Characterization of Shear Strength and Cracking Resistance of a Chemically Stabilized Clayey Soil

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CHARACTERIZATION OF SHEAR STRENGTH AND CRACKING RESISTANCE OF A CHEMICALLY STABILIZED CLAYEY SOIL

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABSTRACT

CHARACTERIZATION OF SHEAR STRENGTH AND CRACKING RESISTANCE OF A CHEMICALLY STABILIZED CLAYEY SOIL

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Improving the engineering properties of the subgrade soil by means of chemical stabilization is known to enhance the construction conditions in plastic soils and result in a reduction in design thickness requirements of the base, subbase, and wearing course in a layered pavement structure. This can also potentially lead to an increase in pavement life. This study was undertaken to study the effect of hydrated lime and Portland cement used as a stabilizing agents on the strength properties and the cracking resistance of a clayey soil collected from South Dakota. Hydrated lime was mixed with the collected soil by 2%, 3% and 5% and Portland cement was blended at 7%, 9% and 11% by the weight of the soil. Different tests, namely Particle size distribution, Atterberg limits, pH, Proctor test, freeze-thaw (F-T) cycles, unconfined compressive strength, and semicircular bend test were conducted before and after treatment with hydrated lime and Portland cement. The results indicated that use of 1% cement was more effective than 1% lime in improving soil's shear strength. In general, shear strength of the natural soil was found to become more sensitive to F-T cycles with increasing both Portland cement and hydrated lime contents. The flexural stiffness and fracture energy of the natural soil were found to improve by stabilizing it with both lime and cement. This improvement was more pronounced when Portland cement was used. Reduction in the flexural stiffness and fracture energy of the lime-stabilized soil was found to be more sensitive to F-T cycles

than cement-stabilized soil. The only stabilizing agent found to be capable of improving the flexibility index of the natural soil was hydrated lime. Cement-stabilized soil was concluded to be highly brittle and may result in instantaneous propagation of the crack in the whole section after reaching the peak load. Therefore, the use of cement stabilization should be carried out more cautiously to avoid premature crack.

1. INTRODUCTION

1.1.Background

Based on 2019 data, the total length of paved and unpaved roads in the United States was more than 7 million miles (FHWA/ HM-260, 2019). Millions of dollars are spent annually by the state and local transportation agencies for repair and maintenance to keep these roads in operational condition. Improvement in pavement design and using high-quality materials have led to an increase in pavement life and substantial savings as a result of a reduced need for frequent repair and maintenance.

The successful design of roads not only depends on a high-quality surface layer (concrete or asphalt) but also requires robust and high-quality foundation layers (base, subbase, and subgrade). The structural integrity of the foundation layer of a pavement plays a critical role in extending its service life. In contrast, an unstable subgrade layer causes a reduction in pavement life and dictates an increase in base, subbase, and surface layer thicknesses in the design phase, leading to additional construction costs. In the case of a weak subgrade, different techniques are applied to improve the engineering properties of the soil to enhance its loadbearing capacity when subjected to traffic. Soil stabilization by chemical additives such as Portland cement and hydrated lime is widely used to prepare project sites for construction equipment and to improve the mechanical properties of the subgrade layer. This improvement is achieved by altering and balancing natural soil properties, such as plasticity, strength, maximum dry density (MDD), optimum moisture content (OMC), shrinkage, and heaving properties among others. Using chemically stabilized subgrade layers increases pavement's resistance to elements such as water and frost action as well as traffic loads. Figure 1.1 shows the load distribution in a stabilized base layer and a non-stabilized layer in a pavement structure.

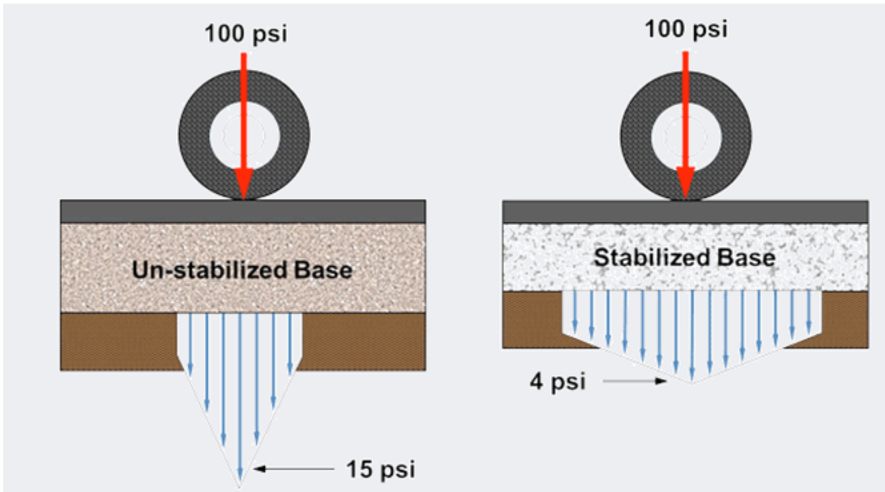

Figure 1.1 Load distribution under a stabilized and non-stabilized base layer (Ruston Paving, 2021).

1.2. Problem Statement

Insufficient subgrade bearing capacity and highly plastic subgrade soils can result in construction difficulties and pavement failure. In addition, they can be sensitive to moisture fluctuation resulting in drastic volume change leading to premature distresses. Therefore, there is a need to improve the mechanical properties of these soils to minimize the risks, as mentioned earlier. Two of the most common additives used are Portland cement and hydrated lime. This study was undertaken to investigate the effectiveness of cement and hydrated lime stabilization conducted on a local highly plastic soil collected from west Sioux Falls in South Dakota. In addition, the effect of stabilization of the brittleness and susceptibility to cracking of the subgrade soil was investigated by applying the fracture energy concept. Highly brittle pavement layers, especially when used in a flexible pavement structure, are known to be susceptible to flexure-induced cracking that can propagate as reflective cracks during the pavements' service life.

1.3. Significance

Collected plastic soil was stabilized in the laboratory using Portland cement and lime. For this purpose, the important engineering properties of the soil were determined in the laboratory before and after adding different amounts of additives. More specifically, the moisture-density relationship, pH, and Atterberg limits of the natural soil and that containing different amounts of additives were measured. Then, optimum additive contents were established. Finally, the unconfined compressive strength (UCS) and the flexibility index (FI) of the soil containing different types and amounts of additives after being subjected to freeze-thaw (F-T) cycles and those without F-T cycles were measured. The results indicated the effectiveness of each stabilizing agent in improving the engineering properties of the subgrade soil when it is subjected to resistance to F-T cycles. Due to the severe winter conditions in South Dakota, construction materials are expected to be subjected to F-T cycles. Therefore, the findings of this study are expected to help pavement design engineers gain more information about the properties of stabilized soils in severe frigid climates.

1.4. Objectives

i- Determine the engineering properties of a natural plastic soil in South Dakota, namely MDD, OMC, pH, Atterberg limits, UCS, and FI.

ii- Determine the effect of stabilizing the collected soil with different amounts of hydrated lime and Portland cement on its engineering properties, namely MDD, OMC, pH, , UCS, and FI.

iii- Determine the effect of F-T cycles on the UCS and FI values of the natural soil and that stabilized with hydrated lime and Portland cement.

1.5. Thesis organization

Chapter 1: Introduction – Provides a brief summary of the background, problem statement, the significance of the study, and objectives.

Chapter 2: Literature Review – Summarizes selected studies related to soil stabilization by hydrated lime and Portland cement with a focus on their effect on soil's engineering properties.

Chapter 3: *Materials and Methods* – Summarizes details about the collected soil and the materials used in this study. Also, the procedures followed to prepare samples and conduct different tests are discussed in this chapter.

Chapter 4: Results and Discussion – Summarizes the results of the tests conducted on soil samples and provides an interpretation of the collected test data.

Chapter 6: Conclusions and Recommendations – Important outcomes of this study are summarized, and recommendations are made.

1.6. Summary of introduction:

An important factor in affecting the service life of a pavement is the structural integrity of the foundation layer. An unstable subgrade layer shortens the life of the pavement and necessitates an increase in the thicknesses of the subbase, base, and surface layers during the design phase, resulting in an increase in construction cost. In order to increase the life and load bearing capacity of a pavement, chemical stabilization of subgrade soil is commonly used. Among chemical stabilizing agents, Portland cement and hydrated lime are widely used by the pavement industry. Current study aims to evaluate the effect of stabilizing a clayey soil using hydrated lime and Portland cement on its mechanical properties.

2.LITERATURE REVIEW

2.1. Soil Stabilization

In a study conducted by Afrin et al. (2017), different types of soil stabilization methods were reviewed. Soil stabilization is an improvement of one or more engineering properties of the soil, such as compressive strength, shear strength, Atterberg limits, maximum dry density, optimum moisture content, and California bearing ratio (CBR) values. Also, several additives were reported to be used to stabilize the soil, such as lime, cement, fly ash, rice husk ash, and waste products. Lime and cement are the oldest and most widely used means of soil stabilization.

Guyer et al. (2009) studied different types of stabilizing agents like Portland cement, hydrated lime, lime-fly ash, lime-cement-fly ash, bitumen, lime-cement, and lime-bitumen. Six factors, namely soil type (the most critical factor), stabilization purpose, required strength, durability, cost, and environmental conditions, affect selecting the type of stabilizing agent. There are some guidelines for selecting a stabilizing additive and determining its optimum content through laboratory procedures.

2.2. Soil Stabilization by Cement

In a study by Emmert et al. (2017) on improving forest roads, the cement chemical stabilization method was studied. Several soil tests, namely grain size distribution, compaction test, UCS, and CBR were conducted. According to the results of compaction tests, UCS, and CBR, an increase in compaction energy resulted in improved compressive strength compared to natural soils. However, it was also found that the strain on natural soil at failure (4%) was higher than that of cement-stabilized soil (3%).

Da Fonseca et al. (2009) evaluated the influence of the amount of cement and porosity on the strength of cement-stabilized soil. UCS, compaction, and moisture content tests were conducted. It was found that an increase in voids/cement ratio resulted in a reduction in the UCS values. Also, no relationship was found to exist between the water to cement ratio and UCS. Finally, it was reported that the voids to cement ratio could be used for the selection of the amount of cement and compaction energy to get the highest benefit from cement stabilization of the soil.

Askari et al. (2015) studied the effects of two types of additives, namely lime and Portland cement, on the geotechnical and engineering properties of the soil. Different soil tests, including Atterberg limits, compaction, moisture content, and UCS were performed to evaluate the effectiveness of those additives. According to the Atterberg limits test, the plasticity index of soil treated with cement increased up to 3% of cement, then decreased with higher cement contents. Similar results were also reported when lime was used for stabilization. In addition, the compaction test indicated that the use of lime and cement additives both increased the MDD and OMC. Overall, the unconfined compressive strength for the soil treated with cement was higher than that with lime.

In a study by Chemise et al. (2014), the influence of the cement and lime mixture treatment on the strength and ductility of compacted expansive clay was investigated. The Atterberg limits test, Methylene blue value (MBV), CBR, and triaxial shear tests were conducted. It was found that plasticity index, liquid limit, and swelling potential were lower in treated clay compared to those of the untreated soil. The results from CBR test indicated that using cement and lime increased the CBR values of both soaked and unsoaked samples compared to their untreated counterparts. Finally, the triaxial shear test results indicated that the shear strength of treated clay was higher than that of untreated clay.

Barghini et al. (2015) evaluated the effects of using a bitumen emulsion and Portland cement on the long-term performance of road base materials. Different tests, namely UCS, flexural strength (FS), wetting and drying (WD), soaked and unsoaked CBR, dynamic creep (DC), and wheel-tracking (WT) were conducted. Results of the UCS, FS, and CBR tests indicated that 4% Portland cement and 3% bituminous emulsion improved the strength of the mixture. For the same additives at the same percentages, the WD tests showed a reduction in water absorption, volume change, and weight change compared to untreated samples. From DC and WT tests, it was found that the treated samples' resistance to permanent deformation was higher than those of the untreated ones. This observation indicates that treated samples will have a superior resistance to rutting than untreated samples.

