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Chemical Subgrade Stabilization of Tennessee Soils – Recommended Practices

Final Report

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16. Abstract

This report summarizes the state-of-practice in the evaluation, design, and implementation of chemical subgrade stabilization. Four Tennessee soils (two A-6 and two A-7-6) were obtained and mix designs were prepared to provide examples of the testing required for chemical stabilization. The stabilized soils met the design unconfined strength criteria of 100 psi using 3 to 5% Type IL cement. In addition, a testing manual was developed for the laboratory and field testing of chemically stabilized subgrade. Concise fact sheets were compiled for the major surficial AASHTO soil types in TN that provide typical treated and untreated soil properties. The fact sheets also graphically depict the extent of the various soil types within Tennessee. Finally the chemical subgrade treatment specification was revised to reflect the state of practice.

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Executive Summary

The soil-chemical processes that occur in chemical subgrade treatment reduce the soil's plasticity index, lower the shrink/swell potential, and increase the shear strength. The traditional admixtures, for which the most experience exists, are lime, cement, and fly ash. Because these admixtures interact differently with the soil chemistry, the selection of an appropriate admixture depends on the particular properties of the soil.

Chemical subgrade treatment can be performed as either modification or stabilization. Modification is often based on typical admixture percentages. The purpose of modification is temporary improvement of the subgrade to create a stable working platform for construction. Stabilization uses an engineered design process, called a mix design. The selected admixture and percentage for stabilization achieves specified criteria, such as shear strength and durability, in a site-specific laboratory testing program. Stabilization results in more consistent subgrade properties compared to modification. The improved subgrade properties following stabilization are sometimes incorporated in the pavement design.

Once the need for chemical treatment has been identified, the important components of the construction process are spreading the admixture, mixing the admixture and water into the subgrade, compaction, curing to allow strength gain, and field verification of treated subgrade. Quality assurance and control measures must be used throughout the process to produce consistent results.

Chemical treatment will improve the support characteristics of the subgrade, including its strength and stiffness. For example, the resilient modulus of the subgrade tends to increase by at least 50% when chemical stabilization is employed. In order to be considered in pavement design calculations, the treatment must meet the criteria for stabilization, and a full mix design is required. Some states have begun to include this increase in resilient modulus in pavement design, but few incorporate it as fully as recommended by the Mechanistic-Empirical Pavement Design Guide (AASHTO 2020).

Key Findings

The key findings of this Research Report are:

- Most state Departments of Transportation (DOTs) that regularly use chemical subgrade treatment follow relatively similar procedures for the selection of the appropriate type and percentage of chemical stabilizer. These procedures were used as guidance for the development of a mix design procedure for Tennessee.
- Incorporation of the effects of chemical subgrade stabilization into pavement design varies widely by locale. It appears that few states directly use the Mechanistic-Empirical Pavement Design Guide (AASHTO 2020) and measured resilient moduli to represent stabilized subgrade in pavement design.
- The construction of high quality chemically treated subgrade requires good construction practice, including spreading, mixing, compaction, and curing. The use of current procedures for chemical stabilization requires that up-to-date equipment, such as rotary tillers, be used to mix the chemical stabilizer with the soil.

- Samples of four soils from Tennessee were obtained, two of which classify as A-6 and two of which classify as A-7-6. The mix design process was completed on these four soil samples and representative reports were generated. These mix design reports illustrate the type of result to be expected from TDOT or its consultants for the design of chemical subgrade treatment.
- The results from the four mix designs showed that the Tennessee behaved similarly to other stabilized soils of the same type.
- Type IL cement was selected as the best chemical stabilizer for all of the soils tested. The strengths measured were similar or lower than those obtained using conventional Type I cement. As Type IL cement replaces Type I, slightly higher percentages of cement will likely be required to obtain the same performance level as previously experienced with stabilization using Type I cement.
- Data on the response of various soil types to chemical subgrade treatment was collected from the literature and divided based on AASHTO soil classification. Fact sheets were created for the seven most prevalent soil types, which summarize typical response to common stabilizers and the effects of stabilization. In addition, the prevalence of each AASHTO soil type throughout the near-surface soils of Tennessee was determined using data from the USDA Soil Survey.
- The current specification governing subgrade treatment, Section 302, was specifically written for treatment with lime. A review of subgrade stabilization specifications from multiple DOTs provided a basis for a recommended revision to Section 302 of the TDOT specifications.

Key Recommendations

The key recommendations of this Research Report are:

- Employ the mix design procedure recommended in Section 2.2.3, which is based on a review of the state of practice for chemical subgrade treatment. The procedure includes initial soil characterization, selection of a chemical stabilizer and percentage (Phase I), and verification of stabilized subgrade properties for pavement design (Phase II).
- Use 28-day curing for specimens used to measure parameters required for pavement design. The methods to determine pavement support characteristics are (in order of preference) laboratory resilient modulus (M_r) tests, laboratory California Bearing Ratio (CBR) tests, and correlation to CBR or M_r from unconfined compressive strength.
- Implement laboratory and field procedures for chemical subgrade treatment using the Soil Stabilization Manual attached as Appendix B. This manual includes step-by-step guidance from pre-stabilization sampling through the mix design process and into field verification testing.
- Incorporate the revised version of Section 302 into TDOT's specifications. The revised specification requires the use of more current construction practices and allows for the use of chemical stabilizers other than just lime.

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Chapter 1 Introduction

The stability of the subgrade has a dramatic influence on the long-term performance of pavements. In many cases, poor subgrade conditions can detract from or prevent construction of a high quality pavement structure. Following construction, unstable soils can lead to excess pavement deflection, resulting in cracking and/or permanent deformation. While pavements can sometimes be designed to account for these poor subgrades, it is often more cost-effective to increase the strength of the subgrade (FHWA 2006). Chemical treatment is one of the common methods used to improve subgrade soils and increase their shear strength and stiffness. Traditional chemical admixtures include lime, portland cement, and/or fly ash. Alternative chemical admixtures include fly ash and cement kiln dust. The soil classification, sulfate content, and organic content are all important factors that should be considered in the selection of admixtures.

State Departments of Transportation (DOTs) employ a wide variety of approaches to chemical treatment. Some widely use chemical treatment while others only use it for special cases. DOTs that use chemical treatment extensively have well-developed mix design procedures to guide consultants and contractors through the selection of appropriate chemicals and treatment rates. Pavement design practices vary widely across the United States. Similarly, the incorporation of chemical subgrade treatment into pavement design is still evolving.

Construction techniques for chemical subgrade treatment have evolved substantially from the use of farming equipment starting in the 1930s (Highway Research Board 1938) to current practice, which utilizes rotary reclaimer/stabilizers to efficiently and uniformly mix chemicals into the soil. Confident use of chemical subgrade treatment requires an understanding of these processes and the methods available for quality assurance and control.

A key distinction in terminology must be at the outset between subgrade modification and subgrade stabilization (e.g., IDOT 2020, INDOT 2022, KTC 2018, TXDOT 2019). *Modification* refers to subgrade treatment that provides a stable working platform for construction but does not have a design purpose in the pavement structure. Modification requires less design and laboratory testing and tends to employ typical, non-site-specific admixture percentages. A broader range of admixtures, including byproducts, is often considered for modification. *Stabilization* refers to subgrade treatment performed to increase the strength and/or modulus of the subgrade. The improved subgrade support properties that result from stabilization may be considered in the pavement design. In order to achieve reliable results, stabilization uses a thorough design methodology, such as those described in Section 3.3. This report will use the term *chemical subgrade treatment* to refer more generically to both modification and stabilization.

1.1 Objectives

Briefly, the objectives of this project were 1) to increase TDOT's knowledge of the state of the art and practice in chemical subgrade treatment, 2) to complete representative mix designs on Tennessee soils, 3) to prepare chemical stabilization fact sheets, 4) to develop a manual to guide TDOT personnel through the field and laboratory testing procedures for chemical stabilization, and 5) to suggest appropriate revisions to Section 302 of the TDOT Standard Specifications.

The intent of these objectives is to increase TDOT's implementation of chemical stabilization for its projects and to ultimately provide more economical and durable pavement subgrades.

1.2 Chemical Subgrade Treatment Background

1.2.1 Soil-Chemical Processes

Clay is a hydrated aluminosilicate-based material that develops plasticity under varying water contents. When used as a subgrade, clayey soils can lead to problems, facilitating the need for chemical treatment. The primary objectives of chemical subgrade treatment are to stabilize volume change, modify plasticity, and improve strength (Petry and Little 2002).

While different clay minerals and chemical agents may be combined, the basic premise of chemical treatment is to depolymerize the clay aluminosilicate structure (in a high pH environment) and react with free calcium in the surrounding medium. Depolymerization or a breakdown of the clay structure to resulting ions only occurs at a sufficiently high pH. With the addition of chemical stabilization agents, such as lime and portland cement, the pH can become very alkaline due to the availability of free hydroxyl ions.

Upon depolymerization, additional calcium will react to form more stable compounds. This calcium can come from lime, portland cement, or other stabilizing agents. The calcium-alumino-silicate molecules can chemically react to forms new, more dimensionally stable (and physically stronger) compounds through a pozzolanic surface reaction (Diamond and Kinter 1965). This process requires time, which is commonly referred to as mellowing (Mitchell and Hooper 1961, TXDOT 2019). Ultimately, the creation of new compounds will reduce the soil's plasticity index, lower swell/shrink potential, and increase strength (INDOT 2022).

While chemical subgrade treatment has proven effective in multiple situations, water soluble sulfate in the soil can potentially prove to be a deleterious substance during and after stabilization. Available sulfate can react with available calcium and aluminate compounds to form calcium sulfo-aluminate phases. These phases, such as ettringite, cause expansive pressures within the soil, ultimately leading to heaving and premature pavement failure.

Lastly, while less frequently problematic, organics in the soil can have an impact on the performance of the chemical stabilization agents. Organics most commonly slow the rate of formation of stable compounds, requiring more mellowing or excess addition of chemical stabilizers.

1.2.2 Common Chemical Stabilizers

The three traditional chemical stabilizers for soil are lime (in various forms), cement, and fly ash. These three materials will be the focus of this report. Their preferred applications and uses, limitations, and typical application rates are summarized in Table 1.

Petry and Little (2002) indicate that modification and stabilization have also been accomplished using byproduct materials, such as cement kiln dust and lime kiln dust. The application of these byproducts is often regional and associated with the prevalence of cement and lime production. A third category of stabilizers can be labeled nontraditional (Petry and Little 2002) and includes sulfonated oils, potassium compounds, ammonium chloride, enzymes, and polymers.

1.3 Assumptions and Limitations

This report assumes that TDOT intends to use chemical subgrade treatment primarily for stabilization applications and that mix designs will be prepared during the design phase of roadway projects. The findings and recommendations of this report may not be strictly applicable to subgrade modification purposes.

Table 1 Comparison of traditional chemical stabilizing agents

Stabilizing agent	Preferred Applications and Uses	Limitations	Typical rate
Hydrated lime, quick lime, or lime slurry	• Lowers soil plasticity and shrink/swell • Most common in many locales • Base soil should content at least 15% clay, preferably >30% clay • Good for plasticity index > 20 • Quick lime is most active and can rapidly dry out wet soil • Causes moisture reduction that must be accounted for • Slurry minimizes dusting and is easier to mix • Strength gain continues with time	• Base soil limited to 10% organic content • Requires 24 hr mellowing period • Quick lime requires extra time and water • Can increase frost susceptibility, pavement roughness, and cracking • Hydrated lime is dusty • Quick lime requires safety precautions to prevent burns	Up to 7%
Portland cement & slag modified cement	• Increases strength and durability • Good for sandy and silty soils with less than 30% clay • Good for plasticity index ≤ 20 • Slag-modified requires lower application rate • Good for projects needing high strength subgrade	• More mixing required for slag-modified	2 to 5%

Fly ash	• Good for sandy and silty soils with low % clay • More useful for modification than stabilization • Optimum water content for strength gain typically much lower • Requires strength testing with specific soil and fly ash blend • Good for projects needing strength and moisture resistance • Class CS for low PI • Class FS for high PI	• Usually requires lime or cement as well • Class F requires Ca source • Two-step process isn't always economical • Requires immediate compaction and 24 hr curing period • Fly ash properties are variable • Must consider sulfate content • Metals may migrate from fly ash	Up to 20%

Sources: Petry and Little (2002), IDOT (2005), IDOT (2020), INDOT (2022), Skok et al. (2003), and TXDOT (2019)

Chapter 2 Literature Review

This chapter reviews the literature regarding the design and construction of a chemically stabilized subgrade. The subgrade stabilization process includes evaluation of the need for stabilization, laboratory assessment of stabilization options (i.e., mix design), pavement design considerations with chemically stabilized subgrade, and the construction steps.

