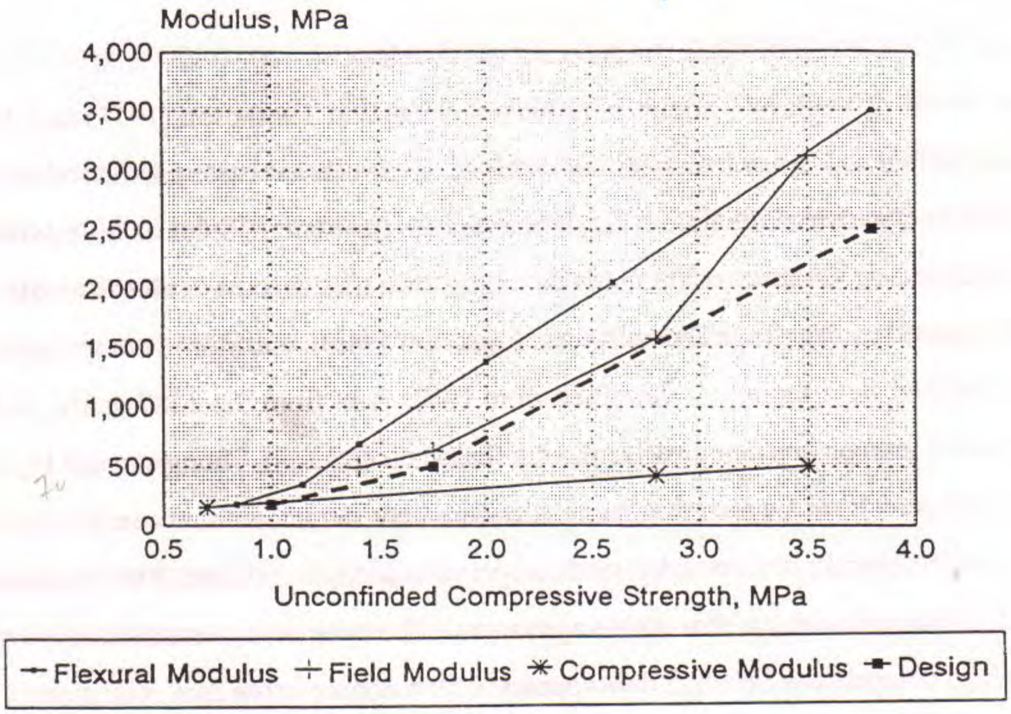

Figure 2-10. Design M_r vs. UCS relationship for lime-stabilized soil recommended by Little et al. (1994) based on three sets of findings: (a) UCS versus compressive modulus E from Thompson (1966); (b) UCS versus flexural modulus from Thompson & Figueroa (1989); and (c) UCS versus back-calculated FWD modulus from Little et al. (1994)

In summary, there is a considerable difference between how Equation (1) was developed, how resilient modulus testing is performed today, and how UCS testing is performed in Colorado practice (Proctor samples). Further, there is very limited data in the literature to confidently validate Equation (1).

CHAPTER 3: TEST PROGRAM AND RESULTS

3.1 Test Program

3.1.1 Soils and Lime Treatment

Six soils from the Denver metropolitan area with plasticity indexes (PI) ranging from 13 to 37 were selected for laboratory testing. The key characteristics of the untreated (natural) soils selected for testing are summarized in Table 3-A. Soils were homogenized and processed over the ASTM No. 4 sieve (0.187 in.) prior to specimen preparation. The AASHTO classifications provided in Table 3-A reflect minus No. 4 material. Soil 1 was collected after lime treatment, mixing, 48 hours of mellowing and re-mixing (with additional moisture conditioning to achieve w_{opt}) in the field (see Fig. 3-1). Soil 1 was processed on the No. 4 sieve following field lime treatment and prior to specimen preparation. Moisture content was not altered from field conditions. Test specimens were prepared using standard Proctor energy in accordance with ASTM D698. Sampling the field-prepared lime-treated soil is the standard industry practice for QC/QA UCS testing. This practice was not followed for soils 2 through 6 because lime-stabilization projects were not available during the project timeline. Soils 2 through 6 were sampled from various field sites (Table 3-A), processed over the No. 4 sieve, and lime-treated in the laboratory using a high-speed drill with rotary paddle attachment (see Fig. 3-2). This procedure is commonly used during mix design in local practice.

Accelerated curing was performed at 105ºF in this study. As previously mentioned, the difference between 100°F and 105°F curing is deemed negligible (the variation in reporting resolution and measurement accuracy is 2-5°F). The CDOT Study Panel 80.26 decided by committee (November 2008) to support the use of 105ºF as the specified accelerated curing temperature for this research.

Table 3-A. Summary of soils investigated

	Untreated Soil							Treated Soil	
Soil	**Location[d]**	**AASHTO Classification**	**% Clay**	**% Silt**	**LL[c]**	**PL[c]**	**PI[c]**	w_{opt} **(%)**	$\gamma_{d(max)}$ **(pcf)**
1[a]	C470 & Alameda	A-6	8	29	39	26	13	28	93
2[b]	98th & Sheridan	A-6	28	35	39	15	24	25	94
3[b]	98th & Sheridan	A-7-6	29	50	41	15	26	26	94
4[b]	University & County Line	A-7-6	29	19	55	18	37	29	87
5[b]	I-25 & Douglas	A-6	12	41	33	16	17	19	105
6[b]	98th & Sheridan	A-7-6	15	58	43	15	29	25	97

[a]Field mixed with 6 % lime. [b]Lab mixed with 6 % lime.
[c]LL=Liquid Limit, PL=Plastic Limit, PI=Plastic Index
[d]All locations in Denver metropolitan area in Colorado

Figure 3-1. Final field mixing of lime-treated soil 1

Figure 3-2. Laboratory mixing used for lime-treated soils 2 through 6

The processing for soils 2, 3 and 4 is differed from that used on soils 5 and 6. For soils 2, 3 and 4, small aggregations of clay particles were broken using a mortar and pestle, and then re-sieved. Moisture was added during initial mixing and final mixing to achieve w_{opt}. Soils 5 and 6 were received in an air-dried state and contained a much greater portion of clay clods requiring additional processing to a degree beyond that observed in typical practice. Prior to laboratory lime treating, soils 5 and 6 were mechanically processed using a Bico Braun Chipmunk Rock Crusher. Moisture was added gradually over a 10-day period to ensure uniform distribution prior to sieve processing. Similar to soils 2, 3 and 4, soils 5 and 6 were initially mixed with lime and moisture, mellowed for 48 hours, and final mixed with additional moisture to achieve w_{opt} and maximum dry unit weight $\gamma_{d(max)}$ (determined per ASTM D698). The lime content for each of these six soils was 6% by dry mass, consistent with Colorado practice.

3.1.2 Specimen Preparation

Both 4.0 in. diameter × 4.5 in. tall Proctor specimens and 4.0 in. diameter × 8.0 in. tall specimens were prepared and cured for UCS testing (see Fig. 3-3) and for resilient modulus testing (4.0 in. × 8.0 in. specimens only). The 4.0 in. × 4.5 in. samples were prepared using standard Proctor energy in accordance with ASTM D698 (i.e., 3 layers, 25 hammer blows per layer). The 4.0 in. × 8.0 in. specimens were prepared to similar $w = w_{opt}$ and $\gamma_d = \gamma_{d(max)}$ conditions using a procedure commonly employed in local practice and similar to that used to prepare specimens for resilient modulus testing per AASHTO T307 (i.e., 4 layers, hand tamped) (see Fig. 3-4). Each 4.0 in. × 8.0 in. specimen was prepared using four 2-inch thick layers; each layer was prepared by compacting a pre-defined mass of soil into a known layer volume.

Figure 3-3. Two specimen geometries used during testing: 4.0 in. diameter × 4.5 in. tall and 4.0 in. diameter × 8.0 in. tall

Figure 3-4. Preparation of 4.0 x 8.0 in. specimens

As summarized by the test matrix in Table 3-B, UCS testing was performed on specimens subjected to accelerated (A) curing (105°F) prior to testing, as well as on specimens subjected to normal (N) room temperature curing (73°F) prior to testing. All specimens were cured individually in sealed bags. The notation used in Table 3-B reflects the curing regime (A vs. N) and the specimen height (4.5 in. vs. 8.0 in). For each soil, UCS testing was performed on A4 specimens after 2, 4, 6 and 8 days and N4 specimens after 6, 14 and 28 days. UCS testing was performed on N8 specimens after 3, 6, 7, 14, and 28 days. Resilient modulus testing was performed on 28-day N8 specimens for soils 4, 5 and 6 prior to UCS testing.