Aghazadeh et al. (2018) researched the effects of adding cement to a mixture of reclaimed asphalt pavement (RAP) and soil. Different tests, including the modified Proctor, UCS, elastic modulus, and CBR, were conducted. Modified Proctor test results showed that increasing the amount of cement in the mixture resulted in decreasing the OMC and MDD values of RAP/soil mixture—at only 20% of RAP and 3% of cement, the MDD increased. USC test results indicated that increased amounts of cement resulted in higher UCS, and increased RAP content resulted in a decrease in UCS. On the other hand, the elastic modulus of treated soil increased by increasing cement or decreasing RAP content. The CBR test results indicated that increased RAP content led to a reduction in CBR and swelling before approaching a constant value.

In a study conducted by Zamari et al. (2018), the effect of lime and cement treatment of peat soil on its drained shear strength was evaluated. A direct shear box test was conducted to obtain the shear strength for treated and untreated soil samples. The results indicated that the additives increase shear strength by 14% compared to untreated samples. In addition, the lime-treated soil sample showed a shear strength that was 14.07% higher than that of the cement-treated sample. It was concluded that cement and lime could be successfully utilized for the stabilization of soils with high moisture content.

In a study conducted by Gonnade et al. (2020), black cotton soil, medium to high compressibility inorganic clay, was stabilized using slightly alkaline liquid sodium silicate and cement. Also, the effectiveness of stabilizing agents was evaluated by conducting the Atterberg limits test, Proctor test, CBR test, swelling test, and UCS test on soil samples. The results indicated a reduction in plasticity index, swell index, and water content with an increase in sodium silicate amount. Also, the UCS and CBR values increased with the addition of sodium silicate to the cement-black cotton mixture.

Ghadir and Rajbir (2018) compared the behavior of clayey soil stabilized by Portland cement and volcanic ash geopolymer. The results showed that when volcanic ash geopolymer was used as the stabilizing agent, the compressive strength of the soil improved by 200% compared to soil stabilized with Portland cement.

Naidu et al. (2021) studied the effect of Portland cement when used for stabilizing gravelly soil on its CBR. It was reported that adding 5% to 7% Portland cement to soil lowered the plasticity index value of the untreated soil. Also, adding 3% to 5% of Portland cement to the soil reduced the void ratio. Furthermore, the results showed that the values of CBR increased with an increase in cement content.

2.3. Soil Stabilization by Lime

In a study conducted by Console et al. (2009), the effect of lime content, porosity, molding moisture content, water/lime ratio, and voids/lime ratio on the strength of lime-treated sandy lean clay was evaluated. Different tests, namely pH test, UCS tests, Proctor test, moisture content, and porosity tests, were conducted on the samples. Based on the modified initial consumption of lime (ICL) method, the minimum amount of lime for soil stabilization was determined to be 3%. According to the UCS tests, compaction test, and moisture content, the lime content has a noticeable effect on the UCS value. Also, the strength was reported to increase approximately linearly with an increase in lime content. Furthermore, it was found that the UCS values increased linearly with a reduction in soil porosity. Finally, no correlation was observed between the water/lime ratio or voids/lime ratio with the unconfined compression strength.

Thiagarajan et al. (2012) conducted a laboratory investigation to study the precipitation of lime in the soil. Calcium chloride ($CaCl_2$) and sodium hydroxide solution (NaOH) were mixed with expansive soil to determine the effect of the sequential mixing on the physicochemical properties, Atterberg limits, swell potential, and UCS value of the soil. The soil used in this investigation was CH soil. Index limits test, odometer swell potential test, and UCS were conducted. Sequential mixing of $CaCl_2$ and NaOH with expansive soil led to drastic reductions in the liquid limit and plasticity index. Also, the swell value was found to reduce to 0% because as a result of the sequential mixing of $CaCl_2$ and NaOH with expansive soil. Furthermore, the UCS values were found to increase with an increase in the amount of lime precipitation. This study also mentioned some lime stabilization techniques such as lime columns, lime piles, and lime slurry injections.

The effect of a long series of freeze-thaw cycles (temperature between +20 ºC and -17.5ºC) on the properties of a lime-stabilized soil (LSS) was investigated by Tebaldi et al. (2016). A clayey soil was mixed with 2.5% of calcium oxide (lime), and the mechanical properties of the lime-stabilized soil before and after freeze-thaw cycles were compared. Two types of soil tests, namely direct shear strength test (DSS) and UCS test, were conducted on the soil samples. The results of these tests indicated that the strength reduction of LSS was not due to physical damage but rather because of the lack of volume increase observed after freeze-thaw cycles and that full recovery of the soil strength occurs when the temperature was increased back to +20ºC.

Dash and Hussain (2012) conducted a study to evaluate the effect of lime stabilization on the plasticity of the soil. Two different types of soil, an expansive soil (ES) and a non-expansive residual soil (RS), classified according to unified soil classification as CH and CL, respectively, were evaluated. Six samples were prepared by mixing the soils and the lime in different amounts. Soil properties were evaluated by conducting liquid limit, plastic limit, oedometer swell, UCS, and x-ray diffraction (XRD) tests. It was found that the liquid limit decreased with an increase in lime content. However, lime contents of more than 5% resulted in an increase in the plastic limit while the consistency limits did not change, and the workability of the soil was not improved. Furthermore, the swell of the soil decreased with an increased percentage of lime to a practically negligible value and improved the strength and stiffness of the soil.

Alderwood et al. (2014) studied the impact of freeze-thaw cycles on the mechanical and mineralogical behavior of fine-grained soil content with different gypsum amounts (0, 5, 15, and 25%) stabilized with 3% of lime. Soil tests, including freeze-thaw cycles, UCS, wave velocity, pH, electrical conductivity, water content, and volume change, were conducted. It was found that the UCS values increased as a result of soil treatment before applying freeze-thaw cycles; then, from the first freeze-thaw cycle onward, the strength decreased. Moreover, the pH and electrical conductivity values of treated soil decreased after freeze-thaw cycles were applied and showed changes in the mineralogy because of lime reaction. However, the water content of the soil samples increased significantly with the first cycle of freeze-thaw and kept rising with the subsequent cycles. Also, when the amount of gypsum in the soil increased, the water absorption increased during thawing. In addition, volume changes increased with the number of freeze-thaw cycles.

In a study conducted by Andaman and Pagadala (2020), the effect of lime and fly ash on the geotechnical properties of the soil were evaluated. Standard Proctor and UCS tests were conducted to assess the influence of soil treatments on its properties. The results showed that the strength of lime-fly ash increased soil stability and its density according to the Proctor test. However, the strength of the clay soil decreased when lime was added.

Keagan et al. (2019) conducted a study that evaluated the impact of sawdust ash and lime on the geotechnical properties of black cotton soil. Different amounts of sawdust ash were mixed with black cotton soil, and the results indicated that 16% was the optimum amount of ash added to the soil. However, the outcomes of the Atterberg limits test, swelling test, and CBR test showed that 16% of sawdust ash with 4% of lime reduced the liquid limit, reduced swelling, and increased CBR values of black cotton soil.

Liu et al. (2019) evaluated the influence of lime on soda saline soil using different soil tests, such as the Proctor compaction test, Atterberg limits, cation exchange capacity test (CEC), and UCS test. The results showed that with the addition of lime, the MDD of lime saline soil decreased while the OMC increased. Additionally, the liquid limit decreased with increased lime content, while the measured UCS values increased. The ash-lime added to the saline soil changed its classification from clay for untreated soil to sand and silt after treatment.

In a study conducted by Sharma et al. (2012), the influence of fly ash-lime on the geotechnical properties of clayey soil was evaluated. According to the results, adding fly ash-lime to clayey soil resulted in an increase in its strength and CBR values when 8.5% lime and 20% fly ash were added.

2.4. Soil Stabilization by other additives

Soleimani et al. (2013) researched the geotechnical properties of recycled asphalt shingles (RAS) stabilized with fly ash (FA) for use as structural filler material. Compaction, hydraulic conductivity, compressibility, and shear strength of stabilized RAS were evaluated. Standard Proctor compaction test results showed that the maximum dry unit weight of the stabilized RAS increased with an increase in fly ash content. Also, it was found that the hydraulic conductivity of unstabilized and stabilized RAS reduced with increasing confining pressure and fly ash content. The triaxial test indicated that the stabilization of RAS increased its shear strength and changed the volumetric behavior from compressive to dilative.

Soleimani et al. (2015) also evaluated the shear strength, compressibility, and hydraulic conductivity of recycled asphalt shingles (RAS) mixed with bottom ash (BA) and self-cementing fly ash (FA). Different soil tests, namely the triaxial compression, one-dimensional (1-D) compression, and hydraulic conductivity, were conducted. According to the triaxial compression test, the shear strength of compacted RAS-BA and RAS-FA mixtures consistently decreased with an increase in temperature. In contrast, 1-D compression test showed that increasing temperature resulted in an increase in the vertical strain, strain rate, secondary compression ratio, and hydraulic conductivity.

In a study conducted by Avirneni et al. (2016), the durability and long-term performance for RAP and virgin aggregates (VA) mixed with fly ash were evaluated. Different tests, including compaction, pH, UCS, XRD, and durability tests (wet/dry cycles), were conducted. According to the compaction test, there was not much difference in OMC and MDD of different samples. Also, it was found that the pH values increase with an increase in NaOH content. In addition, the UCS values increased when NaOH content increased. On the other hand, the XRD test indicated that the intensity of calcium hydroxide (CH) peak decreased with increasing NaOH. Finally, from the durability test, it was found that weight loss after the durability cycles was less than 14%.

Linsha et al. (2016) compared the change in the engineering properties of soil stabilized by different amounts of bitumen by conducting Atterberg's limits, direct shear tests, relative density, UCS, CBR, modified Proctor compaction, and specific gravity tests. Test results indicated that with an increase in bitumen emulsion in the soil, the relative density, plastic limit, and specific gravity decreased, while the liquid limit and maximum dry density increased. On the other hand, the strength of the soil increased with an increase in bitumen emulsion content.

He et al. (2018) evaluated the effect of liquid ionic soil stabilizer (LISS) on swelling and shrinkage behavior of expansive soils. The results indicated that the plasticity index (PI) of the soil decreased with an increase in LISS dosage. In addition, it was reported that the use of LISS resulted in a reduction in the swelling and an increase the strength of the soil.

In a study conducted by Iyengar et al. (2013) the potential of polymer binders to stabilize a soil classified as a gravel–sand–silt–clay mixture (GM-GC) was investigated. Various soil tests were conducted to determine compressive strength, elastic modulus, total energy to compressive failure, and toughness. However, to evaluate the effective of polymer-based binders as stabilizer agent a comparation with using Portland cement was conducted. Moreover, the results found that the polymer-stabilized soil to have higher UCSs, higher stiffness (E50), a greater toughness and a better capacity to the loads compared to cement stabilized soil.

2.5. Summary of literature review

The literature review indicated that the Portland cement and hydrated lime effectively improve the engineering properties of the subgrade soil such as unconfined undrained shear strength with an increase in stabilizer content. In addition, the literature review showed alternatives stabilizers such as fly ash, RAP, RAS, polymeric binders, and liquid ionic soil stabilizers (LISS) can be used to improve the engineering properties of the subgrade soil. Furthermore, environmental factors such as freeze-thaw cycles were found to cause a redaction in the strength of the treated soil.

3. MATERIALS AND METHODS

3.1. Introduction

This chapter provides an overview of the materials used in this study and soil tests conducted to evaluate the influences of lime and cement on the mechanical properties of a soil sample collected from South Dakota. The following steps were performed during this study:

I. Collect natural soil.

II. Conduct performance tests to evaluate soil properties before and after stabilization.

3.2. Soil

A soil sample reported to be problematic with the geotechnical properties shown in Table 3.1 was collected from north of Sioux Falls, South Dakota (43° 37’11.9” N 96°57’27.2” W). According to the Unified Soil Classification System (USCS), the collected soil sample was classified as CL **(**shown in Table 3.2 and Figure 3.1**)** as the percent passing sieve No. 200 was found to be more than 50%, the plasticity index was 13.16, and the liquid limit was less than 50. CL is considered to be unstable soil due to high swelling and low strength values and constructability issues.