2.1 Evaluation of Need for Stabilization

2.1.1 Subgrade Evaluation

The first step is to evaluate the need for chemical stabilization. As discussed by KTC (2018), many natural pavement subgrades consist of fine-grained soils that lose strength and swell when wetted. These subgrades are especially susceptible to damage in late winter and early spring. During construction, these soils have the tendency to rut, which slows construction progress and impedes compaction of the pavement structure. Chemical treatment is an attractive means of addressing these issues. For example, chemical treatment is recommended by KTC (2018) for subgrade CBR less than 4 and by ODOT (2021) for subgrade standard penetration test blow count (N_{60}) between 4 and 12.

Pavement subgrade evaluation can be performed by a variety of means, including natural moisture content (w_n), corrected SPT blow count (N_{60}), and proof rolling during construction (ODOT 2021). If the natural moisture content of a subgrade is more than 3% above the standard Proctor optimum, it will likely be unstable.

The optimum moisture content can be measured or estimated based on soil type and Atterberg limits. Values of w_n likely to indicate instability are provided by soil type in Table 2.

Table 2 Indication of Instability and Usefulness of Chemical Treatment by Soil Type (after ODOT 2021)

Soil Type	Instability Likely if w_n Exceeds:	Chemical Treatment Useful To:
A-2 (silty or clayey sand or gravel)	≈ 13%	Reduce susceptibility to sloughing and frost heave
A-4 (low liquid limit silt)	≈ 13% or ≈ PL – 2%	Reduce susceptibility to sloughing and frost heave
A-5 (high liquid limit silt)	---	Reduce moisture sensitivity
A-6 (low liquid limit clay)	≈ 17% to 19% or ≈ PL – 2%	Reduce moisture content and improve compaction
A-7 (high liquid limit clay)	≈ 18% or PL	Reduce moisture sensitivity and shrink / swell potential
LL > 65%	---	Reduce shrink / swell potential

Alternatively, the results SPT or proof rolling can be used with Table 3 to determine if chemical treatment will be effective for improving unstable subgrade conditions. Very soft to soft subgrades usually cannot be chemically treated unless the soft layer is very thin. Conventional undercutting and replacement are required for soft to very soft subgrades. Geosynthetics can be used to reduce the undercut depth. Chemical treatment of stiff subgrades with N_{60} greater than 12 is only necessary if the natural moisture content is more than 3% above optimum (ODOT 2021).

Some of the soil types listed in Table 3 can be problematic in subgrades, even if the soils are stable during construction. As indicated in the third column of Table 2, chemical treatment can be used to reduce the potential for sloughing, frost heave, moisture sensitivity, and shrink/swell behavior.

Table 3 Use of SPT or Proof Rolling for Subgrade Evaluation (after ODOT 2021)

Soil Consistency	Representative N_{60} (blows/ft)[1]	Proof Roll Rut Depth (in)	Chemical Subgrade Treatment
Very soft	< 2	NA	Usually ineffective, undercutting required
Soft	2 to 4	> 12	
Medium stiff	4 to 8	6 to 12	Can use chemical treatment with a depth of 14 inches
Stiff	8 to 12	2 to 6	Can use chemical treatment with a depth of 14 inches
	12 to 15	< 2	Can use chemical treatment with a depth

			of 12 inches, only if moisture content is more than 3% above optimum

[1] Representative N_{60} is the average for a group of borings of the lowest values of N_{60} in the upper 6 ft of the subgrade.

2.1.2 Extent of Chemical Subgrade Treatment

After the need for chemical subgrade treatment has been established, the depth and type of treatment must be determined. At this stage, it is important to remember the distinction between soil modification and soil stabilization. Modification refers to subgrade treatment that provides a stable working platform for construction but does not have a design purpose in the pavement structure. Stabilization refers to subgrade treatment performed to increase the strength and/or modulus of the subgrade. In order to achieve reliable results, stabilization uses a thorough design methodology, such as those described in Section 2.2.

Chemical subgrade treatment can be incorporated into a project in two ways. First, subgrade treatment can be planned prior to construction based on unstable subgrade conditions encountered during the geotechnical investigation. In this case, the treatment can be applied in a global manner to the entire highway subgrade, which is the most economical approach. ODOT (2021) requires global chemical treatment on all four lane projects over 1 mile in length and recommends that CST be considered for projects where more than 30% of the subgrade requires treatment. Logically, in order to include the effects of stabilization in pavement design, it must be incorporated into the plans. The second method for using chemical treatment is on an as-needed basis to address unstable subgrade encountered during construction. This approach is less economical and has the purpose of providing a working platform. This type of as-needed application of chemical treatment always should be considered modification rather than stabilization.

2.2 Laboratory Mix Design

Laboratory mix design for chemical subgrade stabilization is the process used to select an appropriate chemical stabilizer and percentage of the stabilizer for the project. Soils representative of the site are used along with trial stabilizing agents. In order to incorporate chemical subgrade stabilization into the pavement design, the mix design process must be completed prior to the pavement design and appropriate strength and stability tests must be performed on the laboratory stabilized soil.

The following sections discuss the general procedure for admixture selection, typical mix design practices, and a brief summary of the recommended mix design process. The mix design process is described in detail in the proposed *Soil Stabilization Testing Manual* in Appendix B.

2.2.1 Admixture Selection

Cement and lime are the most common admixtures used for subgrade stabilization. Some states allow the use of lime kiln dust and fly ash for stabilization; however, these appear to be more often used for modification. Cement is most appropriate for coarse-grained and low plasticity soils including A-3, A-4, and some A-6 soils. Lime is often preferred for higher plasticity soils (PI > 20), namely some A-6 and A-7 soils, but does not always react in a manner than improves strength directly. Cement tends to be able to treat softer soils with lower N_{60} or undrained shear strength, or greater rut depth (ODOT 2013). For borderline soils, multiple admixtures can be assessed. Selection criteria based on grain size analysis and Atterberg limits are provided in Table 4. For silty subgrade soils, the combination of fly ash with lime or cement can be beneficial (FHWA 1992). Higher plasticity clays with PI greater than 30 may be difficult to mix thoroughly with the stabilizer, particularly for cement. The addition of lime tends to reduce the plasticity, which may make the use of cement feasible.

Table 4 Soil Stabilization Index System (SSIS) Criteria for Admixture Selection (after FHWA 1992)

Percent Fines (Passing #200)	Plasticity Index (PI)	Preferred Admixture
<25%	< 10[A]	Cement
	> 10	Cement
		Lime
> 25%	< 10	Cement
	10 < PI < 30[B]	Lime
		Cement
	> 30	Cement with prior addition of lime to reduce PI < 30
		Lime

[A] Bituminous stabilization may be considered

[B] Bituminous stabilization may be considered with prior addition of lime

Another important consideration for the selection of admixtures is material availability. Much experience has been gained over the past 80 years with the use of Type I portland cement for stabilization. However, the cement industry in many locales, including Tennessee, has recently switched cement production to Type IL for improved sustainability in the concrete industry. Because the two cements are not identical in composition, some difference in soil stabilization behavior would be expected. Three of the four mix designs completed for this project used both Type I and Type IL cements to allow for a direct comparison between the two.

2.2.2 Typical Mix Design Practices

As described in Petry and Little (2002), a variety of approaches have been developed for the mix design of chemical soil treatment. Many are based on the procedures developed by Thompson (1970) and Little (1999). Other methods have been developed by various admixture manufacturer associations, such as the National Lime Association (NLA), the Portland Cement Association (PCA), and the American Coal Ash Association (ACAA) methods.

TXDOT (2019) points out that subgrades must provide shear strength, stiffness, moisture resistance, volumetric stability under load or moisture, and durability. Chemical treatment is typically performed to improve at least one of these characteristics. Chemical treatment achieves improvement by drying the soil and improving compaction, which in turn increases shear strength, stiffness, and volumetric stability. Treatment also creates chemical bonds between soil particles, which increase strength, stiffness, stability, and durability. Some admixtures reduce soil plasticity by reacting with clay minerals, which increases moisture resistance and reduces shrink/swell potential.

The mix design process consists of finding a good or optimal admixture or admixture combination to accomplish the goals of the chemical subgrade treatment in an economical manner. This typically means selecting the minimum admixture percentage that achieves a set of performance criteria. These criteria are evaluated using laboratory tests. Table 5 summarizes the relationship between the desired subgrade characteristics and the laboratory tests used in the mix design process.

Table 5 Relationship between Subgrade Characteristics and Laboratory Testing Procedures

Desired Subgrade Characteristic	Laboratory Tests on Stabilized Soil Mixtures (AASHTO/ASTM specification)
Shear strength	• Unconfined compressive strength (T208/D2166) • Moisture-unit weight relationship (T99/D698)
Stiffness (modulus)	• California Bearing Ratio (CBR) (T193/D1883) • Resilient modulus (T307/D7369)
Moisture resistance	• Atterberg limits of stabilized mixture (T90/D4318)
Volumetric stability under loading and moisture changes	• Soaked CBR (T193/D1883) • Various soaking procedures
Durability	• Freeze-thaw testing • Wet-dry testing

Mix design procedures must also screen for problematic soil constituents, particularly sulfates and organic matter. TXDOT (2019) recommends using the USDA Soil Survey, preferably using the online Web Soil Survey tool, to make preliminary assessment of the sulfate and organic content. Where the sulfate content exceeds 3000 ppm, there is increased potential for differential swelling of chemically stabilized subgrade and special procedures are required. Similarly, if the organic content is greater than 1% by mass, the low pH created by the organic acids can inhibit strength gain and prevent development of the high pH conditions required for chemical stabilization to be effective.

In states that actively use chemical subgrade treatment, the DOTs have developed mix design procedures. These existing procedures represent the state-of-practice in mix design for chemical subgrade treatment in highway construction. Table 6 summarizes the admixture percentages, admixture selection criteria, and pavement design testing used by Illinois, Indiana, and Ohio. The approaches used by these states were judged to be the most well-developed of those reviewed for this report. Their procedures are reviewed in detail in Appendix A.

Table 6 Summary of Admixture Percentages, Selection Criteria, and Pavement Design Testing

	State	Lime	Cement
Admixture Percentage	Illinois	Use 5% to complete the standard Proctor test Trial range between 3% and 8%	Estimated percentage A-1-a – 5% A-1-b – 6% A-2 – 7% A-3 – 9% A-4 and A-5 – 10% A-6 – 12% A-7 – 13% Other specimens at +/-2% from estimated value
	Indiana	Use minimum lime percentage determined by Eades Grim pH test	Estimated range = 5% to 8% Start with 5%
	Ohio	Use minimum lime percentage (MLP) determined by Eades Grim pH test, MLP + 2%, and MLP + 4%	3%, 5%, and 7%
Selection Criteria	Illinois	Compressive strength gain of 50 psi and minimum average compressive strength of 100 psi	7-day UCS>500 psi Max. loss from wet/dry or freeze thaw: A-1, A-2-4, A-2-5, or A-3 – 14% A-2-6, A-2-7, A-4, or A-5 – 10% A-6 or A-7 – 7%
	Indiana	Compressive strength gain of 50 psi and target design compressive strength of 150 psi	Compressive strength gain of 100 psi and target design compressive strength of 300 psi
	Ohio	Compressive strength gain of 50 psi and target design compressive	Compressive strength gain of 50 psi and target design compressive

		strength of 100 psi	strength of 100 psi
Pavement Design Testing	Illinois	CBR (Illinois modified) on treated mix	CBR (Illinois modified) on treated mix
	Indiana	Resilient modulus tested by DOT	Resilient modulus tested by DOT
	Ohio	None, estimate from untreated CBR	None, estimate from untreated CBR

2.2.3 Recommended Mix Design Process

Based on a review of the current state of practice among other DOTs, a recommended procedure has been developed for chemical stabilization in Tennessee. The procedure is presented in more detail in the Soil Stabilization Testing Manual in Appendix B.

1. Obtain a representative soil sample for each soil that requires stabilization.
2. Characterize the untreated soil, including grain size distribution, Atterberg limits, specific gravity, organic content, sulfate content, Standard proctor, and Eades-Grim. Perform CBR and unconfined compression tests on specimens prepared at 100% relative compaction.
    a. The sulfate content should typically be limited to 3000 ppm (0.3%) or less for general soil stabilization. The use of lime may be appropriate for sulfate contents between 3000 and 7000 ppm (0.3 to 0.7%), provided the sulfate content falls below 3000 ppm after mellowing.
    b. Soils with corrected organic content up to 2% were successfully stabilized in this study. It may be feasible to stabilize soils with higher organic contents, if laboratory tests indicate that the organics do not inhibit the strength gain.
3. Select one or more trial chemical stabilizers to test in Phase I. Suggested percentages are:
    a. Type IL cement: 3%, 5%, and 7%
    b. Lime: MLP, MLP + 2%, MLP + 4%
4. Perform Phase I testing to determine a design chemical stabilizer percentage.
    a. Determine treated optimum water content and maximum dry unit weight for each percentage using either one-point or conventional Standard Proctor.
    b. Test unconfined compression test specimens after curing for 7 days and capillary soaking for one day.
    c. Select the minimum treatment percentage as that producing a strength gain of at least 50 psi and a minimum strength of 100 psi.
    d. Determine the design percentage by adding 1% to the minimum percentage.
5. Perform Phase II testing to provide design parameters for pavement design.

a. Determine the Atterberg limits and Standard Proctor optimum water content and maximum dry unit weight for the soil mixed with the design percentage of chemical stabilizer.

b. Prepare and test unconfined compression test specimens after curing for 7 days and 28 days followed by a capillary soak. Consider testing specimens tested a range of water contents.

c. Prepare and test CBR test specimens after curing for 28 days followed by soaking. Consider testing specimens tested a range of water contents.