Table 3-B. UCS testing matrix

Soil	Duration of Curing (days) prior to UCS Testing								
	2	3	4	5	6	7	8	14	28
1	A4[1,2]		A4		A4		A4		
					N4			N4	N4
					N8			N8	N8
2	A4		A4		A4		A4		
					N4			N4	N4
		N8			N8	N8		N8	N8
3	A4		A4		A4		A4		
					N4			N4	N4
		N8			N8	N8		N8	N8
4	A4		A4		A4		A4		
					N4			N4	N4
		N8			N8	N8		N8	N8[3]
5	A4		A4		A4		A4		
					N4			N4	N4
		N8			N8	N8		N8	N8[3]
6	A4		A4		A4		A4		
					N4			N4	N4
		N8			N8	N8		N8	N8[3]

[1]Each cell represents a set of three test specimens, unless otherwise noted
[2]A = accelerated curing, N = normal curing, 4 = 4.0 × 4.5 in. samples, 8 = 4.0 × 8.0 in. samples
[3] Specimen set consists of 5 cylinders

3.1.3 UCS Testing

The vast majority of UCS tests (195 of total 210) were performed in the Colorado School of Mines (CSM) geotechnical laboratory. Figure 3-5 shows the UCS test setup and data acquisition system used in the CSM geotechnical laboratory. All UCS testing was performed in accordance with ASTM D5102. After curing, specimens were capped with Hydrocal gypsum cement to ensure uniform surface contact and force application. Testing was performed using a 10 kip ELE/Soiltest uniaxial load frame. A 10 kip load cell and 1.0 in. range displacement sensor were used to measure axial force and vertical deformation, respectively. Data from both transducers was recorded continuously using computerized data acquisition. UCS tests were performed at a constant axial rate of deformation of 1% per minute beyond measurement of peak strength. Samples achieved peak strength at axial strain levels ranging from 0.5-4%.

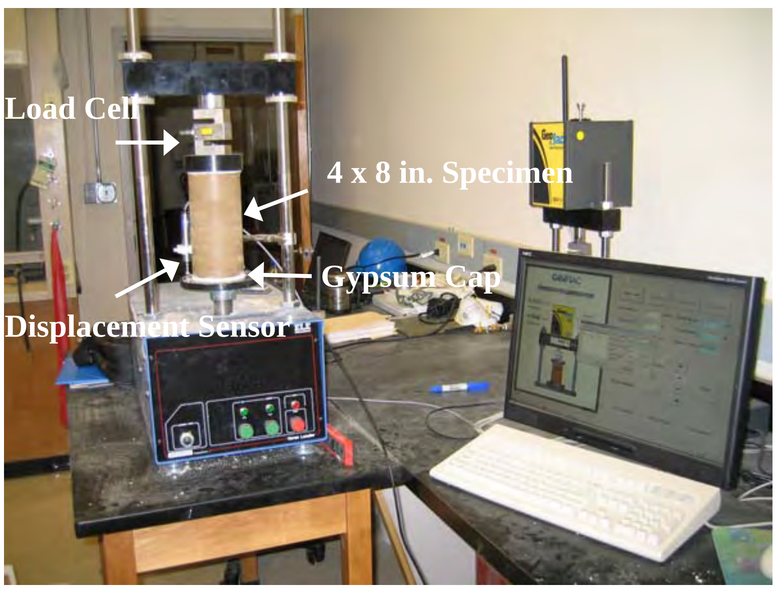

Figure 3-5. Load frame and data acquisition system at CSM research facility

Ground Engineering Consultants, Inc. (Denver, CO) performed UCS testing on fifteen 28-day N8 specimens following resilient modulus testing. A Soiltest Versa Tester uniaxial load frame with 2 kip load cell was used (Fig. 3-6). Axial displacement was recorded manually from a Teclock AI-921 Dial Gauge. Force application was recorded manually from an ADMET Buster Digital Gauge. Thirteen of the fifteen specimens were capped with Hydrocal gypsum cement to smooth and level loading surfaces out of plain by 0.002 inches. Two of specimens did not require capping. Specimens were compressed at an axial strain rate of 1% per minute. Specimens achieved peak strength at axial strain levels of 0.6-2.0%

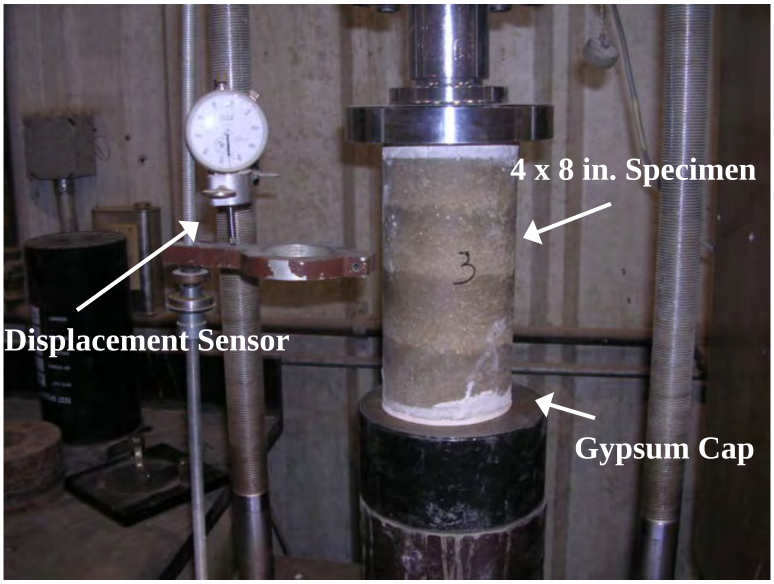

Figure 3-6. UCS test setup used by Ground Engineering

3.1.4 Resilient Modulus Testing

Resilient modulus (M_r) testing was performed on fifteen 28-day N8 specimens prior to UCS testing by Ground Engineering Consultants, Inc. (Denver, CO). Thirteen of the samples were capped with Hydrocal gypsum cement to smooth and level surface irregularities. M_r testing was performed using a Geotechnical Testing Consulting Systems (GTCS) testing system (see Figure 3-7).

Figure 3-7. M_r test setup used by Ground Engineering

M_r testing was performed in accordance with AASHTO T-307 using the subgrade soils testing sequence (Table 3-C). Specimens were conditioned for 500 cycles with a confining pressure of 6 psi and deviator stress of 4 psi prior to the testing sequence in Table 3-C. Each stage (confining pressure and deviator stress combination) was applied for 100 cycles. The M_r values recorded reflect the average of the last 3 cycles.

Table 3-C. Subgrade Soil Testing Sequence (AASHTO T-307)

Stage	Confining Pressure (psi)	Deviator Stress (psi)	Stage	Confining Pressure (psi)	Deviator Stress (psi)	Stage	Confining Pressure (psi)	Deviator Stress (psi)
1	6.0	2.0	6	4.0	2.0	11	2.0	2.0
2	6.0	4.0	7	4.0	4.0	12	2.0	4.0
3	6.0	6.0	8	4.0	6.0	13	2.0	6.0
4	6.0	8.0	9	4.0	8.0	14	2.0	8.0
5	6.0	10.0	10	4.0	10.0	15	2.0	10.0

3.2 Test Results

3.2.1 UCS from Specimens Cured under Normal and Accelerated Conditions

The results of UCS testing on 4.5 in. tall specimens cured under normal (N4) conditions and accelerated (A4) conditions are presented in Figure 3-8 for soils 1 through 4. Summary data is provided in Table 3-D. Results from soils 5 and 6 are presented separately because they were processed more rigorously and different from typical industry practice (Section 3.1.2). As shown in Figure 3-8, each soil exhibited reasonably linear growth in UCS under normal and accelerated curing. Least squares linear regression was sufficient in characterizing the strength gain with time (all $R^2 > 0.7$).