Table 3.1 Geotechnical properties of the collected soil.

Soil Properties	**Value**
Classification	CL
Liquid Limit (%)	36.3
Plastic Limit (%)	23.1
Plasticity Index (%)	13.2
Moisture Content (%)	15.1
Maximum dry density (g/cm^3)	1.59

This study used the Unified Soil Classification System (USCS) introduced by A. Casagrande in the early 1940s. The USCS system classifies the soils into 15 groups based on the particle size distribution and Atterberg limits.

Table 3.2 Unified Soil Classification System According to ASTM D2487 (ASTM, 2021).

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests.				Group Symbol
COARSE-GRAINED SOIL More than 50% retained on No. 200 sieve	Gravels (More than 50% of coarse fraction retained on No. 4 sieve	Clean Gravels (Less than 5% fines)	Cu ≥ 4 and 1 ≤ Cc ≤ 3	**GW**
			Cu < 4 and/or (Cc < 1 or Cc > 3)	**GP**
		Gravels with fines (More than 12% fines)	Fines classify as ML or MH	**GM**
			Fines classify as CL or CH	**GC**
	Sand (50% or more of coarse fraction passes No. 4 sieve	Clean Sand (Less than 5% fines)	Cu ≥ 6 and 1 ≤ Cc ≤ 3	**SW**
			Cu < 6 and/or (Cc < 1 or Cc > 3)	**SP**
		Sand with fines (More than 12% fines)	Fines classify as ML or MH	**SM**
			Fines classify as CL or CH	**SC**
FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve	Silts and Clays Liquid limit less than 50	inorganic	PI>7 and plots on or above “A” line	**CL**
			PI<4 and plots below “A” line	**ML**
		organic	$\frac{\text{Liquid limit} - \text{oven dried}}{\text{Liquid limit} - \text{not dried}} < 0.75$	**OL**
	Silts and Clays Liquid limit 50 or more	inorganic	PI plots on or above “A” line	**CH**
			PI plots below “A” line	**MH**
		organic	$\frac{\text{Liquid limit} - \text{oven dried}}{\text{Liquid limit} - \text{not dried}} < 0.75$	**OH**

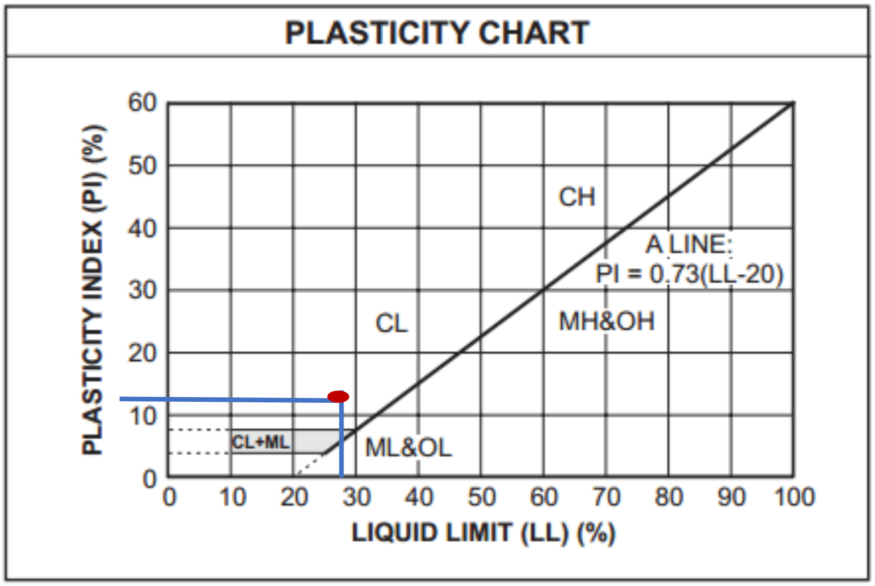

Figure 3.1. Plasticity Chart of USCS (Guyer, 2011).

3.3 Stabilization Additives

3.3.1 Portland Cement

Portland cement is a chemical mixture of different compounds of aluminum, calcium, silicon, iron, and other elements. Portland cement has several different types to satisfy many condition requirements. The American Society for Testing and Materials (ASTM) in C 150 standard provides specifications for eight categories of Portland cement, namely type I, II, III, IA, IIA, IIIA, IV, and V.

In this study, Portland cement type I was used as an additive to stabilize CL soil. Portland cement type I is used for all purposes when there are no specific requirements. This type of Portland cement can be used for different construction projects such as pavement, buildings, sidewalks, and many others.

Figure 3.2. Portland cement type I used in this study.

3.3.2. Hydrated Lime

Hydrated lime, also known as slaked lime or calcium hydroxide, $Ca(OH)_2$, is a dry white powder (shown in Figure 3.3) widely used in different construction projects. Hydrated lime can improve the geotechnical characteristics of the soil. It is produced by mixing calcium oxide (CaO) with water.

$$CaO + H_2O \rightarrow Ca(OH)_2$$

In this study, hydrated lime was mixed with soil as a stabilizing agent. The optimum amount of lime was found to be 2%, depending on the pH and PI wet method. In addition, two more percentages of lime (3% and 5%) were mixed with the soil to determine the effect of the application of different amounts of lime on the properties of the stabilized soil.

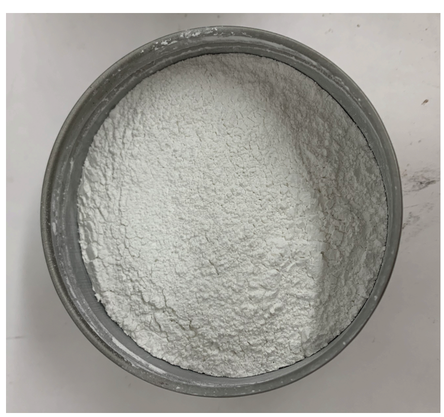

Figure 3.3. Hydrated lime used in this study.

The PI method was used to obtain the optimum lime content percentage to mix with the soil under evaluation. In this method, two parameters, namely the PI and the percentage of soil passing a No. 40 sieve were used to determine the hydrated lime content from the chart shown in Figure 3.4.

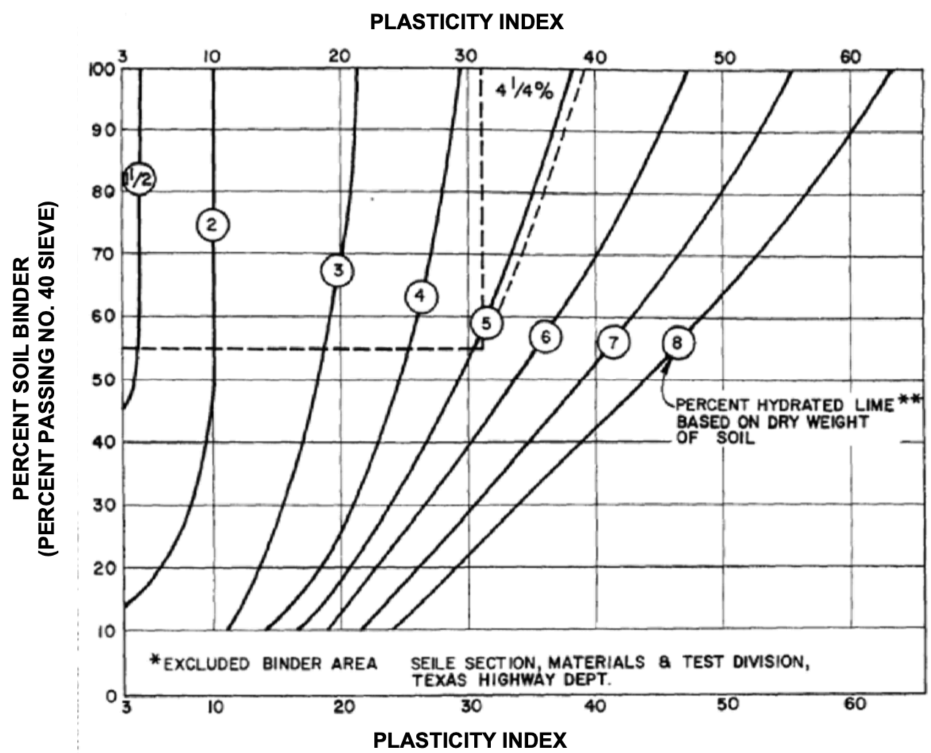

Figure 3.4. Lime content determination chart from PI test (PI wet method) (Guyer, 2011).

3.4. Test Methods

3.4.1. Particle Size Distribution (Sieve Analysis)

Sieve analysis is one of the oldest soil tests and is used to determine the different percentage of particle sizes of the soil. The distribution of soil particles can impact the geotechnical properties of the soil. In addition, the classification of the soil depends on particle size gradation. According to the soil classification system of the Massachusetts Institute of Technology (MIT), soil particle sizes larger than 2 mm are considered as gravel size, particle sizes less than 2 mm to 0.06 mm are considered sand, and particle sizes less than 0.06 are considered silt or clay. The sieve analysis test was conducted as per ASTM D 6913 standard (ASTM, 2021). According to ASTM D 6913, sieve sizes, as shown in Table 3.3 and Figure 3.5, are used.

Table 3.3 Standard sieves set (ASTM, 2021).

Sieve	**Opening Size**	**Sieve**	**Opening Size**
3 in.	75 mm	No. 10	2.00 mm
2 in.	50 mm	No. 20	850 µm
1-1⁄2 in.	37.5 mm	No. 40	425 µm
1 in.	25.0 mm	No. 60	250 µm
3⁄4 in.	19.0 mm	No. 100	150 µm
3⁄8 in.	9.5 mm	No. 140	106 µm
No. 4	4.75 mm	No. 200	75 µm

Figure 3.5 Sieves set.

3.4.2. Atterberg Limits

In 1911, Albert Atterberg defined the moisture states of the soil as liquid state, plastic state, semi-solid state, and solid-state to identify the most important geotechnical characteristics of the soil. In addition, Atterberg defined these limits to delineate between moisture states, called Atterberg limits. Two of these indices, namely the liquid limit (LL) and the plastic limit (PL), are the moisture contents that separate the liquid state from the plastic state and the plastic state from the semi-solid state, respectively. Additionally, Arthur Casagrande developed an idea to determine these limits and invented a device to determine the liquid limit called the Casagrande device.

In this study, the liquid limit and plastic limit tests for the soil were conducted to determine the plasticity index of the soil and optimum lime content. The soil sample was further dried at a low temperature (60°C) before testing and the portion passing a No. 40 sieve (<0.425 mm) was set aside for testing. The liquid limit test was conducted according to the ASTM D 4318 method A (i.e., three points, 25-35, 20-30, and 15-25 drops) by using the Casagrande device shown in Figure 3.6a (ASTM, 2021).

The plastic limit test was conducted according to ASTM D4318 by using a rolling device for the same sample at the liquid limit (Figure 3.6b). Provided papers with the device were attached to the top and bottom plates of the plastic limit rolling device. In the middle of the bottom plate of the rolling device, the soil sample was placed, and then the upper plate was gently moved to roll the sample. In addition, the soil mass was exposed to a downward force and movement by the top plate of the device until the diameter of the soil mass became 3.2 mm and started to break into smaller pieces. Pieces of the rolled sample were collected and dried in an oven to obtain their moisture content.

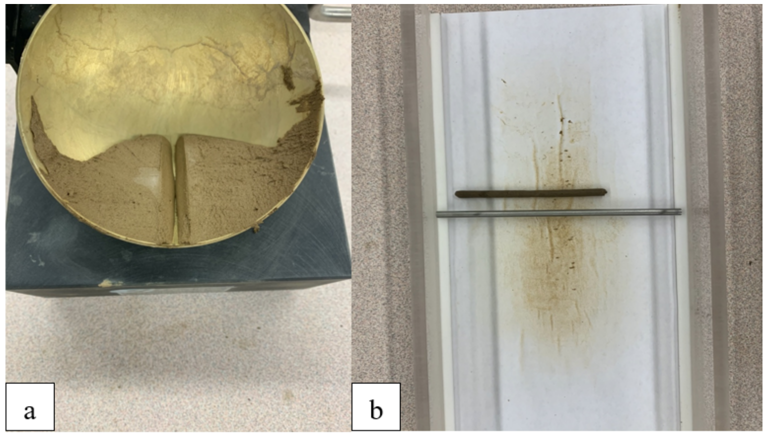

Figure 3.6. .6 Photographic views of (a) liquid limit test; and (b) plastic limit test.