6. Prepare a report detailing the results of the initial, Phase I, and Phase II testing.

2.3 Pavement Design with Stabilized Subgrade

Pavement and base layers are supported by the subgrade and foundation soil both for rigid pavement and flexible pavement, as illustrated in Figure 1. The subgrade can consist of the foundation soil in its natural state, which may be compacted to improved its properties. Compacted embankment soils may also make up the subgrade. As discussed in FHWA (2006), the support characteristics of the subgrade have a substantial impact on the pavement cost and longevity. Thus, subgrade improvement using chemical stabilization during construction can result in a more sustainable pavement system.

Most highway pavements in the United States are designed using either the *Guide for Design of Pavement Structures* (AASHTO 1993) or the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) (AASHTO 2020). AASHTO (1993) is based on observations from empirical road tests to which a variety of correction factors were added to refine the methodology. The newer MEPDG, now in its third edition, attempts to remove much of the empiricism from the pavement design process. Despite these improvements, acceptance of the MEPDG at the state DOT level has been slow (NCHRP 2008).

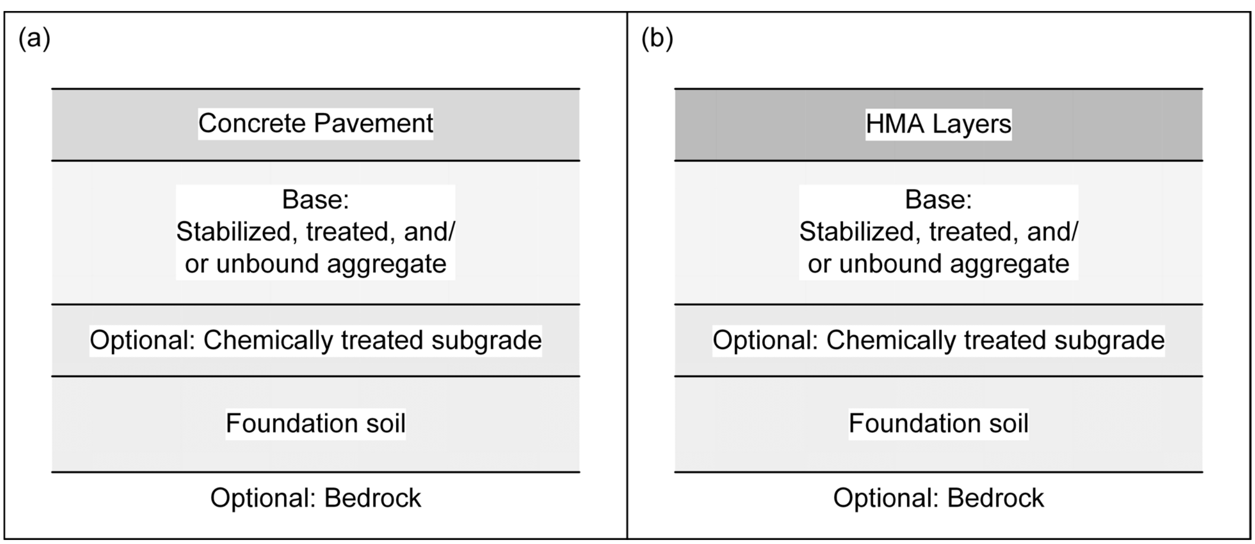

Figure 1 Pavement design layer options in MEPDG – (a) rigid and (b) flexible (after AASHTO 2020)

2.3.1 Subgrade Properties for Pavement Design

Both AASHTO (1993) and the MEPDG represent the pavement subgrade using a measure of stiffness known as the resilient modulus. The resilient modulus (M_r) is defined as "the ratio of the applied cyclic stress to the recoverable (elastic) strain after many cycles of repeated loading" (FHWA 2006). The resilient modulus can be measured using a variety of laboratory tests, including repeated load triaxial (RLT), resonant column, simple shear, and hollow cylinder, of which RLT is the most common (NCHRP 2008).

A wide range of field testing methods can also be used to measure or estimate M_r. The falling weight deflectometer (FWD) is the most common field approach (NCHRP 2008). Many correlations have been developed to predict M_r based on soil index properties as well as strength and stiffness properties, such as unconfined compressive strength (UCS) and California Bearing Ratio (CBR). The correlations indicate that M_r decreases with increased water content, silt content, and deviator stress level. Likewise, M_r tends to increase with increases in clay fraction, CBR, UCS, confining stress, relative compaction, and age (NCHRP 2008).

Figure 2(a) shows that M_r is typically below 20 ksi for relatively weak (SPT N less than 8) unstabilized fine-grained soil. For comparison, typical ranges of M_r for well-compacted fine-grained soils are indicated Figure 2(b).

Considering the subgrade, AASHTO (1993) requires values of M_r that account for the seasonal variation in subgrade stiffness (FHWA 2006). These seasonal values are used to calculate damage potential by month, which is summed and used to calculate a weighted M_r for design. Other subgrade properties that may be needed by AASHTO (1993) are the maximum potential swell, probability of swelling, frost heave rate, potential serviceability loss from frost heave, and probability of frost heave. Frost heave and swell potential are incorporated in estimates of loss of serviceability.

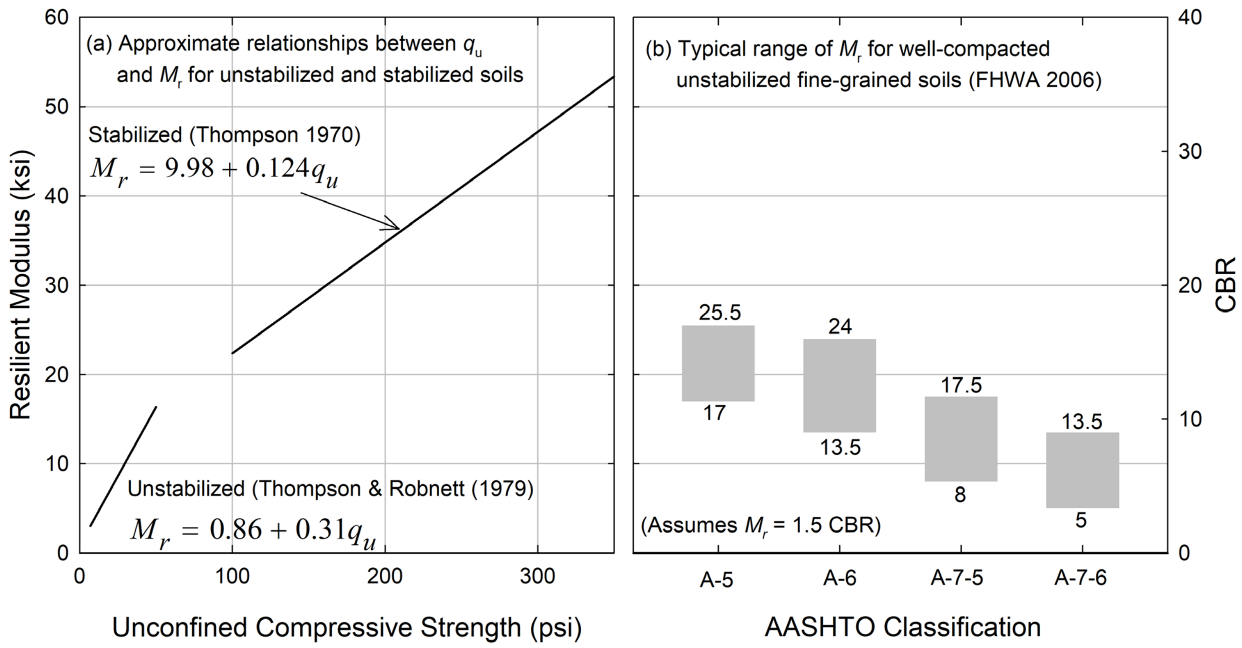

Figure 2 Typical Resilient Modulus Values for (a) Unstabilized and Stabilized Fine-Grained Soils related to Unconfined Compressive Strength and (b) Unstabilized Fine-Grained Soils based on AASHTO Classification

For flexible pavements, the required structural number (SN) is calculated from the seasonal adjusted M_r, traffic loading, and loss of serviceability. For rigid pavements, M_r is used to calculate the modulus of subgrade reaction, which is used to calculate the required pavement thickness.

The MEPDG (AASHTO 2020) uses a hierarchical system that recognizes differences in roadway importance and resources, which affect the availability of the inputs for pavement design. Of the three levels defined in the MEPDG, Level 1 represents thorough knowledge of the pavement design inputs, while Level 3 indicates poorer knowledge of design inputs. Level 2 is an intermediate design level.

MEPDG Level 1 requires direct measurement of M_r to determine three parameters for a nonlinear M_r model. Either these values are seasonally adjusted, or the effects of moisture and freeze/thaw are considered directly in the calculations (FHWA 2006). Values of Poisson's ratio and interface friction between the base and subgrade must also be assumed. The climatic calculations require measurements of thermal conductivity and heat capacity (AASHTO 2020).

At Level 2, the MEPDG allows subgrade properties to be estimated based on correlations to other properties (AASHTO 2020), such as those based on R-value, CBR, or UCS (NCHRP 2008, FHWA 2006). Soil classification, grain size distribution, and Atterberg limits are used in lieu of thermal and hydraulic properties. Common correlations for resilient modulus (in ksi) include:

$$M_r = 1.925 \cdot CBR^{0.686}$$

and

$$M_r = 9.98 + 0.124 \cdot q_u$$

where: q_u is the unconfined compressive strength in psi.

Level 3 relies primarily on subgrade properties that are either estimated from historical records or selected as typical values for a particular soil type.

2.3.2 Properties of Chemically Stabilized Subgrade

Chemical stabilization will increase the support characteristics of the subgrade. Most mix design procedures required the UCS of stabilized subgrade to be in the range of 100 to 300 psi. As shown in Figure 2(a), this correlates to M_r in the range of 25 to 50 ksi. A similar range of 30 to 45 ksi is recommended for stabilized subgrade by the TXDOT Pavement Manual (2021). This represents an increase of 50% to 100% over the highest values expected for compacted, unstabilized subgrade and a substantially greater increase over the M_r for soft fine-grained subgrade. Large increases in the subgrade M_r can lead to substantial changes in the cost of the pavement. In an example case presented in FHWA (2006), an increase in M_r from 5 ksi to 30 ksi causes the required structural number (AASHO 1993) to decrease from 5.5 to 3 and the cost to decrease by about 67%.

Neither the AASHTO (1993) nor the MEPDG (AASHTO 2020) are directly calibrated for chemical stabilization. However, the mechanical properties of the stabilized soil are within the typical ranges considered by both methods. Thus, the methods should be expected to incorporate stabilized subgrade appropriately provided the effects of stabilization on other factors, such as frost susceptibility, are considered.

Skok et al. (2003) studied practices for subgrade construction in poor, wet, or saturated conditions. When weak soils are stabilized, they found that the CBR can increase up to about 25 to 30, which corresponds to a M_r in the range of 30 to 45 ksi. Structural coefficients used in AASHTO (1993) are provided for fly ash stabilized soils, which range from 0.08 to 0.28.

Focusing on lime stabilization, Mallela et al. (2004) recommend that chemical stabilization can be used for both conventional and deep strength asphalt pavements as well as for the rigid base layer for low volume roads. Stabilized subgrade is considered to be insensitive to moisture and frost heave by the MEPDG. Mallela et al. recommend measuring M_r on specimens cured for 28 days at room temp for Level 1 design. An accelerated seven-day curing at 104 °F can also be used. For Level 2, M_r can be estimated from UCS using Thompson (1970) – see Figure 2. The Poisson's ratio of stabilized soil can be assumed as 0.2. Direct measurements of thermal conductivity and heat capacity would be required for Level 1 design.

Section 11 of the MEPDG recognizes the difference between modification and stabilization discussed previously (AASHTO 2020). Modified subgrade soils should be treated as an unbound foundation soil layer, possibly with improved stiffness. In contrast, the MEPDG suggests that stabilized subgrade must be considered a structural layer in the pavement design process. To qualify as stabilized subgrade, the stabilization must be "engineered" and must have a means of measuring the mechanical properties via laboratory testing and/or coring of the stabilized subgrade.

2.3.3 Pavement Design Practices for Chemically Treated Subgrade

Despite the large amount of research that has been performed on chemical treatment of subgrades, substantial research connecting the properties of treated subgrades to long-term pavement performance is still lacking (NCHRP 2014). In particular, the properties of chemically treated soils can change with time, which needs to be considered in the pavement design. For these reasons, direct incorporation of the properties of chemically treated soils in pavement design has been slow, especially at the state DOT level.