Figure 3-8 illustrates the accelerated curing time required to achieve a UCS equivalent to 28-day normal curing. The equivalent accelerated curing durations for the four soils were found to be 5.4, 4.6, 5.9, and 1.8 days, respectively (Table 3-D). Similar to the literature (Chapter 2), a consistent equivalent accelerated curing time was not found. The high PI soil (soil 4, PI = 37) yielded the shortest equivalent accelerated curing time, yet the lowest PI soil (soil 1, PI = 13) did not yield the longest equivalent accelerated curing time. The range of observed equivalent accelerated curing time (1.8-5.9 days) is similar to those reported in the literature (2.5-6.0 days).

The slope of each best fit line ($m = \Delta UCS/\Delta t$) reflects the UCS gain with curing time. As illustrated by visual observation and by the values of *m* in Figure 3-8 and Table-3-E, the rate of strength gain varies considerably across these four soils both for normally cured and accelerated cured specimens. The influence of elevated curing temperature on UCS gain with time is clearly significant for each soil. The high PI soil (soil 4, PI = 37) was most significantly impacted by accelerated curing ($m_A/m_N = 14.4$).

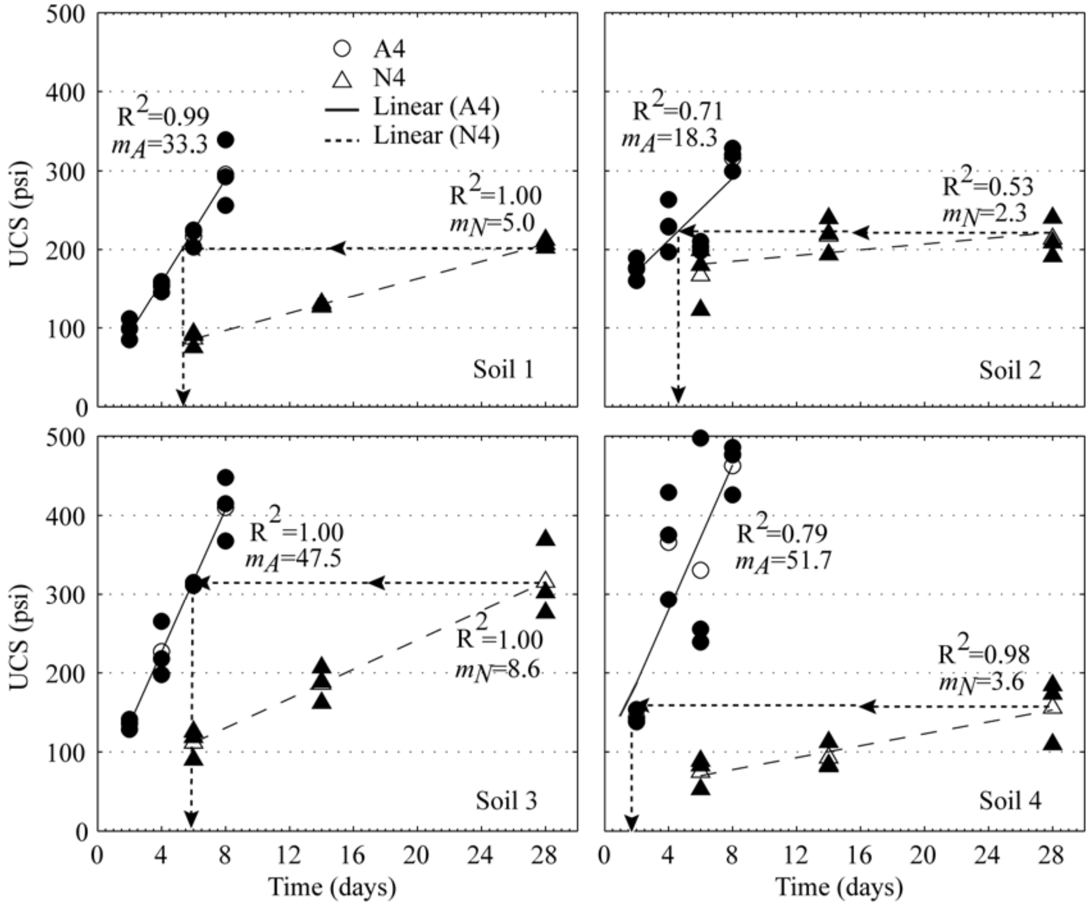

Figure 3-8. UCS vs. curing time for 4- 4 x 4.5 inch accelerated cure (A4) and normal cure (N4) samples. Individual sample UCS in filled symbols, average UCS in open symbols

Table 3-D. Comparison of 6 and 28 day normal and accelerated cured UCS

Soil	PI	% clay	28-day N4 UCS (psi)	6-day N4 UCS (psi)	6-day A4 UCS (psi)	6-day A4/N4 UCS	Equiv. Accel. Curing Time (days)
1	13	8	200	90	210	2.3	5.4
2	24	28	220	170	250	1.5	4.6
3	26	29	310	120	310	2.6	5.9
4	37	29	160	80	350	4.4	1.8

Table 3-E. Comparison of UCS gain with time for normal and accelerated curing

Soil	PI	% clay	*% fines*	m_N (Normal) (psi/day)	m_A (Accel) (psi/day)	m_A/m_N
1	13	8	36	5.0	33.3	6.7
2	24	28	63	2.3	18.3	8.0
3	26	29	79	8.6	47.5	5.5
4	37	29	48	3.6	51.7	14.4

$m = \Delta UCS/\Delta t$, *A*=accelerated curing, *N*=normal curing

When considering the use of accelerated curing in practice, the results presented here and in the literature indicate that 7-day 105°F curing will yield UCS values greater than UCS values from 28-day normally cured specimens for all soils. Table 3-F summarizes the UCS values and the over/underestimation of 28-day normal cure UCS. 7-day 105°F curing overestimates 28-day normal cure UCS by 13-256%. The use of 5-day 105°F curing would slightly underestimate 28-day normal cure UCS for soils 1 and 3 (less than 10%) and overestimate 28-day normal cure UCS for soil 2 (2%) and 4 (94%). The variability in degree of over/underestimation is significant.

Table 3-F. Comparison of UCS from 5 and 7-day accelerated cure with 28 day normal cure

Soil	$N4_{28\text{-day}}$ UCS (psi)	$A4_{5\text{-day}}$ UCS (psi)	$A4_{7\text{-day}}$ UCS (psi)	$A4_{5\text{-day}}/N4_{28\text{-day}}$	$A4_{7\text{-day}}/N4_{28\text{-day}}$
1	200	195	250	0.98	1.25
2	220	225	280	1.02	1.27
3	310	280	350	0.90	1.13
4	160	310	410	1.94	2.56

UCS test results for soils 5 and 6 are presented in Figure 3-9. The strength gain during both normal and accelerated curing exhibit linear behavior similar to soils 1 through 4. However, early strength under accelerated curing was considerably higher than that observed in soils 1 through 4, while normal curing UCS and UCS gain with time was similar to soils 1 through 4. As a result, the equivalent accelerated curing time could not be predicted for soil 5 and was less than 1.5 days for soil 6. The very high early strength under accelerated curing is likely due to the soil processing method employed.

Prior to laboratory lime treating, soils 5 and 6 were processed using a Bico Braun Chipmunk Rock Crusher. This technique resulted in much smaller clay clods and particle aggregations than the technique used for soils 1 through 4. In addition, soils 5 and 6 were moisture conditioned to w_{opt} over a ten day period whereas, moisture was added to soils 2 through 4 in bulk at two instances, prior to mellowing and just before final mixing. Pozzolanic reactions are highly dependent upon the soil's mineralogical content and the uniformity of lime and water distribution. The higher percentage of clods and particle aggregations coupled with increased moisture distribution permitted greater surface area contact between lime and soil particles. Interestingly, this translated to higher early strength for accelerated curing but not for normal curing.