3.4.3. pH Test

The pH test was conducted to obtain the acidity or alkalinity of the soil and its mixture with additives. The pH data were used to determine the optimum amount of additive for soil stabilization. According to ASTM D4972 method A (ASTM, 2021), 25g of the soil with particle size passing a No. 10 sieve (<2 mm) was mixed with 100 ml of distilled water and then left to sit for an hour at 25^{o}C before recording the pH measurements. For this purpose, a pH meter shown in Figure 3.7 was used. This process was conducted separately for natural soil, hydrated lime, cement, soil-lime mixtures (2%, 3%, 4%, 5%, and 6% hydrated lime by soil weight), and soil-cement mixtures (5%, 7%, 9%, and 11% Portland cement by soil weight).

Figure 3.7 A photographic view of the pH meter used in this study.

3.4.4. Compaction (Proctor) test

In 1933, Proctor developed a compaction test to evaluate the compatibility of the soil. Compacting soil can improve its strength and is one of the most important parts of construction. More importantly, this test is used to determine the dry and wet density of the soil at different levels of moisture content and is utilized to find the MDD and OMC from its compaction curves.

Using ASTM D 698 method A (ASTM, 2021), the soil sample was dried at a temperature less than 60° C and passed through a 4.75 mm (No. 4) sieve. In addition, the soil was compacted by a 2.7-kg (5.9 lb.) hammer dropped in a 100-mm (4 inch) diameter mold from a height of 305 mm (12 in), producing 600 kN-m/m^3 (12,400 ft-lb/ft^3) of compaction energy. The soil sample was placed in three layers, and each layer was compacted by applying 25 blows. After removing the collar and trimming the sample, the weight of the compacted soil and the water content were obtained, and the bulk and dry unit weight of the compacted soil sample were calculated. This test was repeated four times at different percentages of added water beginning with 8% based on the original sample mass and repeated with an additional 2% for each subsequent test. Figure 3.8 shows a photographic view of the Proctor mold and the compacted soil sample in it after removing the collar.

Figure 3.8 Photographic view of the Proctor mold and the compacted soil sample.

Equations 3.1 and 3.2 were used to calculate the wet unit weight (γ_b) and dry unit weight (γ_d), respectively.

$$\gamma_b = \frac{T_w}{T_v} \qquad eq. 3.1$$

$$\gamma_d = \frac{\gamma_b}{1 + W} \qquad eq. 3.2$$

where,

T_w = total weight of soil (g)

T_v = total volume (915.7 cm^3)

W = moisture content of the soil

3.4.5. Freeze-thaw cycles (FTs)

To evaluate the effect of frost conditions and thaw on the mechanical properties of the natural soil (shear strength and fracture energy), a number of compacted specimens were subjected to freeze-thaw cycles before testing them. Soil samples including natural soil,

soil-lime mixtures (2%, 3%, and 5%), and soil-cement mixtures (7%, 9%, and 11%) were subjected to three freeze-thaw cycles. First, samples were prepared and compacted at their OMC and MDD as determined in section 3.4.4 and in accordance with the geometries required for testing them. Then, they were wrapped in plastic wrap to preserve their moisture and placed inside the environmental chamber. Each freeze-thaw cycle comprised of keeping samples at -18°C for three hours, followed by subjecting them to 25°C for another three hours. This test was carried out by conditioning the samples in the environmental chamber shown in Figure 3.9.

Figure 3.9 A photographic view of the environmental chamber used for the freeze-thaw test.

3.4.6. Unconfined Compressive Strength (UCS) test

The unconfined compression test is the most convenient, low-cost, and therefore, a common test used to determine the shear strength of a soil sample. In this test, the UCS is calculated as the maximum load per unit area, with the shear stress calculated as half of the compressive stress (σ_c). According to ASTM D2166, the samples for the USC test must be cylindrical and have dimensions specified by the standard and placed on a hydraulic loading device, as shown in Figure 3.10. In addition, the compression test is conducted under atmospheric pressure, and no confining pressure is applied to the specimen. Important test data, including the dimensions of the specimen before testing, peak load, and change in height at peak load, were recorded for all specimens. To calculate the axial strain (ε), equation 3.3 was used. Also, average cross-sectional area (A) and compressive stress (σ_c) were calculated by using equations 3.4 and 3.5.

$$\varepsilon = \frac{\Delta L}{L_0} \times 100 \qquad eq. 3.3$$

$$A = \frac{A_0}{1 - \frac{\varepsilon}{100}} \qquad eq. 3.4$$

$$\sigma_c = \frac{P}{A_0} \qquad eq. 3.5$$

where,

ΔL = change in length of the specimen (mm)

L_0 = initial length of sample (mm)

A_0 = initial cross-sectional area of the specimen (mm^2)

P = peak load (kN)

All the above parameters were calculated to determine the shear strength of the soil, as demonstrated in equation 3.6.

$$s_u = \frac{\sigma_c}{2} \qquad eq. 3.6$$

In this study, the volume of the soil sample was 62.4 cm^3 (1/454 ft^3) for three specimens of natural soil, cement-soil with 7%, 9%, and 11% of cement and lime-soil with 2%, 3%, and 5% of lime. Furthermore, this test was conducted again for the same samples, but this time affected by freeze-thaw cycles.

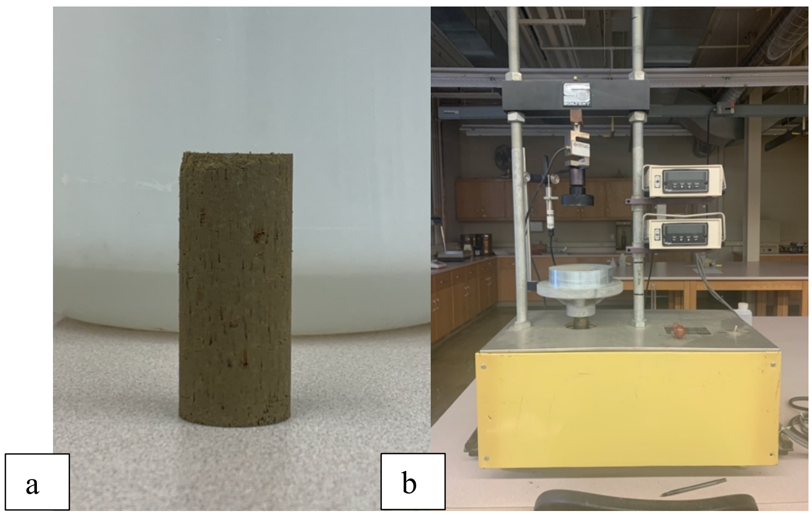

Figure 3.10 Photographic views of (a) UCS soil sample; (b) UCS test loading frame.

3.4.7. Semicircular Bend (SCB) Test

While the cementitious stabilization of soil is known to improve its compressive and tensile strength and modulus, it can also result in embrittlement of the stabilized layer (Nazari et al., 2017, 2019). When exposed to repetitive traffic-induced flexure, embrittled subgrade soil undergoes tensile stresses and becomes prone to cracking (Zhang et al. 2010). The crack initiation under tensile stress and strain at the bottom of stabilized subgrade will eventually propagate into the top layers, resulting in the emergence of reflective cracks at the wearing course of the pavement structure (Nazari et al., 2017).

Therefore, studying the cracking resistance of stabilized subgrade soil is essential (Nazari et al., 2019). While the resistance of the stabilized subgrade to cracking has been studied in the past using a four-point flexural fatigue beam test, difficulties associated with sample preparation, repeatability of the test results, and the need for highly trained laboratory staff have limited its use to research.

The semicircular bend (SCB) test is widely used in different studies to determine the resistance of asphalt mixes to cracking by application of the fracture mechanics principles (e.g., Ghabchi and Acharya, 2021; Ghabchi and Castro, 2021a,b; Ghabchi et al., 2021). In an SCB method, namely Illinois Semicircular Bend (IL-SCB), suggested by Al-Qadi et al. (2015), fundamental fracture characteristics and fracture process are described by a parameter, namely Flexibility Index (FI). The FI parameter is calculated by conducting a 3-point loading test on a notched semicircular geometry (Figure 3.11).

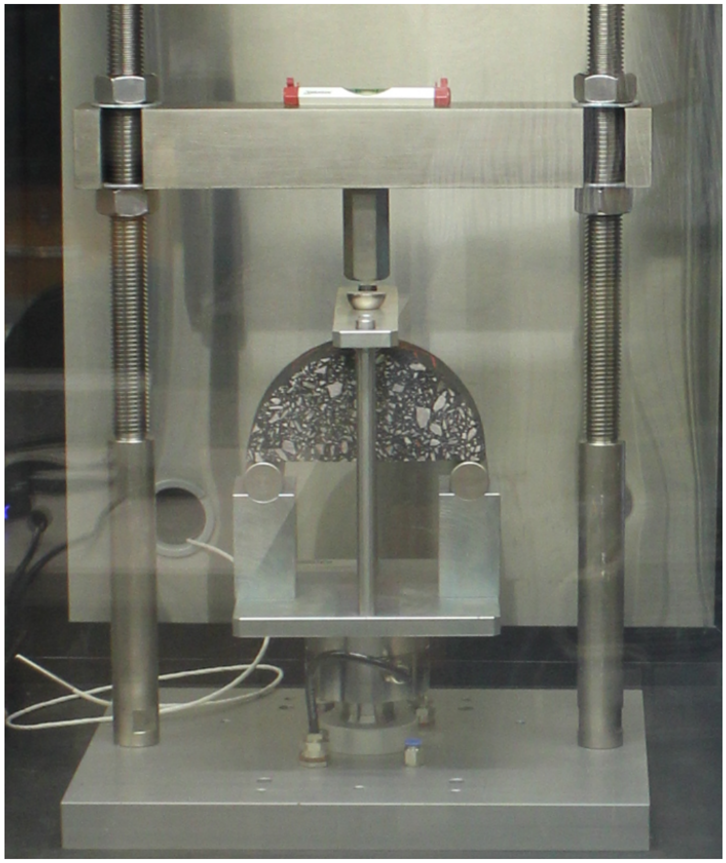

Figure 3.11 A photographic view of the SCB test being conducted on an asphalt sample.

The FI parameter captures the mechanism responsible for the change in the load-displacement curve, mainly depending on the fracture process zone (Al-Qadi et al., 2015). Initiation, formation, and propagation of the microcracks and voids occur in the fracture process zone. According to Al-Qadi et al. (2015), a load-displacement curve after conducting an IL-SCB test (Figure 3.12) can be used to represent the brittleness of the material. As the curve becomes wider, the fracture energy increases, and higher flexibility is expected. According to Al-Qadi et al. (2015), the crack propagation speed increases with the brittleness of the material.