When the chemical treatment consists of modification (i.e., performed solely to provide a working platform), the effects of the treatment on the subgrade properties should not be considered in the pavement design. This distinction is made by most states that discuss chemical treatment in their pavement design procedures (e.g., Caltrans 2022, IDOT 2022, INDOT 2013, ODOT 2022, TXDOT 2021) and by the MEPDG (AASHTO 2020).

If the chemical treatment qualifies as stabilization, some states allow the improved properties of the subgrade to be included in the pavement design. For example, Caltrans (2022) allows M_r to be estimated from an empirical correlation to UCS (Level 2 for the MEPDG). Similarly, ODOT (2022) provides an empirical correlation to estimate M_r for the stabilized soil as being 36% higher than M_r for the unstabilized soil, for use in the AASHTO (1993) method. TXDOT (2021) allows typical values of M_r to be used for stabilized soil, provided a mix design has been completed. While the MEPDG recommends that stabilized subgrade should be considered as a structural layer, it does not appear that many agencies have yet adopted this recommendation.

2.4 Construction of Stabilized Subgrade

This section describes the construction techniques used for chemical subgrade treatment. The construction process for chemical subgrade treatment includes identifying the subgrade requiring treatment, spreading the chemical admixture, mixing the admixture with the subgrade, compacting the treated soil, curing the compacted subgrade, and verifying the results of the treatment. The process is depicted in a flowchart fashion in Figure 3.

2.4.1 Identification of Subgrade for Treatment

Preferably, areas requiring chemical treatment will be identified during design or prior to construction. In this case, the chemical treatment can be completed at a large, or global, scale for the project. In other words, the entire roadbed can be treated, which allows the most continuity of construction and the most continuous pavement support. This approach also allows the effects of the stabilization to be considered directly in the pavement design (see Section 2.3).

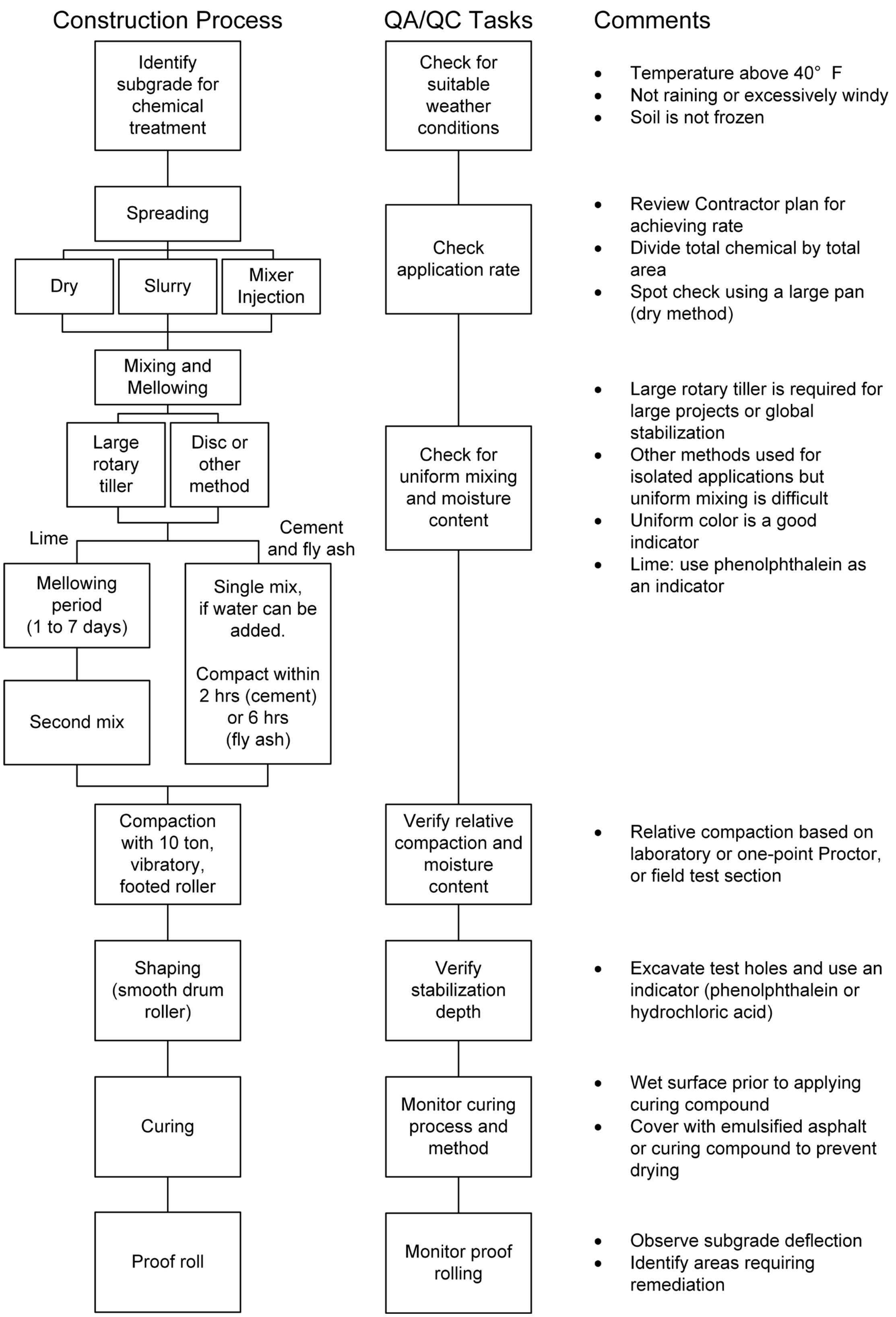

Figure 3 Typical CST Construction Process along with QA/QC Tasks and Comments (after ODOT 2013)

When necessary, unstable subgrade can also be identified during construction. After the subgrade has been brought to the design elevation, proof rolling can be used to identify portions of the subgrade that require chemical modification. While the same construction process generally applies, modification requires a less stringent design process compared with stabilization. The laboratory mix design process would like be limited to the Phase I testing described in Section 2.2.3.

Lime treatment can cause soil to swell. The subgrade should be graded prior to treatment to account for any expected swell.

2.4.2 Spreading

The next step in the chemical subgrade treatment process is to spread the chemical admixture over or into the prepared subgrade. The three major options for this are dry spreading, slurry spreading, and mixer injection.

According to TXDOT (2019), dry spreading is the standard, widely available method. It can be used for most admixtures. Dry application is especially appropriate when the subgrade soil requires drying. However, this approach can be dusty and problematic in windy conditions. Dry spreading is less uniform than the other methods. An example of dry spreading is shown in Figure 4.

Lime and cement can also be mixed with water to create a slurry (TXDOT 2019), which is spread on the subgrade.

This approach minimizes dusting and facilitates a faster and more complete reaction. The slurry adds moisture to the CST mixture, which is beneficial if required for the treatment, but detrimental if the subgrade is already excessively wet. If the surface of the subgrade is graded smooth, the slurry may run off and not be distributed uniformly.

Figure 4 Dry Spreading Chemical Admixture on the Subgrade (from ODOT 2013)

The third method of application is via mixer injection. In this case, the mixing equipment directly injects the admixture slurry during the mixing process, which also minimizes dusting. This is the most precise and uniform process but requires specialized equipment and experience. Mixer injection can be used for both lime and cement slurry; however, caution is required for the latter (TXDOT 2019).

As indicated in Figure 3, the application rate must be checked during the spreading phase. Globally, this is accomplished by tracking the amount of the chemical applied over a given subgrade area. The average rate can be determined by total weight of chemical by the application area, accounting for the soil unit weight and stabilization depth. For the dry method, the rate can also be spot-checked by placing a large pan of known area on the subgrade prior to spreading. After spreading, the pan is carefully removed and the amount of admixture on the pan is measured. The Soil Stabilization Manual (Appendix B) presents the procedures and calculations required for checking the application rate.

2.4.3 Mixing

The soil and admixture should be mixed immediately after spreading. While various types of mixers and equipment have been used in the past, a large rotary mixer, such as shown in Figure 5, should typically be used for chemical subgrade treatment. Self-propelled rotary mixers have widths up to about 8 ft and can mix soil to a depth of nearly 24 inches (Wirtgen 2022). Tractor-towed stabilizers are also available, which treat similar widths to depths of up to 20 inches.

Figure 5 Large Rotary Mixer used for Chemical Stabilization (from ODOT 2013)

Mixing can be accomplished in isolated zones with conventional construction equipment (e.g., disc, excavator, dozer), if necessary. However, the mixing and resulting subgrade will tend to be much less uniform. Subgrade treatment performed in this manner should be considered modification and not stabilization.

If necessary, water should be added during mixing to achieve the moisture content determined by the mix design process. Water can be spread onto the rough subgrade. Alternatively, modern stabilization equipment can inject the water directly into the soil in the mixing process (Wirtgen 2022).

Where stabilizing with cement or fly ash, a single mixing pass can be used provided the water can be added directly during mixing. After mixing, about 60% of the soil should be sand sized (i.e., passing #4 sieve) or smaller, and all of the clods should be smaller than 1-inch diameter (ODOT 2013). Cement and fly ash mixtures should be compacted within a few hours after mixing. Chemical treatment with cement should be completed in a single layer because of bonding issues between multiple layers of soil-cement (Skok et al. 2003).

Where stabilizing with lime, the subgrade must be mixed twice with an intermediate mellowing period. The purpose of the first mixing is to incorporate the lime into the soil, adjust the moisture content to at least 3% above optimum, and break the soil into clods of 2-inch diameter or smaller. The mixture is lightly compacted to seal the subgrade during mellowing. The mellowing period provides time for chemical reactions to occur as described in Chapter 1, improves workability, and allows sulfate reactions to occur prior to compaction (TXDOT 2019). The mellowing period is typically in the range of one to seven days. After the mellowing is complete, the mixing should break down the soil into clods of 1-inch diameter or less with at least 60% being sand sized or smaller (ODOT 2013).

Uniformity is the key quality assurance task during mixing. The process should be monitored to assure that the subgrade is broken down into appropriately small clods and that the admixture is thoroughly mixed with the soil. Uniform color is a good indicator of thorough mixing. In addition, chemical indicators can be used, such as phenolphthalein (color change) or hydrochloric acid (effervescence).

2.4.4 Compaction

Compaction is the next step in the process. Subgrade treated with cement or fly ash should be compacted immediately after mixing. The compaction process should be complete for cement within 2 hrs. Fly ash reacts less quickly and compaction should be completed within 6 hrs after mixing. ODOT (2013) recommends the use of a vibratory, footed, 10-ton roller for chemically treated layers up to 14 inches thick. Final shaping of the surface of the treated subgrade can be accomplished with a smooth drum roller that is operated without vibration. Some studies have explored re-compaction of cement-treated subgrade after one or two days of curing to induce micro-cracks. This may reduce the likelihood of cracks propagating from the treated subgrade into the pavement (TXDOT 2019).

Similar to conventional engineered fill, compaction can be monitored by measuring the compacted dry unit weight and moisture content of the treated subgrade.

The relative compaction and moisture content should be compared to the laboratory Proctor curve or the results of a field test section. One-point standard Proctor tests can be used during construction to verify the consistency of soil conditions with laboratory values.

The thickness of the compacted, treated subgrade should be measured. The simplest method is to excavate test holes through the subgrade. The thickness of the stabilized mixture can be determined using a chemical indicator, such as phenolphthalein or hydrochloric acid. Ground penetrating radar surveys can also be used to evaluate the thickness of the treated subgrade (FHWA 2017).

2.4.5 Curing and Acceptance Testing

Curing and acceptance testing is the final step in the construction process. The purpose of curing is to allow chemical reactions and strength gain to occur prior to loading the subgrade, especially with heavy construction equipment. The recommended length of the curing time varies from one to seven days (ODOT 2013, TXDOT 2019, INDOT 2022), depending on admixture type.

Curing consists of wetting the subgrade followed by application of either emulsified asphalt or a curing compound (ODOT 2013). These steps will keep the subgrade from drying out during the curing process. Curing should remain in place until the next course of pavement is constructed.

After curing, the chemically treated subgrade should be evaluated using proof rolling or other field techniques to identify any areas for which the treatment was ineffective. The treatment procedure must be repeated to remediate insufficiently stabilized areas, and the reason for the instability should be investigated. Subgrade acceptance can also include field testing, such as lightweight deflectometer (LWD), automated plate load testing (APLT), and dynamic cone penetration (DCP) (INDOT 2022).

2.4.6 Safety

Chemical admixtures present a range of safety hazards that must be accounted for during construction. In particular, lime and quick lime can cause chemical burns if contact with skin occurs. Lime products also generate substantial heat. Most admixtures are fine particulates and respiratory protection may be required. Specifics will depend on the particular admixture and application.

Chapter 3 Methodology

In addition to the initial synthesis report, which has been incorporated in this document, four major tasks were outlined for this project: 1) perform representative mix designs, 2) develop a testing manual for soil stabilization in Tennessee, 3) create stabilization fact sheets as a resource for TDOT engineers, and 4) suggest changes to the TDOT specification for soil stabilization.