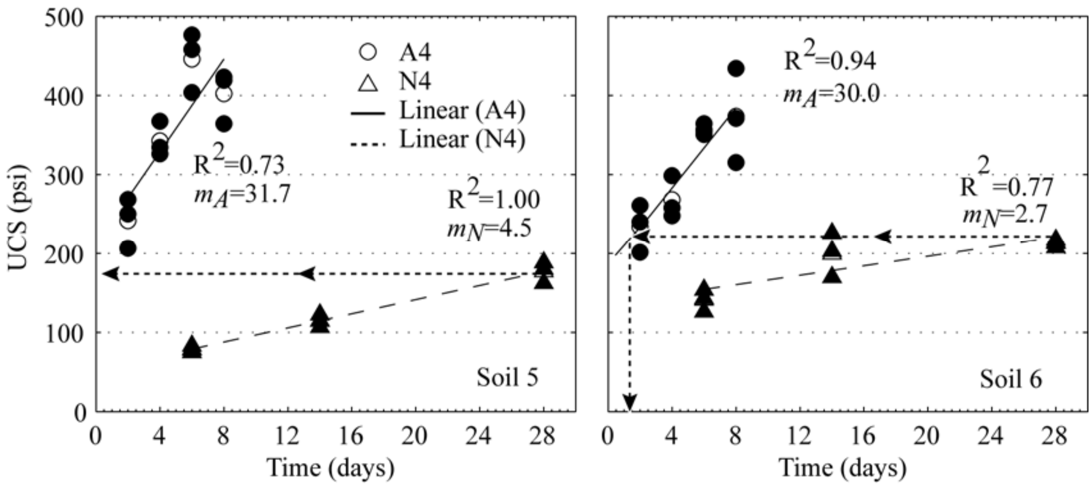

Figure 3-9. UCS with time for soils 5 (left) and 6 (right) for 4- 4 x 4.5 inch accelerated cure (A4) and normal cure (N4) samples. Individual sample UCS in filled symbols, average UCS in open symbols

The axial stress vs. axial strain response measured during each UCS test is shown in Figures 3-10 and 3-11 to illustrate the evolution of stress-strain behavior with time for both curing regimes. Axial strains at peak UCS ranged from 1-4%. Stress-strain behavior within each 3-specimen grouping exhibited some variability. Figure 3-12 compares the 6-day A4 stress-strain behavior with that of the 28-day N4 behavior. The similarity in both UCS and peak strain at UCS for three of the four soils is a positive finding. This suggests that 105°F curing *accelerates* the chemical reactions that occur during normal curing and does not create new chemical reactions. The implication is that 105°F curing does not induce artificial strength gain that would not occur under normal conditions.

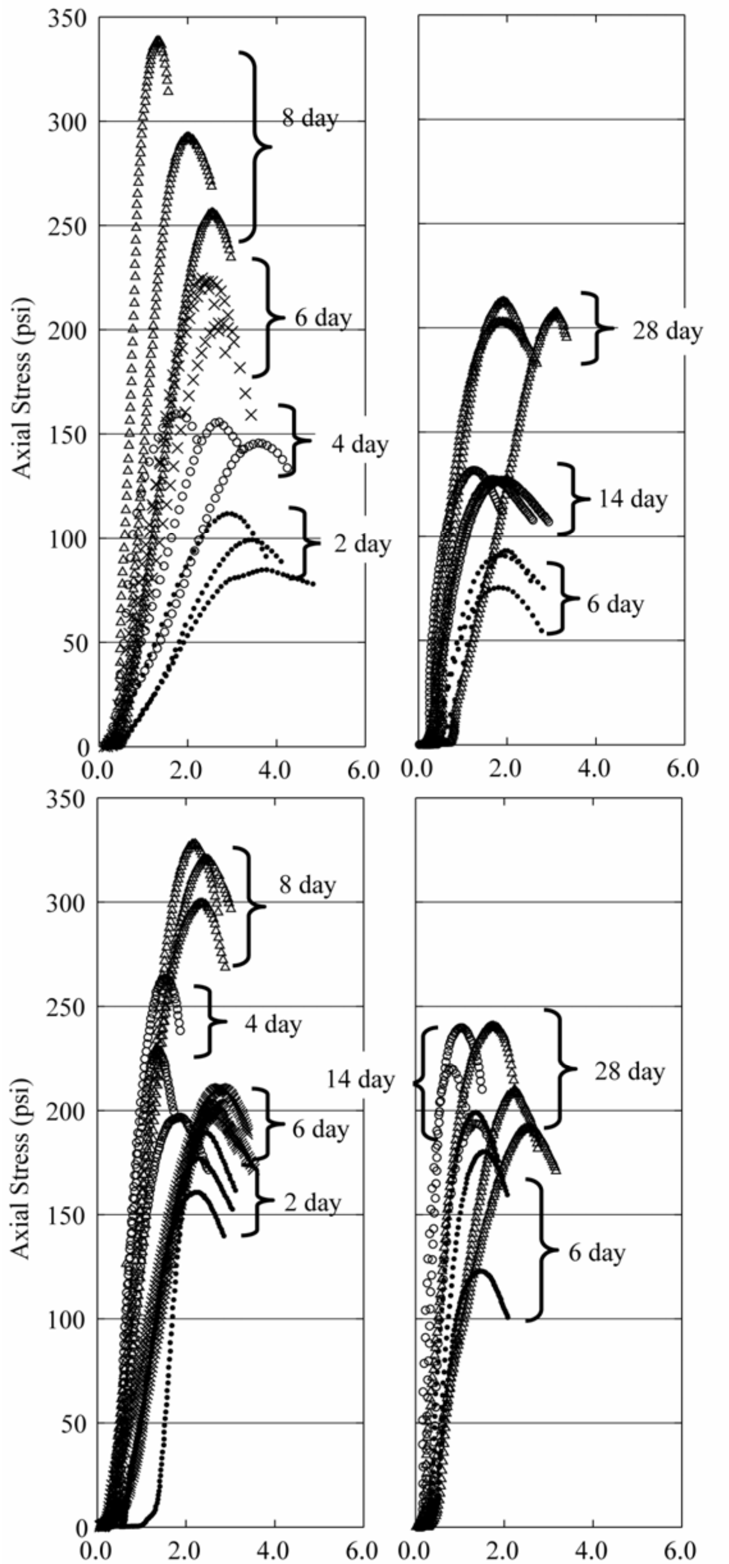

Figure 3-10. Axial stress-strain behavior of soil 1 (top) and soil 2 (bottom) specimens (4 x 4.5 in.). Accelerated cure on left side and normal cure on right