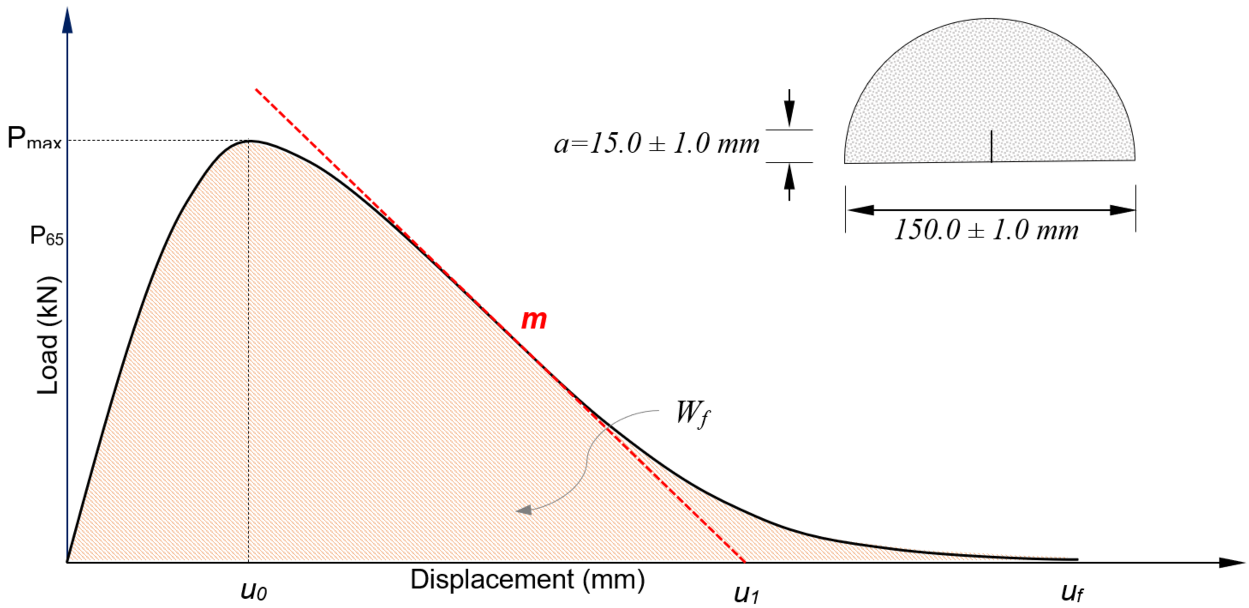

Figure 3.12 A typical load-displacement curve and the IL-SCB parameters (after Al-Qadi et al., 2015).

The parameters shown in Figure 3.12 are described as follows.

P_{max} = peak load (kN)

u = load-line displacement (mm)

u_0 = displacement at peak load (mm)

u_1 = critical displacement defined as the intersection of the tangential post-peak slope with the displacement axis.

u_f = displacement at the 0.1 kN cut-off load

m = post-peak slope tangent to the load-displacement curve at the inflection point (kN/mm)

W_f = work of fracture determined by calculating the area under the load-displacement curve (J)

Additionally, the fracture energy (G_f) is calculated from equations 3.7 and 3.8 (Al-Qadi et al., 2015).

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6 \qquad eq. 3.7$$

$$Area_{lig} = ligament\ length\ \times t \qquad eq. 3.8$$

where,

G_f = fracture energy (J/m^2)

$Area_{lig}$ = ligament area (mm^2)

t = specimen thickness (mm)

Finally, the flexibility index (FI) is calculated from equation 3.9.

$$FI = \frac{G_f}{|m|} \times A \qquad eq. 3.9$$

where,

A = unit conversion and scaling factor (0.01)

In the absence of a standardized method for evaluation of the stabilized soil's susceptibility to cracking, the IL-SCB in accordance with AASHTO T 393 (AASHTO, 2021) was adopted in this study. As a result, the FI value of the natural and stabilized soil before and after F-T cycles was determined. For this purpose, natural and stabilized soil samples in a 150-mm (6 inches) mold were compacted to their OMC and MDD values. Then, using a saw, they were cut to obtain specimens having SCB geometry and with a thickness of 50 ± 1 mm. Finally, notches were cut on SCB samples along their axis of symmetry to a depth of 15± 1 mm, and a width of 1.5 ± 0.1 mm (Figure 3.13).

Figure 3.13 A photographic view of an SCB sample of stabilized soil after cutting.

The SCB tests were conducted on the specimens at a temperature of 25ºC inside the environmental chamber of an IPC asphalt mix performance tester. The specimen was placed on the three-point jig's support with a span of 120 mm and loaded at its midspan at a 50 mm/min rate until failure (Figure 3.14). Load-displacement data was automatically collected using a data acquisition system, recorded on a computer, and used to calculate the FI values.

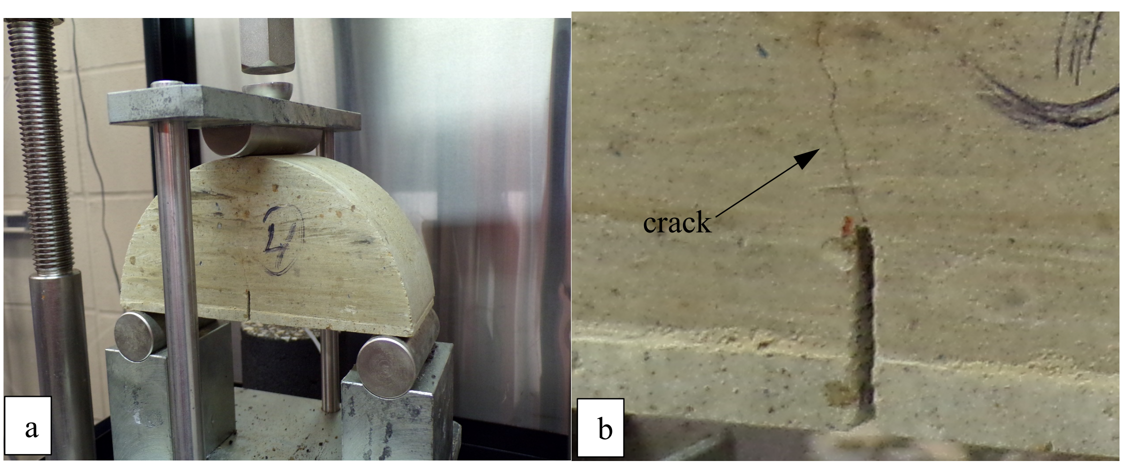

Figure 3.14 Photographic vie of (a) SCB sample in the loading frame; and (b) initiation of a visible crack in the notched sample during testing.

3.5 Summary of materials and methodology

This study used Portland cement and hydrated lime as stabilizer agents for treating a plastic clayey soil collected form South Dakota. To evaluate the effectiveness of Portland cement and hydrated lime in improving different mechanical properties of the subgrade soil, several laboratory tests were employed to evaluate untreated and treated soil. More specifically, sieve analysis, Atterberg limits, pH test, freeze-thaw cycles, unconfined compressive strength test (UCS), and Semicircular Bend (SCB) tests were conducted.

4. RESULTS AND DISCUSSION

4.1. Introduction

This chapter provides a summary of the results of the tests conducted on soil samples. It consists of the outcomes of the particle size analysis, Atterberg limits, Proctor test, pH tests, UCS tests, and SCB tests. In addition, the influence of freeze-thaw cycles on the UCS, the FI was presented in this chapter.

4.2. Particle size distribution

Table 4.1 and Figure 4.1 and summarize the results of the particle size analysis for the collected natural soil. The results of this test were also used to determine the classification of the soil based on the Unified Soil Classification System (USCS). From Table 4.1, due to the high amount (68%) of particles passing the No. 200 sieve (<0.075 mm), the material is classified as clay soil or silt.

Table 4.1 Particle-size distribution of the soil.

ASTM Sieve No.	Sieve Size (mm)	Percent Passing (%)
4	4.75	100
10	2.00	98
30	0.60	95
40	0.425	93
50	0.300	88
100	0.150	79
200	0.075	68
pan	-	0

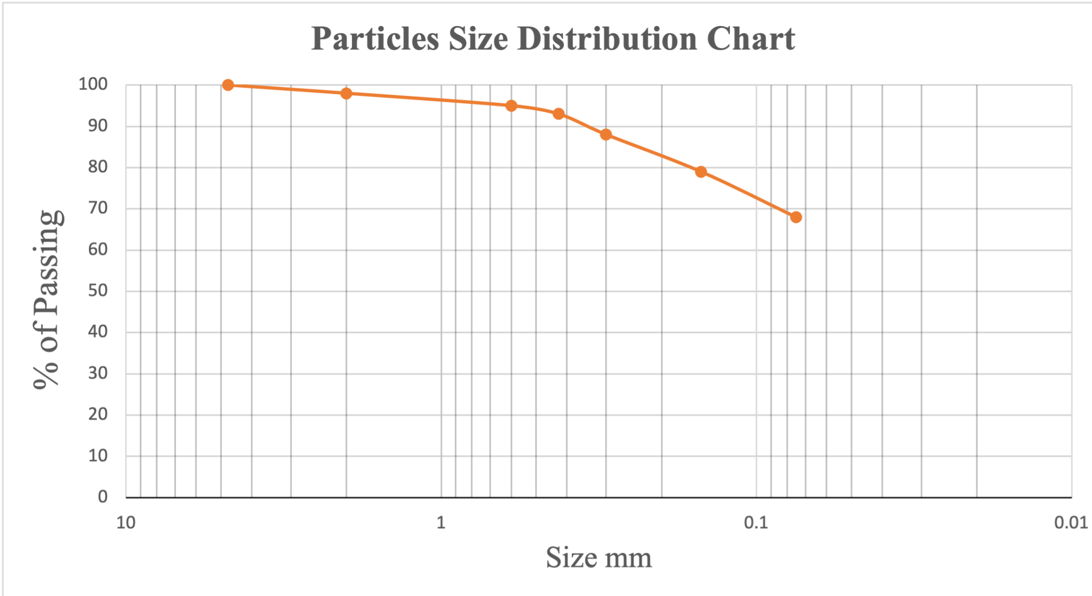

Figure 4.1 Particle size distribution of the soil.

4.3. Atterberg limits test

This test was conducted to determine the soil plasticity and was used to classify the soil according to USCS. Table 4.2 and Table 4.3 provide details of LL and PL tests, respectively. Figure 4.2 indicates the liquid limit of the natural CL soil, which was calculated by drawing a vertical line (blue) from blow 25 until it intersected with the curve (red), then by a horizontal line (also blue) to find the liquid limit of the soil. The red curve shown in Figure 4.2 was drawn according to the percentage of water content and the number of blows (N) for each sample according to the data presented in table 4.2. From Figure 4.2, the liquid limit of the soil was found to be 36.3%.

Table 4.3 shows the results of the plastic limit test. The plastic limit of the soil was the average water content of three soil samples and was found to be 23.1%.

$$PL = \frac{wc1 + wc2 + wc3}{3} = \frac{23.53 + 22.9 + 23.01}{3} = 23.1\%$$

Where,

wc 1, 2 and 3 are the water content of samples 1, 2, and 3.

The plasticity index (PI) of the soil is the difference between the liquid limit (LL) and plastic limit (PL) and was found to be 13.2%.

$$PI = 36.3 - 23.1 = 13.2\%$$

Table: 4.2 Results of the liquid limit test.

Sample Number	1	2	3
Container Weight (g)	20.17	20.13	20.09
Container and Moist Soil Weight (g)	31.37	29.37	31.82
Container and Dry Soil Weight (g)	28.27	26.96	28.86
Dry Soil Weight (g)	8.1	6.83	8.77
Water Weight (g)	3.1	2.41	2.96
Water Content (%)	38.27	35.28	33.75
Number of Recorded Blows (N)	19	29	34

Table 4.3 Results of the plastic limit test.

Sample Number	1	2	3
Container Weight (g)	19.99	20.06	19.98
Container and Moist Soil Weight (g)	21.04	21.67	21.53
Container and Dry Soil Weight (g)	20.84	21.37	21.24
Dry Soil Weight (g)	0.85	1.31	1.26
Water Weight (g)	0.2	0.3	0.29
Water Content (%)	23.53	22.9	23.01
Average Water Content (%)		23.14	

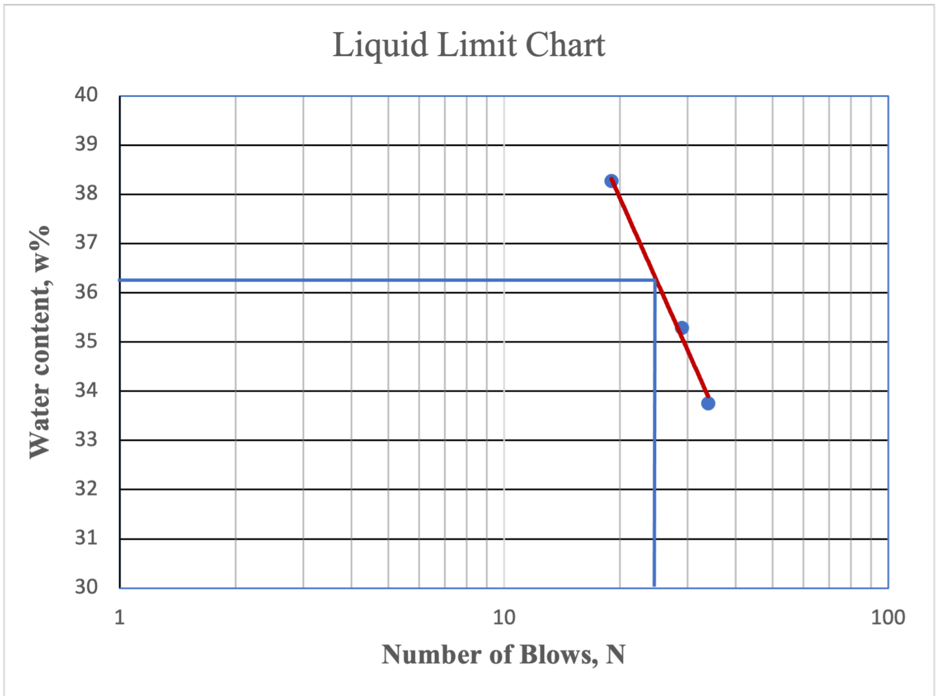

Figure 4.2 The relationship between water content and number of blows.