3.1 Representative Mix Designs for Four Tennessee Soils

Representative mix designs were performed on four Tennessee soils to illustrate the mix design process and benchmark local materials against the broader data available in the literature. The test procedures are summarized in this section and in greater detail in Appendix B. Mix design reports are included in Appendix C, which are meant to be representative of the type of report that will be produced by future mix designs.

3.1 Soils Tested

The soils tested were obtained from four separate locations across the central part of Tennessee. The soils will be referred to by the county from which they were obtained. The specific locations are:

- Cumberland County – pavement subgrade along the east side of SR-28 in project CNV009; approximate address: 4744 SR-28,
- Humphreys County – borrow area at the northwest corner of SR 13 and Cuba Landing Road,
- Robertson County – pavement subgrade along southeast side of I-65 project, approximately MM 118.2 northbound, between SR52 and Byrum Chapel Road, and
- Rutherford County – borrow area for SR-266 project, east of West Fork Recreation Area

3.1.1 Untreated Soil Testing

The index properties of the four soils were determined, including as-received water content, Atterberg limits, grain size distribution, and specific gravity of solids. The moisture-density relationship was determined using the Standard Proctor test. The minimum lime percentage for stabilization was determined using the Eades-Grim procedure.

The organic content measured using the loss on ignition (LOI) test can be complicated by at least two factors (e.g., Hoogsteen et al. 2015). First, structurally bonded water can be released from clay minerals at temperatures higher than those typically used for drying (i.e., 105 C). Second, carbonate compounds tend to decompose at temperatures above 600 C. Both of these can lead to measurements of organic content in LOI that are too high. Designers and testing labs should be aware that LOI may indicate organic contents that are 1 to 2% too high, which is significant for soils with little to no true organics.

The LOI measured using ASTM D2974 ($LOI_{measured}$) and a temperature of 440 C can be corrected for structural water loss using the following correction:

$$LOI_{corr} = LOI_{measured} - 0.025 \cdot CF$$

where: LOI_{corr} = corrected LOI and CF = clay fraction (% finer than 2 μm). Note that the constant increases for higher temperatures (Hoogsteen et al. 2015).

Sulfates tend to cause swelling in stabilized soils. The sulfate content of the soils collected was generally low and below the threshold of 3000 ppm proposed by TXDOT (2019). The laboratory procedure for sulfate testing is beyond the typical practice of most geotechnical laboratories. TDOT may need to assess the prevalence of problematic sulfate levels in the soils in the state, in order to decide if regular sulfate testing is required. Alternatively, the sulfate testing could be performed only for locations where past experience or available information from the USDA Soil Survey indicates problematic sulfate levels.

Untreated soil specimens were compacted at a relative compaction of about 100% for unconfined compressive strength (UCS) and California Bearing Ratio (CBR) testing. The UCS specimens were compacted in five layers in a 2.8 by 5.6 inch split mold using a Standard Proctor hammer and nine blows per layer. The CBR specimens were compacted within the mold as described in the test procedure.

3.1.3 Phase I Testing

The purpose of Phase I is to select a suitable admixture type and percentage. For each soil, three percentages of three admixtures were selected for a total of nine combinations. Three UCS specimens were compacted in for each combination, using the same method described in the previous section. The specimens were wrapped in plastic and sealed in plastic bags for seven days, followed by a 24-hr capillary soak. The unconfined compressive strength tests are used to select the admixture for Phase II.

3.1.4 Phase II Testing

Once an admixture type and percentage were selected for each soil, the Atterberg limits and Standard Proctor tests were repeated on the treated soil. UCS and CBR specimens were compacted and cured for either 7 or 28 days. The UCS tests verify that the mixture meets the target strength, while the CBR tests measure the increase in stability resulting from the chemical stabilization.

3.2 Soil Stabilization Testing Manual

The soil stabilization manual was developed by comparison to similar documents provided by other DOTs. In addition, the experience gained during the completion of the four representative mix designs was used to inform the recommendations of the manual.

3.3 Stabilization Fact Sheets

This section summarizes the development of stabilization fact sheets for various AASHTO soil types. The purpose of these fact sheets is to provide a quick reference tool for the commonly encountered soil types in Tennessee.

The United States Department of Agriculture (USDA) soil survey has catalogued the soils present in the upper approximately 6 ft across the United States. This information is accessible through their GIS platform, Web Soil Survey (WSS) - https://websoilsurvey.nrcs.usda.gov/app/. For a given soil unit, the WSS reports the possible soil classifications in terms of both USCS and AASHTO. The WSS allows reports the amount of land area that is in occupied by each soil unit in each county.

The distribution of AASHTO types throughout Tennessee was determined using the following process:

1. Set each county as an area of interest – The area of interest in WSS was selected by county using the Soil Survey Area option.
2. USDA soil units by county – The Soil Map option was selected next. The Map Unit Legend provided a summary of all of the soil unit names and land area associated with that unit. These were copied into a spreadsheet for further processing.
3. AASHTO soil types in each USDA soil unit – In WSS, the Soil Reports option was selected from the Soil Data Explorer tab. Under Soil Physical Properties, the Engineering Properties report was generated. This report indicates the AASHTO classifications for each soil unit. In the spreadsheet, all indicated AASHTO classifications were recorded for each soil unit. An example is shown in Table 7 for Baxter cherty silt loam in Putnam County. The "1" values indicate that this soil tends to classify as A-4, A-6, or A-7-6.;
4. Data processing – For each soil unit, the full land area for that unit was assigned to each of the indicated AASHTO classification as shown in Table 8. The total area possible for each AASHTO classification was then summed for the county and the percentage was calculated based on the total area of the county. The WSS data does not allow more refined distinction in the classification. For this reason, the total area assigned the AASHTO classifications is greater than the area of the county. Similarly, the total percentage is greater than 100%. Thus, the maps are labeled "Percentage of Surficial Soil Types in Each County Containing A-# Soil" rather than the percentage of that classification of soil.

In addition to determining the distribution of the various AASHTO soil types in Tennessee, the fact sheets are intended to summarize the typical effects of chemical stabilization on each soil type. Data was gathered from a wide variety of sources in the geotechnical literature. In order to limit the complexity of the figures and to include maximum information on each fact sheet, the sources are summarized and condensed in Table 9.

Table 7 **Example Tally - Baxter cherty silt loam in Putnam County (Land area: 2740.1 acres)**

AASHTO Classification	**Tally 0 = not present 1 = possible**	**Area Assigned (acres)**
A-1-a	0	0
A-1-b	0	0
A-3	0	0
A-2-4	0	0
A-2-5	0	0
A-2-6	0	0
A-2-7	0	0
A-4	1	2740.1

A-5	0	0
A-6	1	2740.1
A-7-5	0	0
A-7-6	1	2740.1

Table 8 Example County Tally – Putnam County (Land area: 255774 acres)

AASHTO Classification	Area Assigned (acres)	Percentage
A-1-a	5259	2%
A-1-b	19971	8%
A-3	204	0%
A-2-4	85073	33%
A-2-5	62430	24%
A-2-6	91889	36%
A-2-7	67909	27%
A-4	160986	63%
A-5	976	0%
A-6	222859	87%
A-7-5	19932	8%
A-7-6	167908	66%

3.4 Chemical Subgrade Stabilization Specification

TDOT's *Standard Specifications for Road and Bridge Construction* (2021) include "Section 302 – Subgrade Treatment (Lime)". One of the tasks of this project was to suggest a revision to this specification that incorporates the recommendations of this report.

Similar specifications were obtained from other states that actively employ chemical subgrade stabilization, including Arkansas, Kentucky, Mississippi, Ohio, Oklahoma, and Texas. The pertinent sections of those specifications were compared to Section 302. Where judged appropriate, Section 302 was revised.

Table 9 **Summary of Sources for Chemical Stabilization Fact Sheets**

Source	Soil Type						
	A-2-4 & A-2-5	**A-2-6 & A-2-7**	**A-4**	**A-5**	**A-6**	**A-7-5**	**A-7-6**
Adeyanju and Okeke (2019)		X					
Ahmad (2021)		X					
Al-Kiki et al. (2008)							X
Apampa (2017)		X					
Aytekin (1998)							X
Barbero et al. (2021)	X						
Bhattacharja (2003)							X
Blessing (2018)	X	X					
Consoli et al (2016)				X			
Consoli et al (2020)				X	X		
Daniels (2010)	X	X	X			X	X
Eren and Filiz (2009)					X		
Felt and Abrams 2	X		X				
Geiman (2005)	X						X
Harichane (2010)						X	X
Hiep (2022)	X						
Hopkins et al. (1995)	X	X				X	
Ikebude (2018)	X						
Ismaiel (2006)						X	X
John et al. (2022)		X					
Mariri et al. (2019)			X				
Mateos (1964)	X						
McManis (2003)			X				
Mooney and Toohey (2010)					X		X
Obianigwe and Ngene (2018)		X					
Okonkwo (2015)		X					
Olutaiwo and Olushola (2017)		X					
Oluyemi-Ayibiowu (2022)	X	X					
Onyelowe (2016)		X					
Onyelowe (2018)		X					
Osman et al. (2022)		X					
Rogers and Lee (1994)						X	

Sandoval et al. (2019)					X		X
Solanki et al. (2009)			X		X		
Solihu (2020)		X					
Thompson (1967)							X
Utami (2014)						X	
Yin (2022)							X
Yusuf and Zava (2019)		X					

Chapter 4 Results and Discussion

This chapter presents and discusses the results of the four major tasks of the project.

4.1 Representative Mix Design Results Summary

4.1.1 Index Properties of Soils Tested

The index properties and classifications of the four soils are summarized in Table 10. Two of the soils classify as A-6 and two classify as A-7-6. These two soil types are very prevalent in Tennessee as illustrated in Chapter 4. These soil types commonly present unstable subgrade conditions and are good candidates for chemical stabilization.

Table 10 Index Properties and Soil Classifications

Property	Test Results			
	Cumberland	**Humphreys**	**Robertson**	**Rutherford**
Water content	18 to 19%	16 to 19%	18 to 21%	16 to 19%
Liquid Limit	33 to 34	35 to 37	45	65
Plastic Limit	14 to 15	23	12 to 14	22 to 23
Plasticity Index	19	12 to 14	31 to 33	42 to 43
Grain size distribution	29% clay, 35% silt, 36% sand	16% clay, 70% silt, 9% sand, 5% gravel	31% clay, 59% silt, 9% sand, 1% gravel	34% clay, 26% silt, 33% sand, 7% gravel
Spec. Gravity	2.70	2.71	2.73	2.80
Organic Content ($LOI_{measured}$)	2.5%	2.0%	2.5%	1.9%
Corrected Organic Content (LOI_{corr})	1.8%	1.6%	1.7%	1.1%
Sulfate Content	0.01% (100 ppm)	0.044% (438 ppm)	0.26% (2600 ppm)	0.020% (200 ppm)
Standard Proctor	γ_{dmax}=111 to 112 pcf w_{opt}=16.5 to 17%	γ_{dmax}=103.5 pcf w_{opt}=18.5%	γ_{dmax}=108.5 pcf w_{opt}=19%	γ_{dmax}=106 to 107 pcf w_{opt}=20%

Unconfined Compression[A]	36 to 52 psi	26 to 27 psi	29 to 30 psi	43 to 45 psi
CBR[A]	12.5 to 13.5	9 to 12	5 to 7	9 to 12
Minimum Lime	4%	3.5%	6%	6%
AASHTO Type	A-6	A-6	A-7-6	A-7-6
USCS Soil Type	CL	CL	CL	CH

[A] UCS and CBR reported for 100% relative compaction

The soils obtained for the representative mix designs did not visually appear to have significant organic content but had measured LOI between 1.9% and 2.5%. The correction was applied to the soils based on the clay fraction from the hydrometer, as presented in Table 10. The corrected organic content was between 1 and 2%. The laboratory stabilization results did not appear to be substantially affected by this level of organics as measured by LOI.

4.1.2 Phase I Test Results

The purpose of the Phase I testing is to select a chemical stabilizer and trial percentage for further evaluation. The compaction characteristics of each mixture were estimated using the one-point Proctor method. Triplicate unconfined compressive strength specimens were compacted using Standard Proctor energy at the optimum water content. The specimens were cured for seven days and tested to determine the 7-day unconfined compressive strength. These results were plotted and used to select a chemical and percentage for further testing.

Three chemical stabilizers were tested in Phase I for each soil, as summarized in Table 11. The primary focus was on lime and portland cement as the two most commonly used options. Type IL cement was used for all four soils as the type of cement available in the state. For three of the soils, a comparison between Type I and Type IL can be made using the Phase I results.