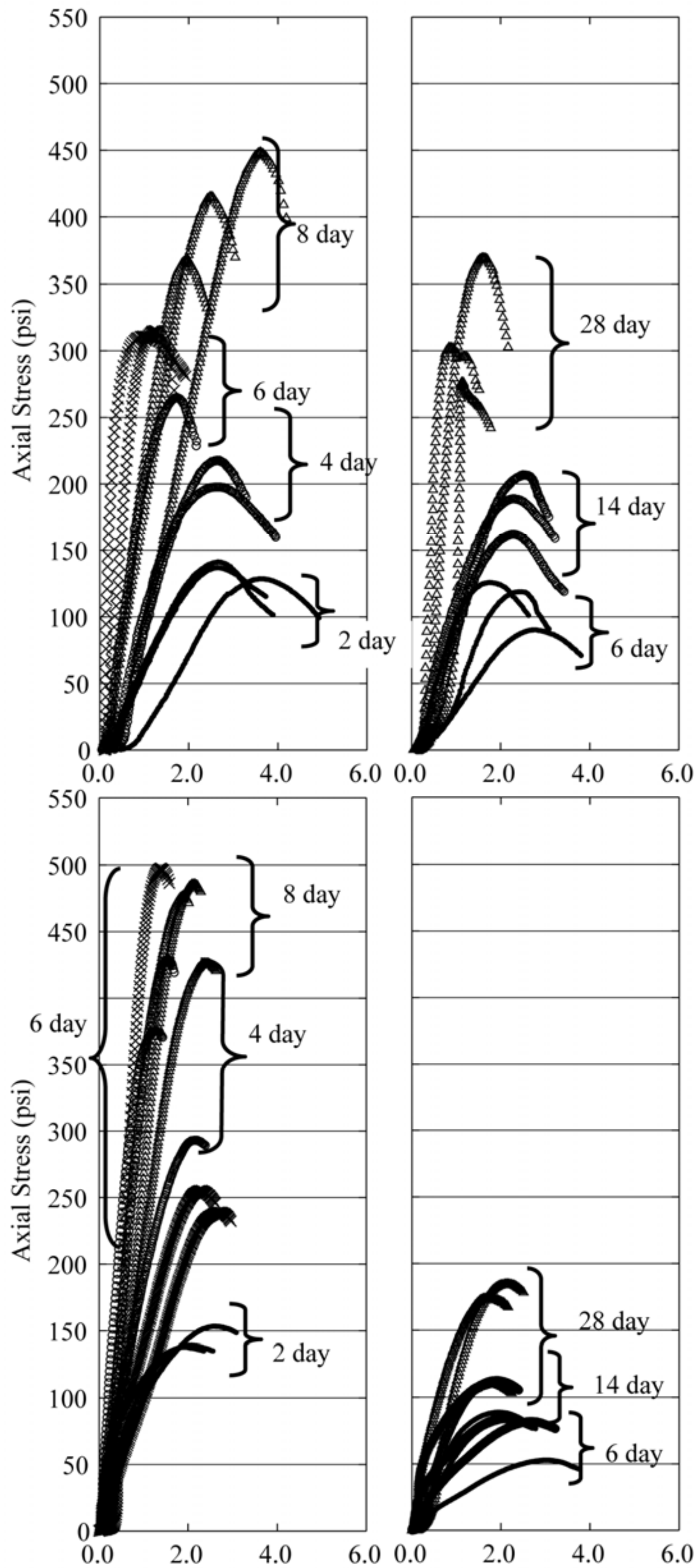

Figure 3-11. Axial stress-strain behavior of soil 3 (top) and soil 4 (bottom) specimens (4 x 4.5 in.). Accelerated cure on left side and normal cure on right

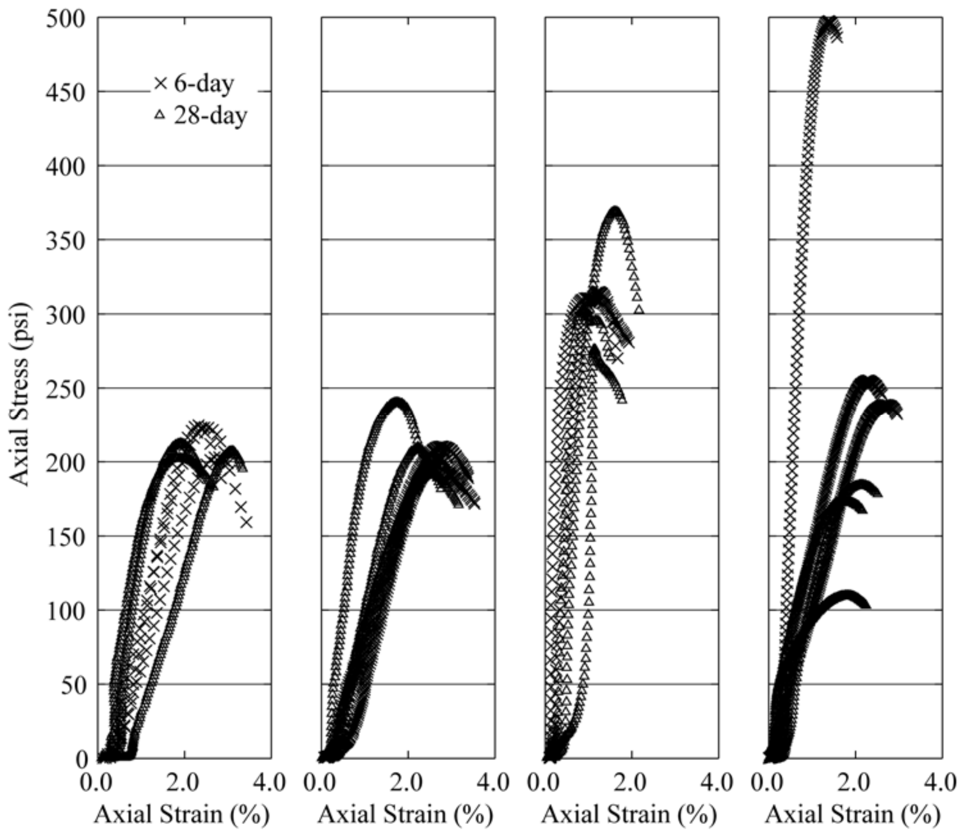

Figure 3-12. Comparison of 6-day accelerated and 28-day normal curing axial stress-strain behavior for soil 1, 2, 3 and 4, left to right respectively

The axial stress vs. axial strain response for soils 5 and 6 is shown in Figure 3-13. Accelerated strength gain for soil 5 after 8 days was on the same order or less than UCS gain achieved after 6 days. This suggests that soil 5 achieved maximum strength gain following 6 days of curing under accelerated conditions. Soil 5 specimens cured under normal conditions exhibited repeatable and consistent trends with respect to strength gain. Soil 6 specimens cured under accelerated conditions exhibited repeatable and consistent trends with respect to strength gain. However, 28-day normally cured specimens show strength gain on the same order as 14-day normally cured specimens. This suggests that soil 6 achieved maximum strength gain following 14 days of curing under normal conditions.

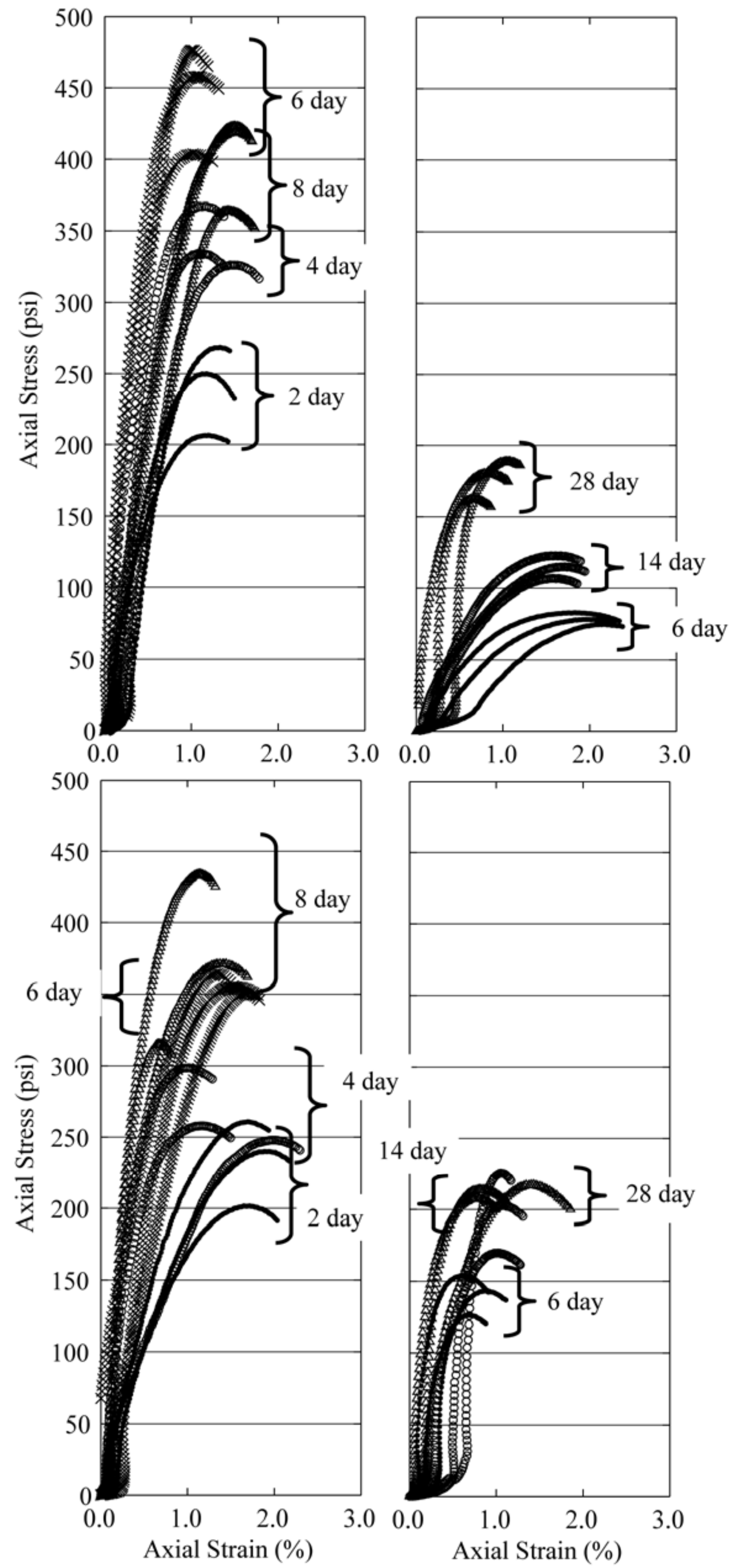

Figure 3-13. Axial stress-strain behavior of soil 5 (top) and soil 6 (bottom) specimens (4 x 4.5 in.). Accelerated cure on left side and normal cure on right