4.4. Soil Classification

According to the results from particle size distribution and the Atterberg limits test, the soil in this study was classified by using the USCS system (Table 4.4). The USCS classification considers soil as fine-grained if 50% of the soil passes sieve No. 200. Due to the value of PI (13.2%) being more than 7, the soil is CL soil, as shown in Figure 4.3.

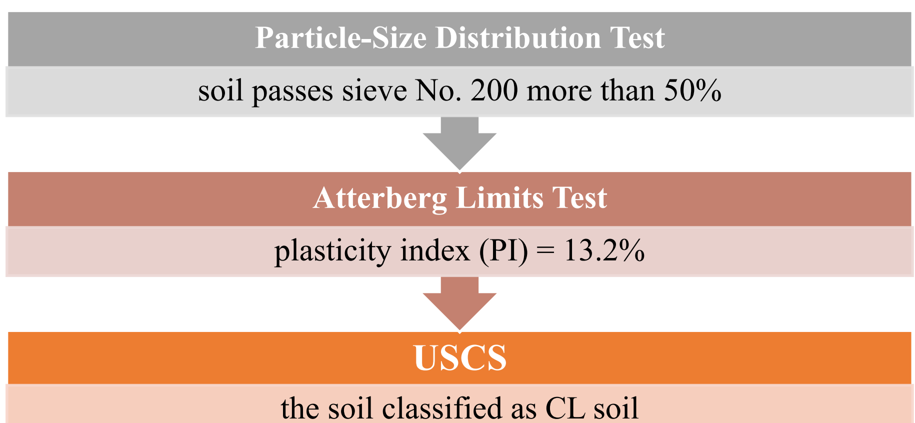

Figure 4.3 Soil classification process.

Table 4.4: Fine-grained soils classification of USCS (ASTM,2021).

<table>
<tr><td colspan="4">Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests.</td><td>Group Symbol</td><td>Group Name</td></tr>
<tr><td rowspan="8">FINE-GRAINED SOILS 50 % or more passes the No. 200 sieve</td><td rowspan="4">Silts and Clays Liquid limit less than 50</td><td rowspan="2">inorganic</td><td>PI>7 and plots on or above “A” line</td><td>CL</td><td>Lean clay</td></tr>
<tr><td>PI<4 and plots below “A” line</td><td>ML</td><td>Silt</td></tr>
<tr><td rowspan="2">organic</td><td rowspan="2">$\frac{\text{Liquid limit} - \text{oven dried}}{\text{Liquid limit} - \text{not dried}} < 0.75$</td><td rowspan="2">OL</td><td>Organic clay</td></tr>
<tr><td>Organic silt</td></tr>
<tr><td rowspan="4">Silts and Clays Liquid limit 50 or more</td><td rowspan="2">inorganic</td><td>PI plots on or above “A” line</td><td>CH</td><td>Fat clay</td></tr>
<tr><td>PI plots below “A” line</td><td>MH</td><td>Elastic silt</td></tr>
<tr><td rowspan="2">organic</td><td rowspan="2">$\frac{\text{Liquid limit} - \text{oven dried}}{\text{Liquid limit} - \text{not dried}} < 0.75$</td><td rowspan="2">OH</td><td>Organic clay</td></tr>
<tr><td>Organic silt</td></tr>
</table>

4.4. pH test

The pH test was conducted to determine the minimum hydrated lime content for soil stabilization in this study. The pH test results for natural soil and soil with different additive content are shown in Table 4.5. It was observed that adding 2% hydrated lime to the CL soil under the study resulted in a change in its pH value from 8.24 for the natural soil to 12.4. In other words, the alkalinity of the soil increased by 50%. Due to the observed pH value, the minimum hydrated lime required to improve the CL soil’s physical properties is 2%. Similarly, it was observed that the addition of 5% Portland cement to natural soil increased its pH from 8.24 to 11.94, a 45% increase. The use of additives beyond 2% lime or 5% Portland cement was found to slightly increase the pH, and in all cases, it almost stayed constant. The results in Table 4.5 indicated that the pH values slightly increase with an increase in hydrated lime or cement content, as shown in Figure 4.4 and Figure 4.5. For example, 100% pure hydrated lime and 100% pure

Portland cement resulted in pH values of 12.53 and 12.25, respectively, negligibly different from those containing less amount of additives. Furthermore, a comparison between the pH values recorded for the soil stabilized by using hydrated lime and Portland cement reveals that the hydrated lime was more effective in raising the pH of the soil than Portland cement. For example, the use of 2% lime and 11% Portland cement was equally effective in raising the pH of the soil.

Table 4.5 Measured pH values as a result of using different types and amounts of additives.

Material	Amount of Hydrated Lime (%)	Amount of Portland Cement (%)	pH
Natural Soil	-	-	8.24
Lime-Stabilized Soil	2	-	12.42
	3	-	12.43
	4	-	12.44
	5	-	12.46
	6	-	12.48
Hydrated Lime	100	-	12.53
Cement-Stabilized Soil	-	5	11.94
	-	7	12.03
	-	9	12.08
	-	11	12.14
Portland Cement	-	100	12.25

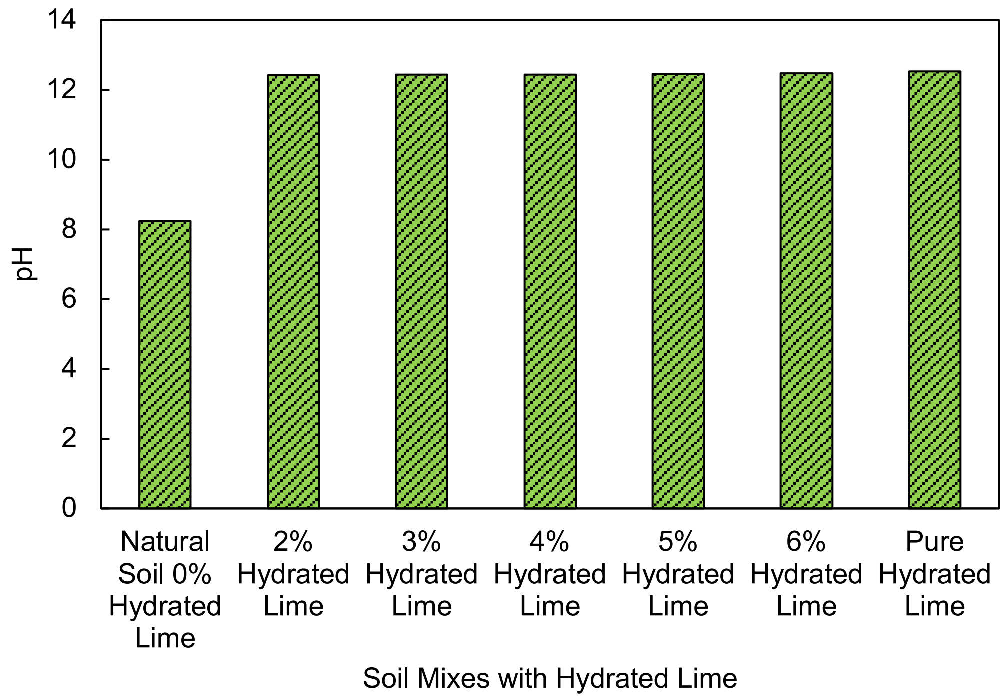

Figure 4.4 Variation of pH with hydrated lime content.

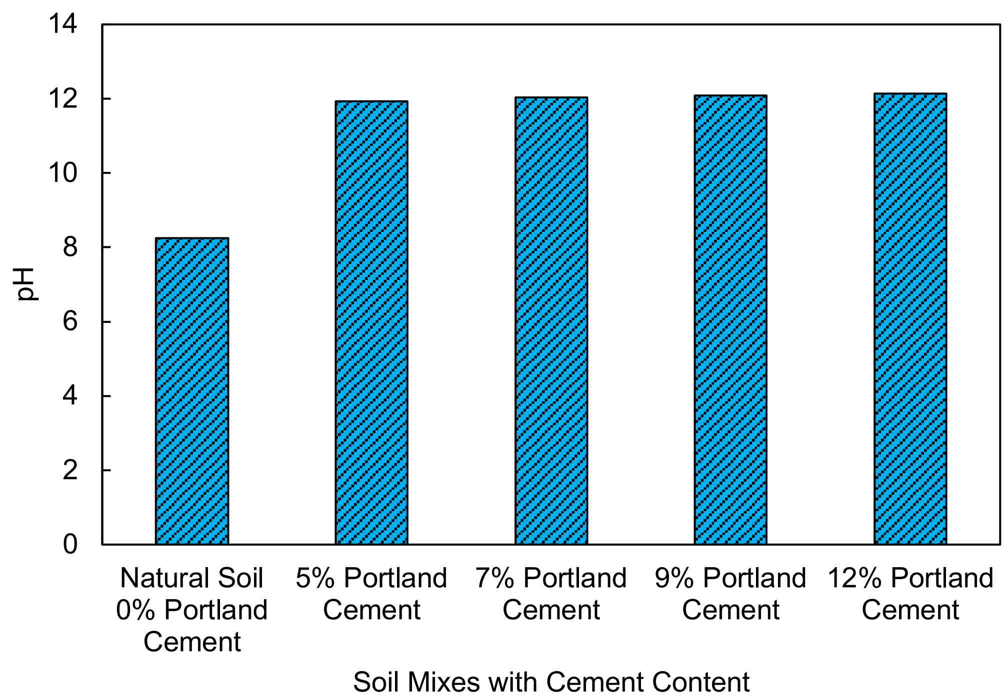

Figure 4.5 Variation of pH with Portland cement content.

4.5. Proctor test

The moisture-density relationship (Proctor) curves are shown in Figure 4.5 for natural soil. Also, the Proctor curves are shown for the soil stabilized by 2% lime and 9% Portland cement. The values of optimum moisture content (OMC) and maximum dry unit weight (MDD) are also shown in Table 4.6. The OMC and MDD of natural soil are 15% and 1.59 g/cm^3, respectively. Using both additives (hydrated lime and Portland cement) for CL soil increased the OMC and MDD. In the case of using 9% Portland cement as a stabilizer for CL soil, the OMC and MDD increased by 20% and 9%, respectively, compared to natural CL soil. From Table 4.6, the OMC and MDD of the soil stabilized by using 9% Portland cement were found to be 18% and 1.72 g/cm^3, respectively. When using 2% lime with CL soil, the OMC values increased about 15% compared to natural CL soil (from 15% to 17.2%). Also, the maximum dry unit weight of soil-lime increased from 1.59 g/cm^3 to 1.71 g/cm^3.

The optimum moisture content increased with an increase in additive content, while the maximum dry unit weight decreased when a high percentage of lime and cement was added to the soil. In addition, the increase of optimum moisture content in both cases is due to an increase in the need for water for additive reactions, while the decrease in maximum dry unit weight was due to the increase in fine-grain particles in the soil (Carrosserie et al., 2009).