Table 11 Chemical Stabilizer Percentages Used for Phase I Unconfined Tests

Chemical Stabilizer	**Chemical Stabilizer Percentages Tested in Phase I**			
	Cumberland	**Humphreys**	**Robertson**	**Rutherford**
Lime	4%, 6%, 8%	3.5%, 5.5%, 7.5%	6%, 8%, 10%	6%, 8%, 10%
Type I portland cement	3%, 5%, 7%	3%, 5%, 7%	3%, 5%, 7%	---
Type IL portland cement	3%, 5%, 7%	3%, 5%, 7%	3%, 5%, 7%	3%, 5%, 7%
4% Lime + Fly Ash	---	---		8%, 12%, 16%
Chemical Stabilizer Selected for Phase II	4.5% Type IL	5% Type IL	3% Type IL	4.5% Type IL

The 7-day unconfined compressive strengths (UCS) are plotted in Figure 6 to Figure 9. In addition to the trends for each admixture, two horizontal lines are plotted. One line is at 100 psi while the other is plotted at 50 psi above the untreated UCS. The minimum 7-day UCS is the higher of these two lines, which was 100 psi for all of the four soils tested. In each case, Type IL cement was chosen as the best admixture. In some cases, the tests indicated that a lower percentage of conventional Type I cement would be required. However, since Type I cement is no longer commonly available in Tennessee, the Type IL cement was selected instead.

The minimum 7-day UCS of 100 psi was met for the Cumberland and Robertson soils using lime. However, much more lime was required for these soils compared to cement, making the lime stabilization uneconomical. For Humphreys and Rutherford, the lime did not produce a significant increase in UCS. Trials were performed with the Rutherford soil using 4% lime to decrease the plasticity and varying percentages of fly ash. This approach did not produce strengths exceeding the 100 psi threshold within a viable range of fly ash percentage.

The selected chemical stabilizer and percentage are listed at the bottom of Table 11. The selected percentages are about 1% higher than the value required to meet the minimum threshold UCS. This allows for some variability in field conditions and application during construction.

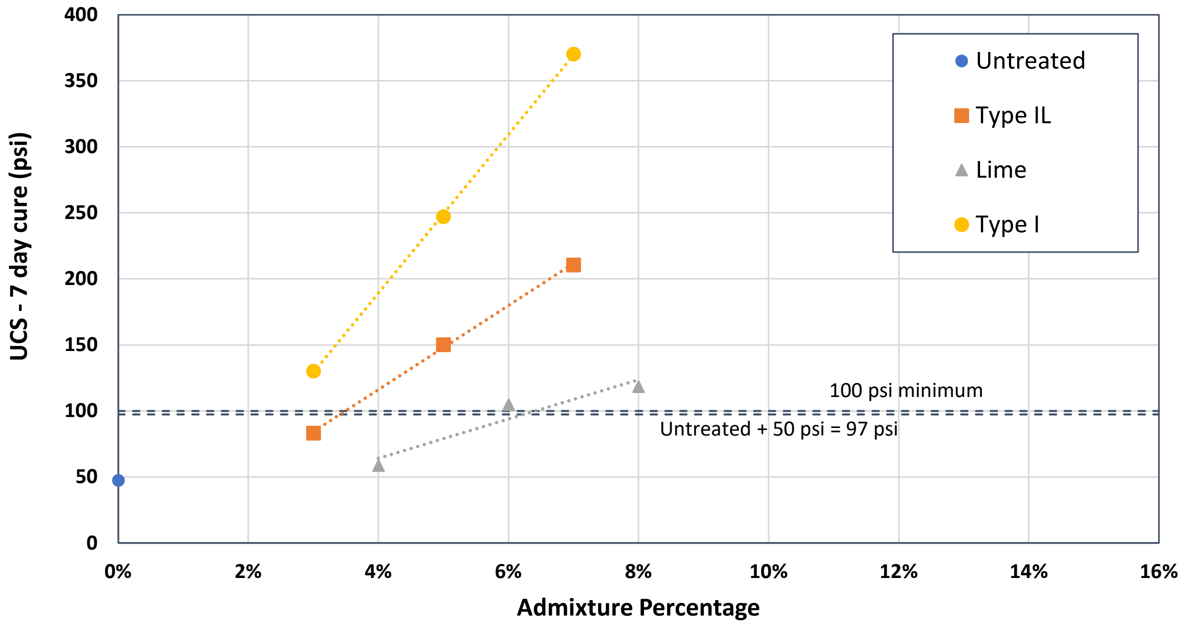

Figure 6 Phase I UCS Results – Cumberland

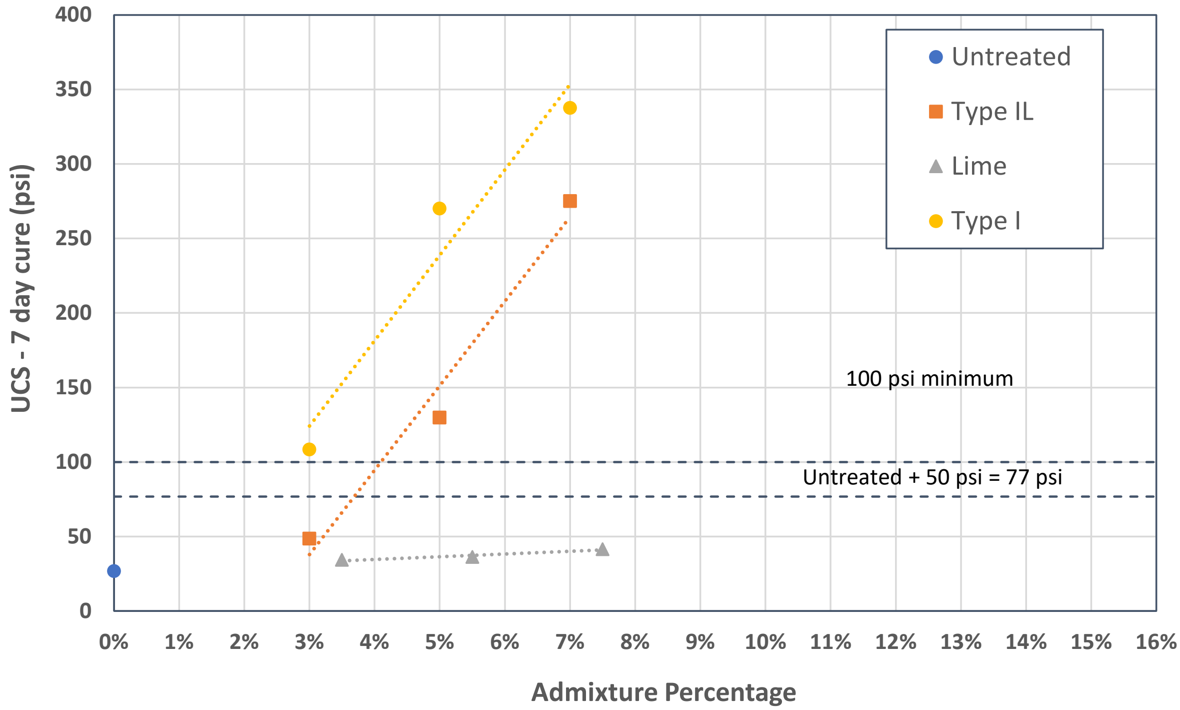

Figure 7 Phase I UCS Results – Humphreys County

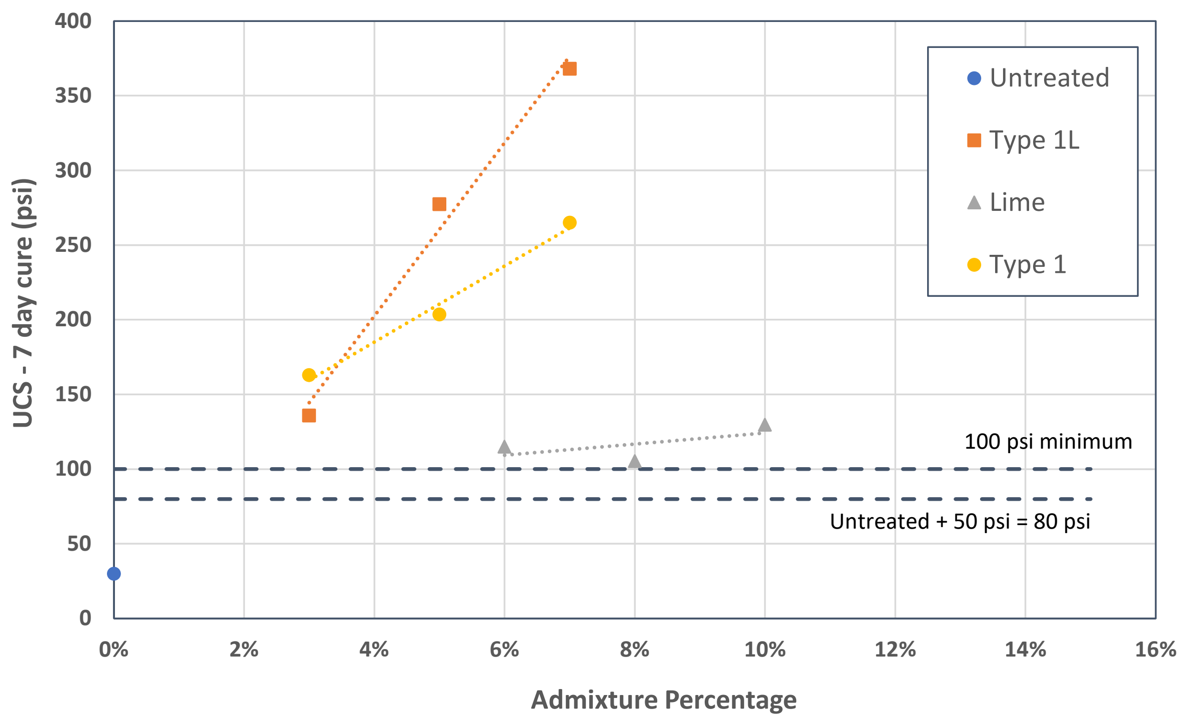

Figure 8 Phase I UCS Results – Robertson County

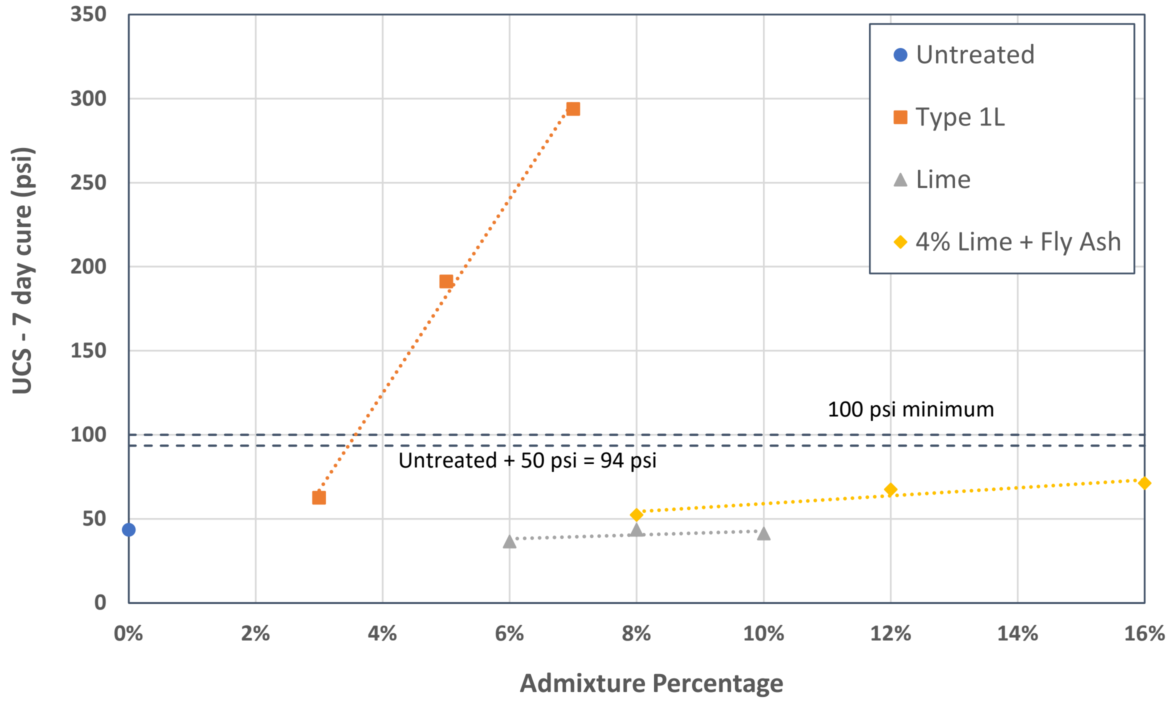

Figure 9 Phase I UCS Results – Rutherford County

4.1.3 Phase II Test Results

For Phase II, Atterberg limits and a Standard Proctor test were completed at the selected chemical stabilizer percentage. Specimens were compacted for both UCS and CBR testing. The data are summarized in Table 12. This section compares the results from the four soils stabilized with Type IL cement with typical results for similar soil types. In particular, the effects of chemical treatment on the Atterberg limits, compaction characteristics, unconfined compressive strength, and CBR are discussed.