3.2.2 Correlation of M_r and UCS

The 2007 Interim M-E Pavement Design Guide (Table 25, p. 122) and Mallela et al. (2004) indicate that the design M_r for lime-stabilized subgrade can be approximated from the results of UCS tests using Thompson's (1966) correlation shown in Equation (1). Per specification (AASHTO T307), M_r testing must be performed on specimens with a 2:1 height to diameter ratio. Equation (1) was developed using 2:1 height to diameter specimens (see Chapter 2).

$$M_r \text{ (ksi)} = 0.124 * \text{UCS (psi)} + 9.98 \qquad \text{[(1) re-stated]}$$

M_r testing was performed on fifteen 4.0 x 8.0 inch specimens of lime-stabilized soils 4, 5, and 6 cured for 28-days under normal conditions. M_r values obtained with confining pressures σ_c = 2 psi and 4 psi at a deviator stress σ_d = 6 psi were used to assess the validity of Thompson's (1966) correlation for LSS. Each specimen's UCS was determined immediately following M_r testing on the same specimens (typical practice since M_r testing is non-destructive).

UCS and M_r data for the three soils are plotted in Figure 3-14a (M_r σ_c=2 psi) and 3-15a (M_r σ_c=4 psi) together with Thompson's equation. The data is also summarized in Tables 3-G and 3-I. The data exhibits considerable scatter as evidenced by the Range/Mean values in Tables 3-G and 3-I. The scatter is particularly high for M_r results from soils 4 and 5. To reduce scatter and uncertainty, the data from the five specimens for each soil was averaged and are presented in Figure 3-14b (M_r σ_c=2psi) and 3-15b (M_r σ_c=4psi). Here, N8 refers to the 8.0 in. tall specimen results. The N4 results are described below. For each soil at both confining pressures, Thompson's correlation (Eq. 1) underestimates M_r considerably and is therefore conservative. Per the summary data in Tables 3-H and 3-J, the measured M_r (σ_c=2 psi) is 20 - 50 % greater than M_r predicted by Thompson's correlation, and the measured M_r (σ_c=4 psi) is 50 - 80 % greater than M_r predicted by Thompson's correlation.

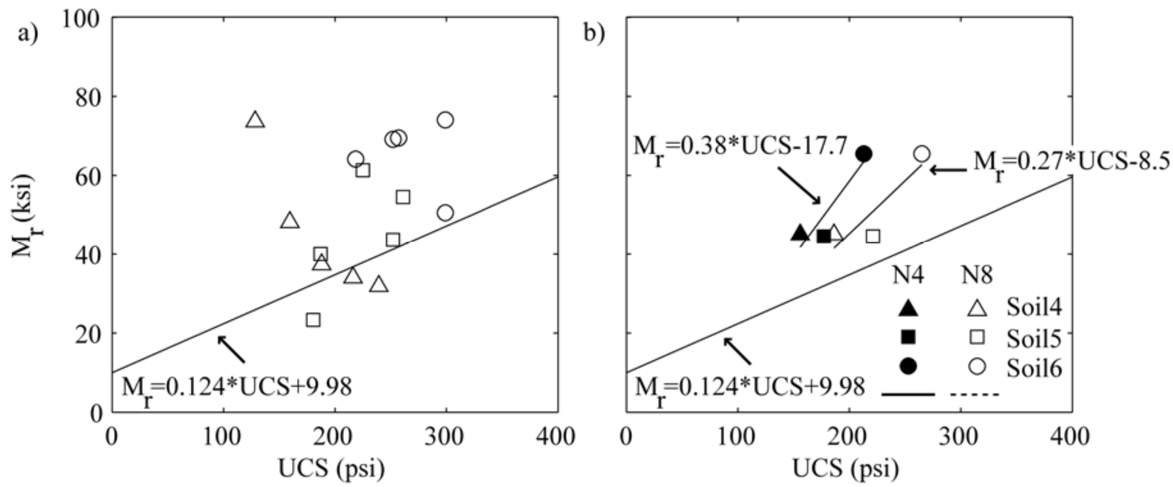

Figure 3-14. Relationship between M$_r$ (σ_c=2 psi, σ_d=6 psi) and UCS: (a) Individual specimen data for 4.0 x 8.0 in. tall specimens; (b) Average results of 5 specimens for 4.0 x 8.0 in. tall and 4.0 x 4.5 inch tall specimens. Thompson's correlation is shown for comparison

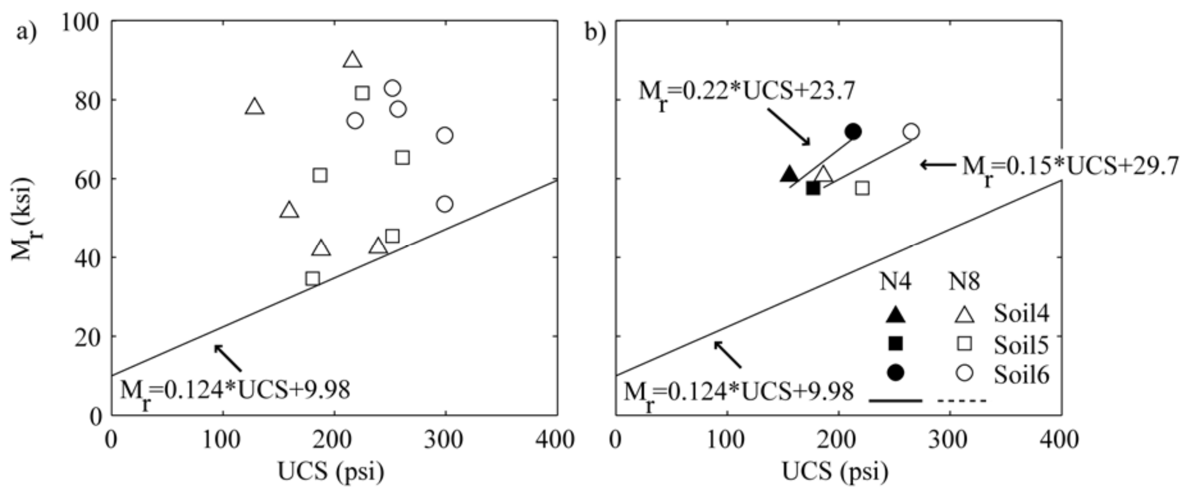

Figure 3-15. Relationship between M$_r$ (σ_c=4 psi, σ_d=6 psi) and UCS: (a) Individual specimen data for 4.0 x 8.0 in. tall specimens; (b) Average results of 5 specimens for 4.0 x 8.0 in. tall and 4.0 x 4.5 inch tall specimens. Thompson's correlation is shown for comparison.