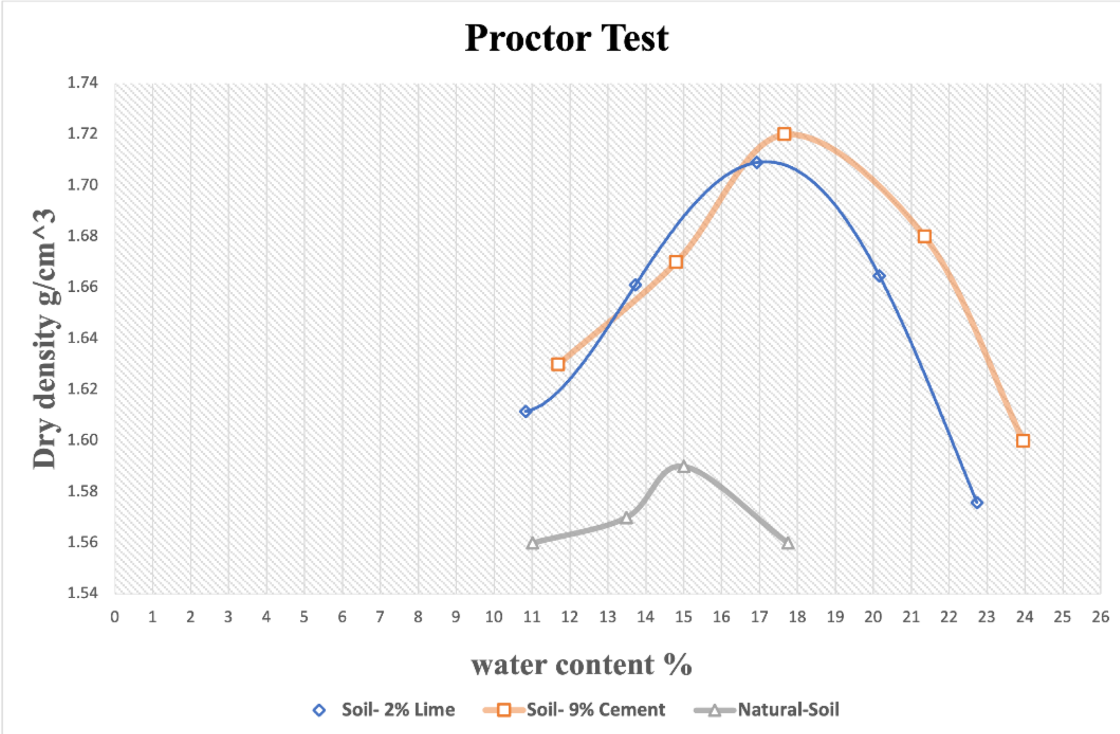

Figure 4.6 Proctor test curves.

Table 4.6 Summary of the Proctor test.

Material	OMC (%)	MDD (g/cm^3)
Natural Soil	15	1.59
Soil - 9% Cement	18	1.72
Soil - 2% Lime	17.2	1.71

4.6. Unconfined Compressive Strength (UCS)

Unconfined compression strength testing was conducted for natural soil and soil mixed with additives and those conditioned by the freeze-thaw cycles to evaluate the effect of additives and environment on the undrained shear strength (S_u) of the soil. The preparation process of specimens began with compacted soil using a Harvard miniature compaction apparatus and included 14 days of curing. Tests were conducted at least on three replicates of each mix. Details of the sample preparation and testing are provided in section 3.4.6. In order to calculate the shear strength (S_u) of the samples, the compressive strength (σ_c) measured for each specimen was divided by 2.

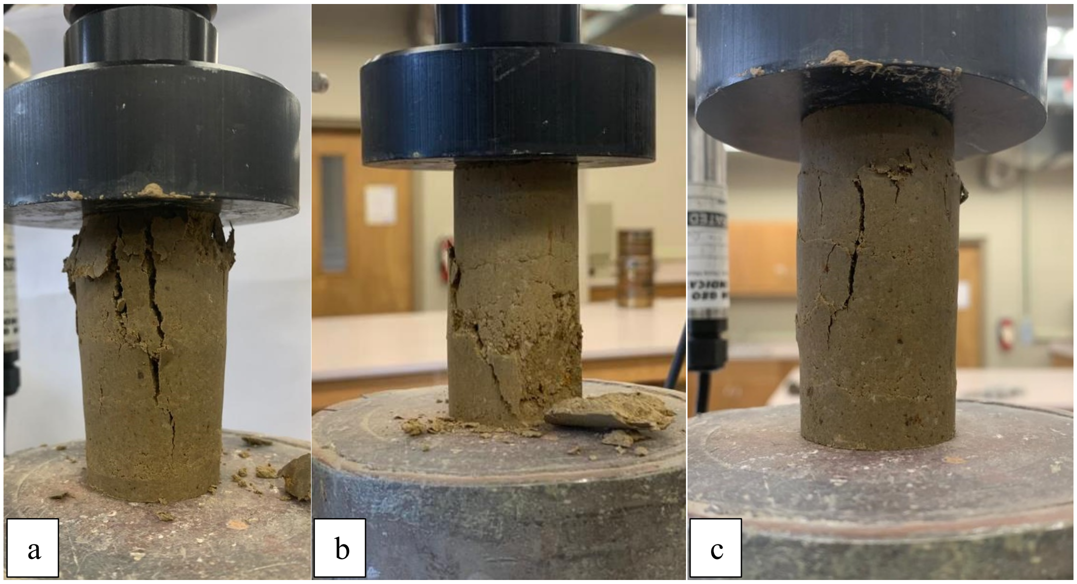

Figure 4.7 Photographic views of UCS tests being conducted on (a) natural soil; (b) lime-stabilized soil; and (c) cement-stabilized soil.

4.6.1 Effect of Additive Type and Amount

A summary of the S_u values recorded by conducting the UCS tests on all soil samples, including natural soil without any additive and that mixed with 2%, 3%, and 5% hydrated lime and 7%, 9%, and 11% Portland cement is presented in Table 4.7, Figure 4.8, and Figure 4.9. The results reported in Table 4.7 are the average of the shear strength values measured for each case.

From Figure 4.8, it was observed that the shear strength of the natural soil (122 kPa) increased by 394% as a result of mixing it with 2% hydrated lime (603 kPa). It is known that the addition of lime to plastic soil (CL in this case) results in the exchange of ions (cation exchange) between lime and clayey soil, manifested as a reduction in soil plasticity index. This fact was observed in the sample preparation stage. A reduced plasticity index is favorable for construction, letting heavy equipment work on the subgrade layer without sinking in. In addition to constructability, when hydrated lime and water are added to pozzolanic compounds (siliceous and aluminous materials) present in clayey soil, calcium hydroxide present in the hydrated lime reacts with the pozzolans (pozzolanic reaction) and form cementitious compounds. The formation of cementitious compounds in the lime-stabilized soil results in an increase in its shear strength as observed in Figure 4.8. Also, from Figure 4.8, it is evident that an increase in hydrated lime content resulted in further increases in the shear strength of the stabilized soil. For example, the addition of 3% and 5% hydrated lime to the soil resulted in shear strength values of 734 kPa and 1231 kPa, respectively, 502% and 909% higher than that of the natural soil containing no additive. A linear regression (S_u = 218.3×lime content (%) + 126.7; R^2=0.99) developed for shear strength (kPa) and lime content (%) shows that, on average, the addition of every 1% hydrated lime resulted in 218.3 kPa (104%) increase in the shear strength of the natural soil. In addition to the formation of the cementitious compounds as a result of lime-stabilization of the soil which lead to a higher shear strength, another mechanism for improved strength is a result of a reduction in porosity, which increases the soil and additive connection and overall density (Greaves, 1996).

Table 4.7 Summary of the UCS tests conducted on samples (no F-T cycles).

Material	Amount of Hydrated Lime (%)	Amount of Portland Cement (%)	Compressive Strength σ_c (kPa)	Shear Strength $s_u = \frac{\sigma_c}{2}$ (kPa)	Standard Deviation (kPa)
Natural Soil	-	-	243	122	1.82
Lime-Stabilized Soil	2	-	1205	603	66.7
	3	-	1468	734	37.3
	5	-	2461	1231	46.7
Cement-Stabilized Soil	-	7	2908	1454	218.6
	-	9	3286	1643	131.5
	-	11	3893	1947	222.5

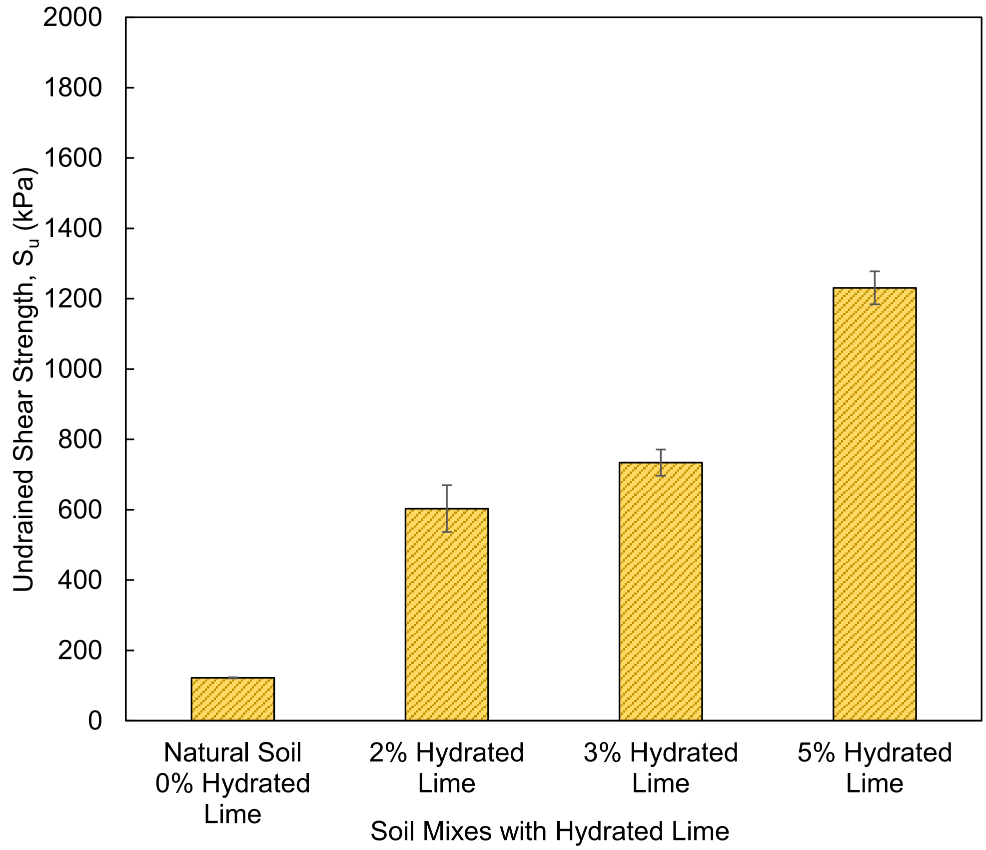

Figure 4.8 Variations of the shear strength with the additive amount for lime-stabilized soil.

From Figure 4.9, it was observed that the shear strength of the natural soil (122 kPa) increased by 11 folds (1092%) as a result of mixing it with 7% Portland cement (S_u = 1454 kPa). The addition of the Portland cement, since it contains lime in its composition, results in the cation exchange between lime from cement and clayey soil, and leads to a reduction in soil plasticity index, as observed in the sample preparation stage. A reduced plasticity index improves constructability on the highly plastic subgrade soil. In addition, Portland cement contains compounds, namely tricalcium silicate ($3CaO \cdot SiO_2$), dicalcium silicate ($2CaO \cdot SiO_2$), tricalcium aluminate ($3CaO \cdot Al_2O_3$), and a tetra-calcium aluminoferrite ($4CaO \cdot Al_2O_3Fe_2O_3$) which can directly participate in cementation, and therefore, when the water is added, form cementitious compounds and significantly improve the strength properties. Since the Portland cement is activated with water and contains aluminates and silicates, it is expected to be effective in improving the shear strength of both clayey and non-clayey soil samples when it was compared with hydrated lime. Furthermore, from Figure 4.9, it is evident that an increase in Portland cement content resulted in further increases in the shear strength of the stabilized soil. For example, the addition of 9% and 11% Portland cement to the soil resulted in shear strength values of 1643 kPa and 1947 kPa, respectively, 1247% and 1496% higher than that of the natural soil containing no additive. A linear regression (S_u = 167.4×cement content (%) + 161.3; R^2=0.99) developed for shear strength (kPa) and Portland cement content (%) shows that, on average, the addition of every 1% Portland cement resulted in 167.4 kPa (137%) increase in the shear strength of the natural soil. This observation reveals that hydrated lime was more effective in improving the shear strength of the investigated CL soil sample (218.3 kPa increase in shear strength per 1% hydrated lime) when it was compared with Portland cement (167.4 kPa increase in shear strength per 1% Portland cement). This was attributed to the fact that the CL soil contained high amounts of pozzolanic materials in its composition and formation of the cementicious compounds in abundance of the pozzolans is controlled directly by the lime content. However, contains lime tricalcium silicate ($3CaO \cdot SiO_2$), dicalcium silicate ($2CaO \cdot SiO_2$), tricalcium aluminate ($3CaO \cdot Al_2O_3$), and a tetra-calcium aluminoferrite ($4CaO \cdot Al_2O_3Fe_2O_3$) and contains less lime.