Table 12 Selected Phase I and Phase II Test Results

Property	Test Results			
	Cumberland	Humphreys	Robertson	Rutherford
Untreated Atterberg Limits	LL = 33 to 34, PL = 14 to 15, PI = 19	LL = 35 to 37, PL = 23, PI = 12 to 14	LL = 45, PL = 12 to 14, PI = 31 to 33	LL =65, PL = 22 to 23, PI = 42 to 43
Untreated Standard Proctor	γ_{dmax}=111 to 112 pcf w_{opt}=16.5 to 17%	γ_{dmax}=103.5 pcf w_{opt}=18.5%	γ_{dmax}=108.5 pcf w_{opt}=19%	γ_{dmax}=106 to 107 pcf w_{opt}=20%
Untreated UCS[A]	36 to 52 psi	26 to 27 psi	29 to 30 psi	43 to 45 psi
Untreated CBR[A]	12.5 to 13.5	9 to 12	5 to 7	9 to 12

Soil + Type IL Atterberg Limits	LL = 40, PL = 24, PI = 16	LL = 45, PL = 30, PI = 15	LL = 55, PL = 32, PI = 23	LL = 62, PL = 33, PI = 29
Soil + Type IL Standard Proctor	γ_{dmax}=112.5 pcf w_{opt}=15.6%	γ_{dmax}=106.5 pcf w_{opt}=18%	γ_{dmax}=108.2 pcf w_{opt}=17.2%	γ_{dmax}=103.5 pcf w_{opt}=18.5%
Soil + Type IL UCS[A]	7-day: 102-135 psi 28-day: 188-227 psi	7-day: 104-112 psi 28-day: 120-140 psi	7-day: 83-169 psi 28-day: 169-187 psi	7-day: 62 to 87 psi 28-day: 86 to 133 psi
Soil + Type IL CBR[A]	28-day: 75-109	28-day: 171-204	28-day: 143-155	28-day: 43-121

[A] UCS and CBR reported for ≈100% relative compaction at optimum water content

Chemical stabilization tends to change the Atterberg limits of fine-grained soils. In particular, the plastic limit tends to increase, reducing the plasticity index. This trend was confirmed by the results which are summarized in Table 13. Figure 10 and Figure 11 plot the changes in plasticity index for similar soil types. The results of this study (star symbols) compare well with typical experience for stabilization with cement.

Table 13 Changes in Atterberg Limits from Stabilization with Type IL Cement

Property	Condition	Test Results			
		Cumberland A-6 (CL) 4.5% Type IL	**Humphreys A-6 (CL) 5% Type IL**	**Robertson A-7-6 (CL) 3% Type IL**	**Rutherford A-7-6 (CH) 4.5% Type IL**
LL	Untreated	33 to 34	35 to 37	45	65
	Treated	40	45	55	62
	Change	+6 to 7	+8 to 10	+10	-3
PL	Untreated	14 to 15,	23	12 to 14	22 to 23
	Treated	24	30	32	33
	Change	+10 to 11	+7	+18 to 20	+9 to 10
PI	Untreated	19	12 to 14	31 to 33	42 to 43
	Treated	16	15	23	29
	Change	-3	+1 to 3	-8 to -10	-13 to 14

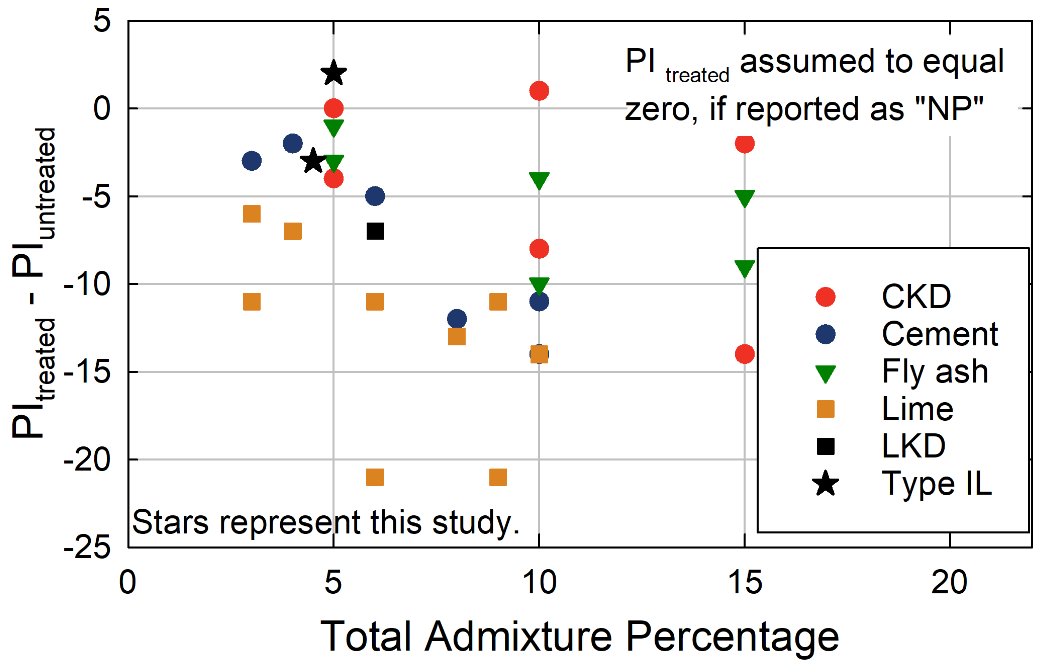

Figure 10 Change in PI Compared to Other Soils – A-6

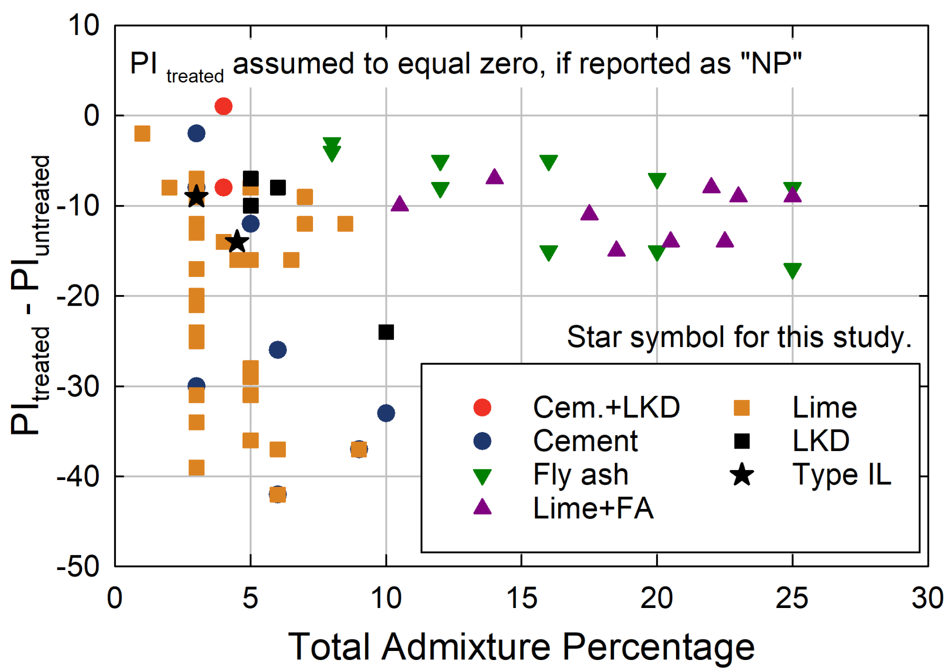

Figure 11 Change in PI Compared to Other Soils – A-7-6

Chemical treatment often causes a shift in the optimum water content and the maximum dry unit weight compared to the untreated properties. The direction of the shift depends on the type of soil and the type of chemical stabilizer. The changes in w_{opt} and $\gamma_{d,max}$ for the four soils in this study are summarized in Table 14.

Table 14 Changes in Compaction Characteristics from Stabilization with Type IL Cement

Property	Condition	Test Results			
		Cumberland A-6 (CL) 4.5% Type IL	Humphreys A-6 (CL) 5% Type IL	Robertson A-7-6 (CL) 3% Type IL	Rutherford A-7-6 (CH) 4.5% Type IL
Maximum dry unit weight γ_{dmax}	Untreated	111 to 112 pcf	103.5	108.5 pcf	106 to107 pcf
	Treated	112.5 pcf	106.5 pcf	108.2 pcf	103.5 pcf
	Change	+1 pcf	+3 pcf	-0.3 pcf	-3 pcf
Optimum water content, w_{opt}	Untreated	16.5 to 17%	18.5%	19%	20%
	Treated	15.6%	18%	17.2%	18.5%
	Change	-1.2%	-0.5%	-1.8%	-1.5%

The changes in w_{opt} and $\gamma_{d,max}$ for the A-6 soils are compared to other studies in Figure 12. The Cumberland and Humphreys soils experienced small increases in $\gamma_{d,max}$ with little change in w_{opt}. This contrasts with other A-6 soils stabilized with cement, which showed a decrease in unit weight. Differences may be due to the plasticity of the particular soils or the percentages of cement used.

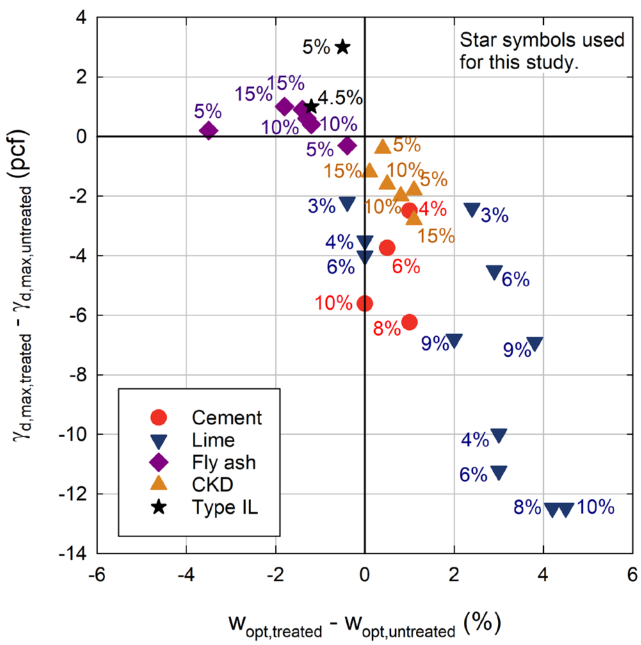

Figure 12 Change in Compaction Characteristics Compared to Other A-6 Soils (numbers adjacent to symbols indicate chemical stabilizer percentage)

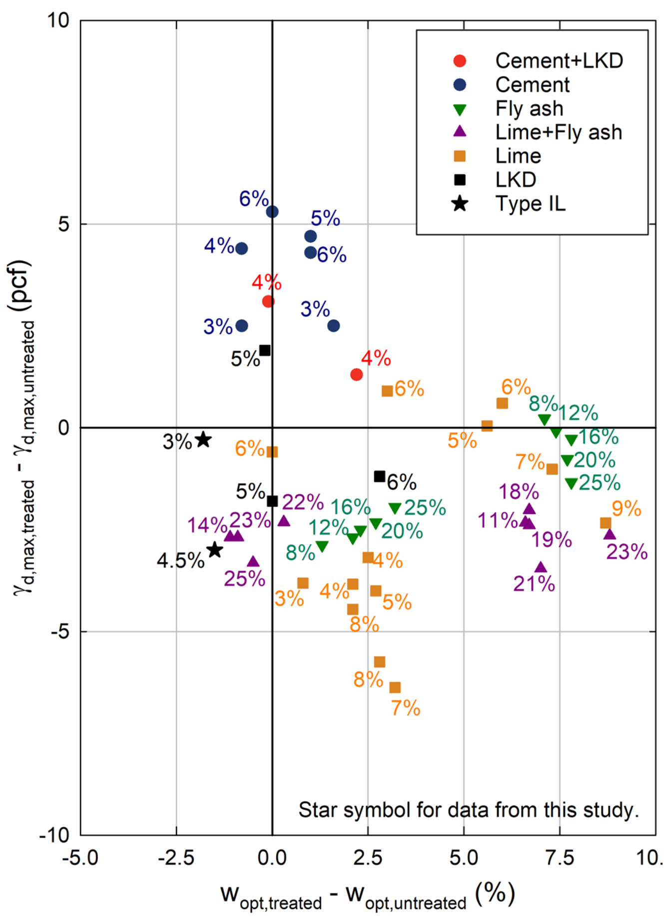

Figure 13 Change in Compaction Characteristics Compared to Other A-7-6 Soils

The changes in w_{opt} and $\gamma_{d,max}$ for the A-7-6 soils are compared to other studies in Figure 13. The Robertson and Rutherford soils experienced a small to moderate decrease in $\gamma_{d,max}$ and a moderate decrease in w_{opt}. This contrasts with other A-7-6 soils stabilized with cement, which showed an increase in unit weight. Differences may be due to the plasticity of the particular soils or the percentages of cement used.

This study made use of the one-point Proctor compaction method (AASHTO 272) to estimate w_{opt} and $\gamma_{d,max}$ for the Phase I tests. Table 15 compares the estimated one-point values with the those measured in Phase II using a full Standard Proctor test. With the exception of the Rutherford soil, the one-point test worked well for estimating the optimum water content and maximum dry unit weight of the treated soils.