Table 3-G. Summary of UCS (N8) and M_r (N8) (σ_c=2 psi, σ_d=6 psi)

Specimen	Soil 4		Soil 5		Soil 6	
	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)
1	37.4	188	23.3	180	50.5	299
2	31.9	239	40.0	187	74.0	299
3	73.6	128	61.3	225	69.4	257
4	48.2	160	54.6	261	64.1	219
5	34.0	216	43.6	252	69.1	252
Mean	45.0	186	44.6	221	65.4	265
Range/Mean	0.93	0.60	0.85	0.36	0.36	0.30

Table 3-H. Comparison of measured (N8) and estimated (N8) (Eq. 1) M_r (σ_c=2 psi, σ_d=6 psi)

Soil	UCS (psi) (N8)	Measured M_r (ksi)	Estimated M_r (ksi) (Eq. 1)	M_r (meas)/M_r (Eq. 1)
4	**186**	**45.0**	**33.0**	**1.4**
5	**221**	**44.6**	**37.4**	**1.2**
6	**265**	**65.4**	**42.8**	**1.5**

Table 3-I. Summary of UCS (N8) and M_r (N8) (σ_c=4 psi, σ_d=6 psi)

Specimen	Soil 4		Soil 5		Soil 6	
	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)
1	41.9	188	34.6	180	53.6	299
2	42.5	239	60.9	187	71.0	299
3	77.9	128	81.7	225	77.6	257
4	51.6	160	65.3	261	74.7	219
5	89.7	216	45.5	252	82.9	252
Mean	60.7	186	57.6	221	72.0	265
Range/Mean	0.87	0.60	0.82	0.36	0.41	0.30

Table 3-J. Comparison of measured (N8) and estimated (N8) (Eq. 1) M_r (σ_c=4 psi, σ_d=6 psi)

Soil	UCS (psi) (N8)	Measured M_r (ksi)	Estimated M_r (ksi) (Eq. 1)	M_r (meas)/M_r (Eq. 1)
4	**186**	**60.7**	**33.0**	**1.8**
5	**221**	**57.6**	**37.4**	**1.5**
6	**265**	**72.0**	**42.8**	**1.7**

In Colorado practice, UCS is performed on 4.5 in. tall specimens. Given the reported influence that slenderness ratio has on UCS, the relationship between $UCS_{4.5}$ and $UCS_{8.0}$ was investigated. Average UCS values from 4.5 in. tall and 8.0 in. tall specimens after normal curing times of 6, 14 and 28 days are shown in Figure 3-16. While the general trend is 1:1, $UCS_{4.5}$ values were found to be lower than $UCS_{8.0}$ values.

In addition to the UCS testing performed on 4.0 x 8.0 in. specimens after M_r testing, UCS testing was performed on 28-day N4 specimens (4.0 x 4.5 in. tall). The results are summarized in Tables 3-K and 3-M, and the average values are plotted in Figures 3-14 and 3-15. $UCS_{4.5}$ values were on average 0.8 times the $UCS_{8.0}$ values. It is possible that the M_r testing densified and thus strengthened the 8.0 in. tall specimens prior to UCS testing. As a result, the predicted M_r values per Thompson's correlation using $UCS_{8.0}$ are likely more conservative. Per the summary data in Tables 3-L and 3-N, the measured M_r (σ_c=2 psi) is 40 - 80% greater than M_r predicted by Thompson's correlation, and the measured M_r (σ_c=4 psi) is 80 - 110 % greater than M_r predicted by Thompson's correlation.

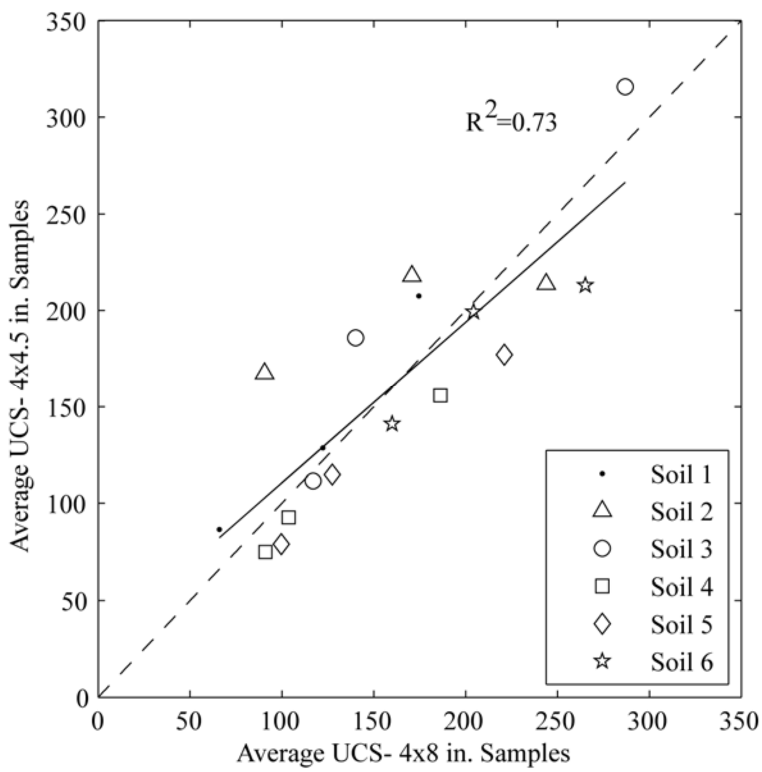

Figure 3-16. Average UCS values of 4.5 in. tall and 8 in. tall specimens

Table 3-K. Summary of UCS (N4) and M_r (N8) (σ_c=2 psi, σ_d=6 psi)

Specimen	Soil 4		Soil 5		Soil 6	
	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)
Mean	45.0	156	44.6	177	65.4	213
Range/Mean	0.93	0.48	0.85	0.15	0.36	0.04

Table 3-L. Comparison of measured M_r (N8) and estimated M_r (N4) (Eq. 1) (σ_c=2 psi, σ_d=6 psi)

Soil	UCS (psi) (N4)	Measured M_r (ksi)	Estimated M_r (ksi) (Eq. 1)	M_r (meas)/M_r (Eq. 1)
4	**156**	**45.0**	**29.3**	**1.5**
5	**177**	**44.6**	**31.9**	**1.4**
6	**213**	**65.4**	**36.4**	**1.8**

Table 3-M. Summary of UCS (N4) and M_r (N8) (σ_c=4 psi, σ_d=6 psi)

Specimen	Soil 4		Soil 5		Soil 6	
	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)	M_r (ksi)	UCS (psi)
Mean	60.7	156	57.6	177	72.0	213
Range/Mean	0.87	0.48	0.82	0.15	0.41	0.04

Table 3-N. Comparison of measured M_r (N8) and estimated M_r (N4) (Eq. 1) (σ_c=4 psi, σ_d=6 psi)

Soil	UCS (psi) (N4)	Measured M_r (ksi)	Estimated M_r (ksi) (Eq. 1)	M_r (meas)/M_r (Eq. 1.)
4	**156**	**60.7**	**29.3**	**2.1**
5	**177**	**57.6**	**31.9**	**1.8**
6	**213**	**72.0**	**36.4**	**2.0**

As described in Chapter 2, Little et al. (1994) concluded that Thompson's correlation is conservative. Little and co-workers proposed a relationship between M_r and UCS based on a comparison of Thompson's 1966 correlation (Equation 1), UCS versus flexural modulus data from Thompson and Figueroa (1989), and UCS versus modulus back-calculated from FWD results. Figure 3-17 illustrates the measured data from soils 4, 5 and 6 with Little's proposed relationship. Little's relationship provides a more reasonable match to the measured data, particularly for σ_c=2 psi, σ_d=6 psi (Fig. 3-17a).

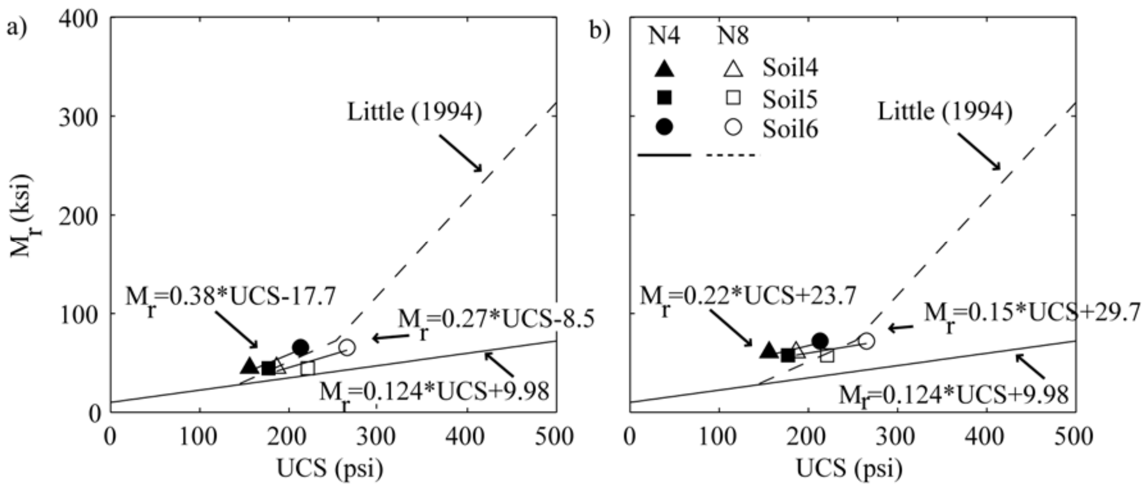

Figure 3-17. Comparison of Measured Data with Proposed Relationship from Little (1994): (a) σ_c=2 psi, σ_d=6 psi, (b) σ_c=4 psi, σ_d=6 psi. Measured Data reflect average results of 5 specimens