Table 15 Comparison between One-Point and Standard Proctor Values for Type IL Cement

Property	Condition	Test Results			
		Cumberland A-6 (CL) 4.5% Type IL	Humphreys A-6 (CL) 5% Type IL	Robertson A-7-6 (CL) 3% Type IL	Rutherford A-7-6 (CH) 4.5% Type IL

Maximum dry unit weight, γ_{dmax}	One-point	112.0 pcf	106.0 pcf	108 to 111 pcf	99.9 to 102.4 pcf
	Measured	112.5 pcf	106.5 pcf	108.2 pcf	103.5 pcf
Optimum water content, w_{opt}	One-point	15.8%	18.6%	16.5 to 17%	20.3 to 21.5%
	Measured	15.6%	18%	17.2%	18.5%

A core purpose of chemical stabilization is the increase of strength, which is often measured using the unconfined compressive strength of the soil. Table 16 summarizes the changes in UCS for a 7-day curing period and compares 7-day and 28-day curing for the four soils tested. In general, larger gains in strength were observed for the A-6 soils compared with the A-7-6 soils. In addition, the A-6 soils showed less variability in the stabilized UCS. This may be due the increased difficulty of mixing the higher plasticity A-7-6 soil with the chemical stabilizer.

Figure 14 and Figure 15 compare the strengths measured by this study with typical behavior of A-6 and A-7-6 soils. The A-6 soils showed similar to slightly UCS compared to similar soils stabilized with Type I cement. The 28-day UCS (in psi) was about 30 to 50 times the percentage of Type IL cement. The two A-7-6 soils showed similar to slightly lower increase in UCS compared to other soils stabilized using Type I cement. The 28-day UCS (in psi) ranged from 24 times (Rutherford) to nearly 60 times (Robertson) the percentage of Type IL cement used.

Table 16 Changes in Unconfined Compressive Strength from Stabilization with Type IL Cement

Curing Period	Condition	Test Results			
		Cumberland A-6 (CL) 4.5% Type IL	**Humphreys A-6 (CL) 5% Type IL**	**Robertson A-7-6 (CL) 3% Type IL**	**Rutherford A-7-6 (CH) 4.5% Type IL**
None	Untreated	Average: 44 psi Range: 36 to 52 psi	Average: 26.5 psi Range: 26 to 27 psi	Average: 29.5 psi Range: 29 to 30 psi	Average 44 psi Range: 43 to 45 psi
7 days	Treated	Average: 118 psi Range: 102-135 psi	Average: 107 psi Range: 104-112 psi	Average: 126 psi: Range: 83-169 psi	Average: 75 psi Range: 62 to 87 psi
	Increase	Average: 74 psi 168% increase	Average: 81 psi 306% increase	Average: 96 psi 327% increase	Average: 31 psi 70% increase
28-days	Treated	Average: 208 psi Range: 188-227 psi	Average: 129 psi Range: 120-140 psi	Average: 178 psi Range: 169-187 psi	Average: 110 psi Range: 86-133 psi

	Increase	Average: 164 psi 372% increase	Average: 103 psi 387% increase	Average: 149 psi 503% increase	Average: 66 psi 150% increase
7 to 28 days	Increase	90 psi	100 psi	52 psi	35 psi
	Percentage	76% higher	93% higher	41% higher	47% higher

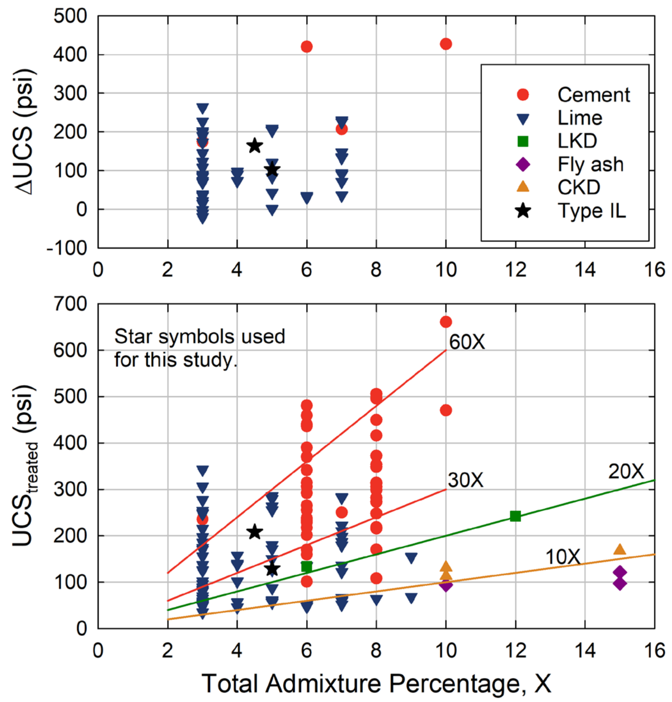

Figure 14 Comparison of Treated UCS to Other A-6 Soils (28-day curing only)

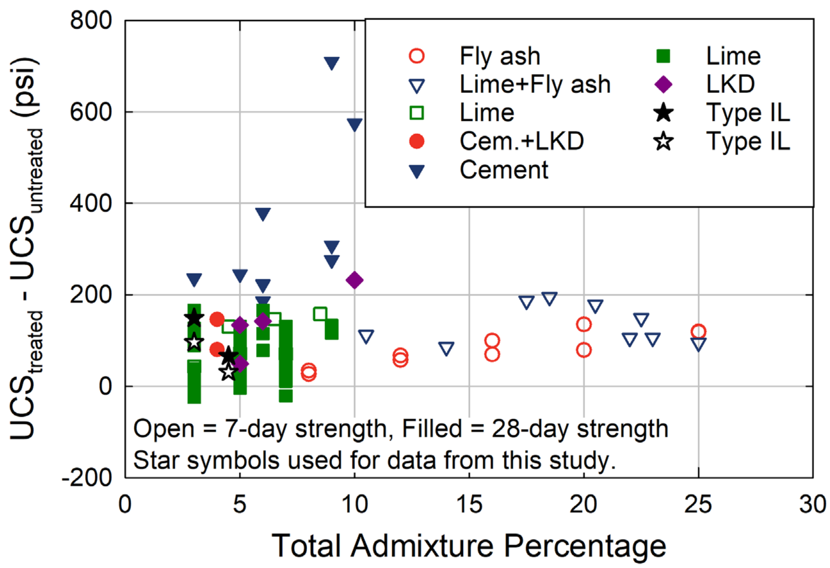

Figure 15 Increase in UCS Compared to Other A-7-6 Soils

Chemical stabilization produces an increase in subgrade stability that can be quantified using the California Bearing Ratio. On average, the treated CBR ranged from 7 to 24 times greater than the untreated value. The Rutherford clay exhibited substantial variability in the treated CBR, possibly attributable to the difficulty mixing high plasticity clay. However, even the lowest CBR of 43 measured for the Rutherford soil represents a four-fold increase from the untreated CBR.

Table 17 Changes in Soaked California Bearing Ratio from Stabilization with Type IL Cement

Property	**Test Results**			
	Cumberland	**Humphreys**	**Robertson**	**Rutherford**
Untreated[A]	Average: 13 Range: 12.5 to 13.5	Average: 10.5 Range: 9 to 12	Average: 6 Range: 5 to 7	Average: 10.5 Range: 9 to 12
Treated[A]	Average: 92 Range: 75 to 109	Average: 188 Range: 171 to 204	Average: 147 Range: 143 to 155	Average: 82 Range: 43 to 121
Increase	79	178	141	71

[A] CBR reported for ≈100% relative compaction at optimum water content, 28-day cure

4.2 Soil Stabilization Testing Manual

The Soil Stabilization Testing Manual is presented in Appendix B. It provides guidance for sampling, storage, Phase I and II testing, and field testing for stabilization purposes.

4.3 Stabilization Fact Sheets

The stabilization fact sheets can be found in Appendix D for AASHTO classifications A-2-4 and A-2-5, A-2-6 and A-2-7, A-4, A-5, A-6, A-7-5, and A-7-6. Fact sheets were not prepared for the coarse-grained classifications of A-1-a, A-1-b, and A-3 because these soils are very sparse in Tennessee and are much less likely to require stabilization.

4.3.1 Untreated and Stabilized Soil Properties

Each fact sheet provides a summary of the typical properties of the AASHTO soil group when compacted to approximately 100% of Standard Proctor maximum dry unit weight. Qualitative descriptions of the drainage characteristics, fill stability, and pavement support capabilities are provided based on USACE (1960). In addition, the typical ranges of unconfined compressive strength and California bearing ratio for the compacted untreated soil are reported (Porter 1943, USACE 1960, PCA 1992).

Each fact sheet also includes a general discussion of the interactions of typical chemical admixtures with the particular AASHTO soil type. The effects of lime, portland cement, and sometimes fly ash are discussed. Typical admixture percentages and 28-day unconfined compressive strengths are summarized based on the broader geotechnical literature.

The back side of each fact sheet contains a compilation of pertinent laboratory test results on the AASHTO soil type for various admixtures. The data was collected from multiple sources which are summarized in Table 9 in Section 3.3. These include:

- Unconfined compressive strength – increase in UCS based on admixture percentage, in some cases compared to natural UCS;
- Plasticity index – change resulting from stabilization;
- Compaction characteristics –change in dry unit weight plotted against change in water content;
- Curing effects – strength gain with time in UCS or CBR; and
- Subgrade stability – increase in CBR or resilient modulus based on admixture percentage.

Where applicable, the results from this study are included with the other data to allow comparison of the behavior of Tennessee soils with a broader range of geologic source materials. The results from the four soils tested by this project generally agree with the broader trends.

4.4 Chemical Subgrade Stabilization Specification

TDOT's *Standard Specifications for Road and Bridge Construction* (2021) include "Section 302 – Subgrade Treatment (Lime)". The suggested revision to Section 302 is provided in Appendix E. The major changes suggested to Section 302 are:

- Make the specification inclusive to apply to all types of chemical stabilization rather than just lime.
- Provide stricter requirements for the mixing equipment in accordance with current stabilization technology.
- Change the compaction specifications to match those required of untreated pavement subgrade (average of 100% and not less than 97% of Standard Proctor maximum density).
- Introduce additional guidance on curing.

Chapter 5 Conclusion

Many state Departments of Transportation (DOTs) regularly use chemical subgrade treatment to improve the stability of subgrades and provide stability during construction. They follow relatively similar procedures for the selection of the appropriate type and percentage of chemical stabilizer. These procedures were used as guidance for the development of a mix design procedure for Tennessee. The incorporation of the effects of chemical subgrade stabilization into pavement design varies widely by locale. It appears that few states directly use the Mechanistic-Empirical Pavement Design Guide (AASHTO 2020) and measured resilient moduli to represent stabilized subgrade in pavement design.

The construction of high quality chemically treated subgrade requires good construction practice, including spreading, mixing, compaction, and curing. The use of current procedures for chemical stabilization requires that up-to-date equipment, such as rotary tillers, be used to mix the chemical stabilizer with the soil. The creation of a high quality stabilized subgrade also requires consistent laboratory and field procedures for QA/QC.

The mix design procedure recommended in the Soil Stabilization Testing Manual should be adopted. The procedure includes initial soil characterization, selection of a chemical stabilizer and percentage (Phase I), and verification of stabilized subgrade properties for pavement design (Phase II). Specimens used to measure parameters required for pavement design should be cured for 28 days. The methods to determine pavement support characteristics are (in order of preference) laboratory resilient modulus (M_r) tests, laboratory California Bearing Ratio (CBR) tests, and correlation to CBR or M_r from unconfined compressive strength.

Samples of four soils from Tennessee were obtained, two of which classify as A-6 and two of which classify as A-7-6. The mix design process was completed on these four soil samples and representative reports were generated. These mix design reports illustrate the type of result to be expected from TDOT or its consultants for the design of chemical subgrade treatment. The results from the four mix designs showed that the Tennessee soils behaved similarly to other stabilized soils of the same type.

Type IL cement was selected as the best chemical stabilizer for all of the soils tested. The strengths measured were similar or lower than those obtained using conventional Type I cement. As Type IL cement replaces Type I, slightly higher percentages of cement will likely be required to obtain the same performance level as previously experienced with stabilization using Type I cement.

Data on the response of various soil types to chemical subgrade treatment was collected from the literature and divided based on AASHTO soil classification. Fact sheets were created for the seven most prevalent soil types in Tennessee, which summarize typical response to common stabilizers and the effects of stabilization. In addition, the prevalence of each AASHTO soil type throughout the near-surface soils of Tennessee was determined using data from the USDA Soil Survey.

The current specification governing subgrade treatment, Section 302, was specifically written for treatment with lime. A review of subgrade stabilization specifications from multiple DOTs provided a basis for a recommended revision to Section 302 of the TDOT specifications.

The revised version of Section 302 should be incorporated into TDOT's specifications. The revised specification requires the use of more current construction practices and allows for the use of chemical stabilizers other than just lime.

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