3.3 Summary of Findings

The following findings are evident from the results presented in this Chapter:

- Consistent with the literature, there was no constant equivalent accelerated curing duration for the soils tested. The equivalent 105°F curing durations for soils 1 through 4 (PI = 13, 24, 26 and 37) were found to be 5.4, 4.6, 5.9, and 1.8 days, respectively.
- Per the results presented here, the 7-day, 105°F accelerated curing regime overestimates 28-day normal curing UCS by 13 to 256%.
- The 5-day 105°F curing would slightly underestimate 28-day normal cure UCS for soils 1 and 3 (less than 10%) and overestimate 28-day normal cure UCS for soil 2 (2%) and 4 (94%).
- Additional processing of soil, i.e., breaking down of aggregations plus moisture conditioning, accelerated the UCS gain with time during 105°F curing.
- M_r and UCS test results from soils 4, 5 and 6 reveal that Thompson's correlation (Equation 1) used to predict M_r from UCS is very conservative. For 8.0 in. tall specimens, measured M_r (σ_c=2 and 4 psi) were found to be 20-80% greater than M_r predicted by Thompson's correlation. For 4.5 in. tall specimens, measured M_r (σ_c=2 and 4 psi) were found to be 40-110% greater than M_r predicted by Equation (1).
- The measured M_r and UCS data matched favorably with the design relationship proposed by Little (1994).

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

4.1 Equivalent Accelerated Curing Regime

This study explored the influence of accelerated curing (i.e., elevated temperature) on short term UCS of lime-stabilized soils (LSS) and the relationship of UCS after accelerated curing (2-8 day 105°F) with UCS after 28-day room temperature curing. In addition, the relationship between resilient modulus (M_r) and UCS, and how it compares with the standard relationship used in CDOT practice (Equation 1) was investigated. A thorough review of the literature and a detailed laboratory testing program were conducted. Six fine-grained soils with plasticity indices (PI) ranging from 13 - 37 were selected for laboratory evaluation. Both 4.5 inch tall and 8.0 inch tall specimens (all 4.0 inch diameter) were prepared and subjected to accelerated (2-8 day 105°F) and normal (28-day 73°F) curing prior to UCS testing. Resilient modulus testing was performed on three of the soils.

Consistent with the literature on the influence of elevated temperature curing on UCS, no constant equivalent 105°F curing duration was identified from the test results of six lime-stabilized soils (see Table 4-A). Soils 5 and 6 were processed to a degree not experienced during field mixing and therefore should not be directly compared to field conditions. The results from soils 1-4 demonstrate that 28-day 73°F UCS is reached after 1.8 – 5.9 days of 105°F curing. Based on these results and the literature, the use of 7-day 105°F curing as a proxy for 28-day 73°F UCS is considerably un-conservative. The use of 5-day 105°F curing is more reasonable per soils 1-3 yet still significantly un-conservative for soil 4.

Table 4-A. Summary of equivalent 105°F curing durations

Soil	AASHTO Classification	% Clay	% Silt	LL	PL	PI	Equivalent 105°F Curing Duration (days)
1	A-6	8	29	39	26	13	5.4
2	A-6	28	35	39	15	24	4.9
3	A-7-6	29	50	41	15	26	5.9
4	A-7-6	29	19	55	18	37	1.8
5	A-6	12	41	33	16	17	NA
6	A-7-6	15	58	43	15	29	1.5

The following recommendations are provided regarding accelerated curing:

1. The study supports the CDOT use of 5-day, 100°F curing over 7-day, 105°F curing; however, 5-day 100°F curing can yield erroneous estimates of 28-day 73°F UCS. Note the difference between 100°F and 105°F curing is deemed negligible (the variation in reporting resolution and accuracy is ± 2°F alone).
2. The philosophy of a single equivalent accelerated curing duration is imprecise and inconsistent with LSS behavior. Strength gain with time in lime-stabilized soils is a function of mineralogy, lime content, moisture content, and temperature. As evidenced by the rapid strength gain in soils 5 and 6, UCS is also influenced by virgin soil processing, a practice that varies across laboratories. CDOT should consider requiring verification of the equivalent 105°F curing duration for each LSS. The procedure would be straightforward (comparison of 4, 6 and 8-day accelerated curing with 28-day normal curing) and could be performed during the design or early construction phase.

4.2 Resilient Modulus – Unconfined Compressive Strength Correlation

Test results from three soils demonstrated that the M_r – UCS equation (Chapter 2, Eq. 1) used by CDOT and proposed in the 2007 Interim MEPDG is conservative in its prediction of M_r from UCS of LSS. As summarized in Tables 4-B and 4-C, Equation (1) underestimates measured M_r (σ_c = 2 psi) by 20 – 50% and measured M_r (σ_c = 4 psi) by 50 - 80% for 8.0 in. tall UCS specimens. More appropriately for Colorado practice, Equation (1) underestimates 8.0 in. tall specimens' measured M_r (σ_c = 2 psi) by 40 – 80% and measured M_r (σ_c = 4 psi) by 80 - 110% for

4.5 in. tall UCS specimens (Tables 4-D and 4-E). The measured M_r – UCS relationship is more comparable to the design equation proposed by Little (2004).

Table 4-B. Comparison of measured (N8) and estimated (N8) (per Chapter 2, Eq. 1) M_r (σ_c=2 psi, σ_d=6 psi)

Soil	**UCS (psi) (N8)**	**Measured M_r (ksi)**	**Estimated M_r (ksi) (Eq. 1)**	**M_r (meas)/M_r (Eq. 1)**
4	186	45.0	33.0	1.4
5	221	44.6	37.4	1.2
6	265	65.4	42.8	1.5

Table 4-C. Comparison of measured (N8) and estimated (N8) (per Chapter 2, Eq. 1) M_r (σ_c=4 psi, σ_d=6 psi)

Soil	UCS (psi) (N8)	Measured M_r (ksi)	Estimated M_r (ksi) (Eq. 1)	M_r (meas)/M_r (Eq. 1)
4	186	60.7	33.0	1.8
5	221	57.6	37.4	1.5
6	265	72.0	42.8	1.7

Table 4-D. Comparison of measured (N8) and estimated (N4) (per Chapter 2, Eq. 1) M_r (σ_c=2 psi, σ_d=6 psi)

Soil	**UCS (psi) (N4)**	**Measured M_r (ksi)**	**Estimated M_r (ksi) (Eq. 1)**	**M_r (meas)/M_r (Eq. 1)**
4	156	45.0	29.3	1.5
5	177	44.6	31.9	1.4
6	213	65.4	36.4	1.8

Table 4-E. Comparison of measured (N8) and estimated (N4) (per Chapter 2, Eq. 1) M_r (σ_c=4 psi, σ_d=6 psi)

Soil	UCS (psi) (N4)	Measured M_r (ksi)	Estimated M_r (ksi) (Eq. 1)	M_r (meas)/M_r (Eq. 1.)
4	156	60.7	29.3	2.1
5	177	57.6	31.9	1.8
6	213	72.0	36.4	2.0

The following recommendations are provided regarding M_r – UCS correlation:

1. Adopt the M_r – UCS correlation recommended by Little (2004) for LSS. Additional testing may be performed in early adopted projects to validate the use of this correlation.
2. Adjust the M_r – UCS correlation per the results presented here. The results of this study (3 soils, 5 tests per soil) are limited and scattered; therefore, additional testing is recommended to validate a shift in the correlation.

A more general recommendation about QC/QA of LSS is warranted. The limitations of accelerated curing and M_r – UCS correlation notwithstanding, QC/QA involving *laboratory* compaction, curing and testing to estimate *field* performance has further limitations. Laboratory and field compaction yield different soil structures and curing conditions (temperature, confinement) differ in the field and lab. For these reasons, and given the relative complexity of LSS construction, we recommend that CDOT investigate alternative methods of QC/QA. Sampling could be conducted in the field on LSS that is field compacted and field cured to be representative of the parent material. Performance-related parameters such as modulus and strength could be measured directly, rather than correlated.

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