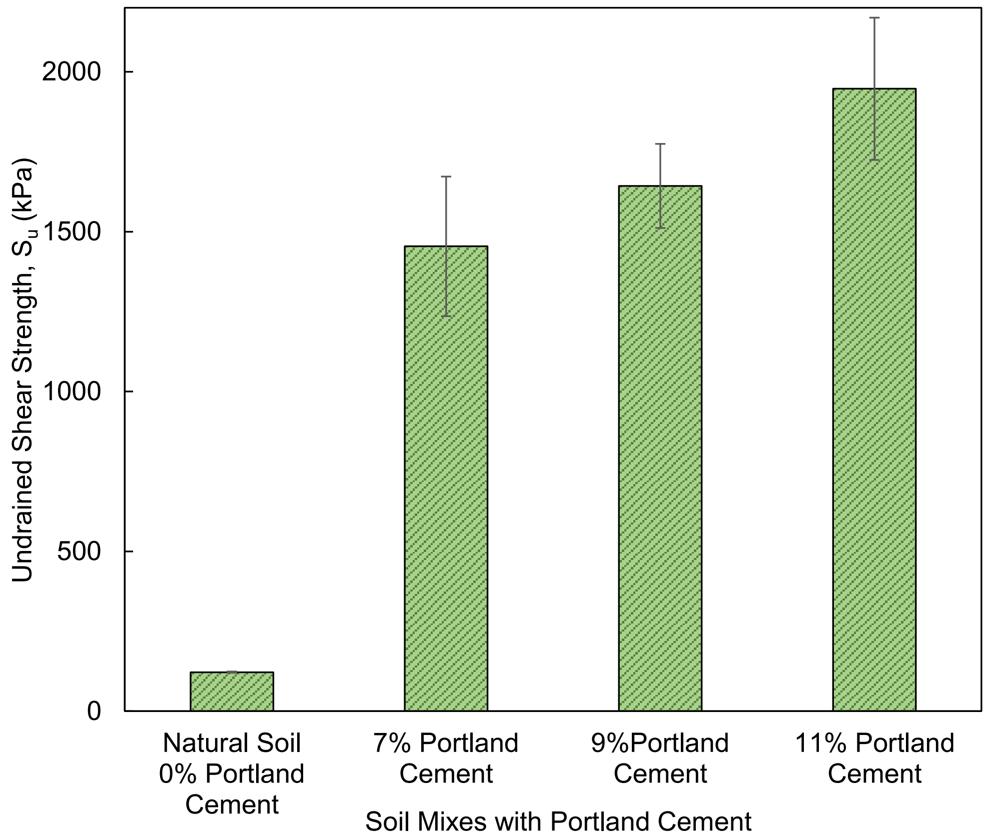

Figure 4.9 Variations of the shear strength with the additive amount for cement-stabilized soil.

4.6.2 Effect of Freeze-Thaw Cycles

South Dakota's climatic condition warrants several freeze-thaw (F-T) cycles during winter storms. Given the soil collection site's location, the UCS samples prepared using natural soil, lime-stabilized soil, and cement-stabilized soil were subjected to freeze-thaw cycles as described in section 3.4.5 and tested. Testing the samples subjected to F-T cycles determined the effectiveness of each stabilizing agent used with the collected CL soil in improving its resistance to frost and environmental elements.

A summary of the S_u values recorded by conducting the UCS tests on all soil samples subjected to F-T cycles, including natural soil without any additive and that mixed with 2%, 3%, and 5% hydrated lime and 7%, 9%, and 11% Portland cement is presented in

Table 4.7, Figure 4.10, and Figure 4.11. The results reported in Table 4.8, and Figures 4.10 and 4.11 are the average of the shear strength values measured for each case. Additionally, the shear strength ratios of samples subjected to F-T cycles to those of the non-conditioned samples ($S_{u\text{-}Wet}/S_{u\text{-}Dry}$) are shown for lime-stabilized and cement stabilized soils in Figures 4.10 and 4.11, respectively.

From Figure 4.10, it was observed that the shear strength of the natural soil (122 kPa) was reduced by 21% as a result of subjecting it to F-T cycles, a strength ratio of 0.79. Additionally, from Figure 4.10 it was found that subjecting the hydrated lime-stabilized samples to F-T cycles resulted in a reduction in their shear strengths compared to their non-F-T conditioned counterparts. For example, subjecting the soil samples stabilized by 2%, 3%, and 5% hydrated lime resulted in a 25%, 26%, and 29% reduction in their S_u values compared to those tested without being subjected to F-T cycles. On the other hand, From Figure 4.10, it was observed that the shear strength of the natural soil subjected to F-T cycles (96 kPa) increased by 374% as a result of mixing it with 2% hydrated lime (455 kPa). Also, from Figure 4.8, it is evident that an increase in hydrated lime content resulted in further increases in the shear strength of the stabilized soil subjected to F-T cycles compared to its non-stabilized counterpart. For example, the addition of 3% and 5% hydrated lime to the soil after carrying out F-T cycles resulted in shear strength values of 545 kPa and 873 kPa, respectively, 468% and 809% higher than that of the natural soil containing no additive and subjected to F-T cycles. A linear regression (S_u = 152.9×lime content (%) + 110; R^2=0.99) developed for shear strength (kPa) and lime content (%) shows that, on average, the addition of every 1% hydrated lime in the samples subjec5ted to F-T cycles resulted in 152.9 kPa (159%) increase in the shear strength of the natural soil conditioned by F-T cycles.

Table 4.8 Summary of the UCS tests conducted on samples subjected to F-T cycles.

Material	Amount of Hydrated Lime (%)	Amount of Portland Cement (%)	Compressive Strength σ_c (kPa)	Shear Strength $s_u = \frac{\sigma_c}{2}$ (kPa)	Standard Deviation (kPa)
Natural Soil	-	-	192	96	5.6
Lime-Stabilized Soil	2	-	909	455	17.2
	3	-	1091	545	28.1
	5	-	1746	873	24.1
Cement-Stabilized Soil	-	7	1959	980	19.4
	-	9	2278	1139	55.1
	-	11	2787	1393	39.0

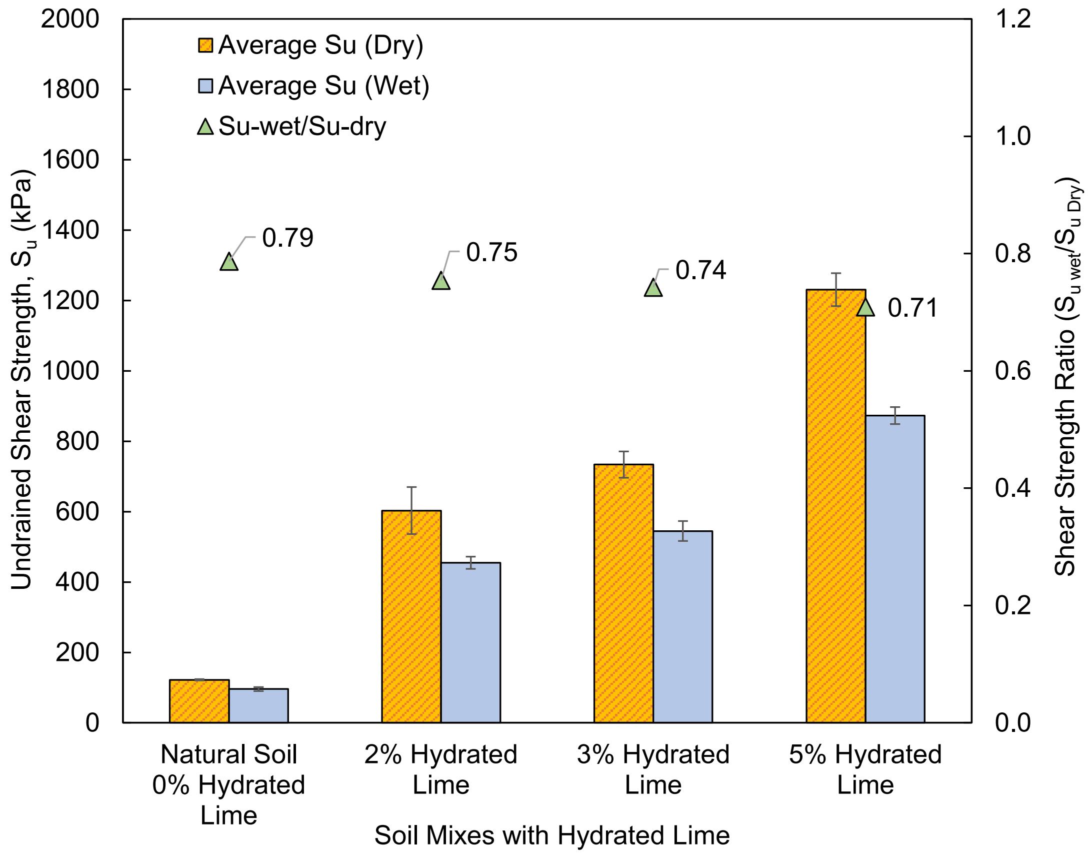

Figure 4.10 Effect of freeze-thaw cycles on shear strength of hydrated lime-stabilized soil.

In other words, while the shear strength of the natural soil subjected to F-T cycles increased with an increase in lime content, it became more sensitive to F-T cycles with lime content as shown by the strength ratio values in Figure 4.10.

From Figure 4.11, it was observed that the shear strength of the natural soil (122 kPa) was reduced by 21% as a result of subjecting it to F-T cycles, a strength ratio of 0.79. Additionally, from Figure 4.11 it was found that subjecting the Portland cement-stabilized samples to F-T cycles resulted in a reduction in their shear strengths compared to their non-F-T conditioned counterparts. For example, subjecting the soil samples stabilized by 7%, 9%, and 11% Portland cement resulted in a 33%, 31%, and 38% reduction in their S_u values compared to those tested without being subjected to F-T cycles. On the other hand, From Figure 4.11, it was observed that the shear strength of the natural soil subjected to F-T cycles (96 kPa) increased by 321% as a result of mixing it with 7% Portland cement after subjecting to F-T cycles (980 kPa). Also, from Figure 4.11, it is evident that an increase in Portland cement content resulted in further increases in the shear strength of the stabilized soil subjected to F-T cycles compared to its non-stabilized counterpart. For example, the addition of 9% and 11% Portland cement to the soil after carrying out F-T cycles resulted in shear strength values of 1139 kPa and 1393 kPa, respectively, 1086% and 1351% higher than that of the natural soil containing no additive and subjected to F-T cycles. A linear regression (S_u = 117.5×cement content (%) + 108.7; R^2=1.00) developed for shear strength (kPa) and lime content (%) shows that, on average, the addition of every 1% Portland cement to the samples subjected to F-T cycles resulted in 117.5 kPa (122%) increase in the shear strength of the natural soil conditioned by F-T cycles. In other words, while the shear strength of the natural soil subjected to F-T cycles increased with an increase in Portland cement content, it became more sensitive to F-T cycles as a result of stabilization with cement, as shown by the strength ratio values in Figure 4.11.

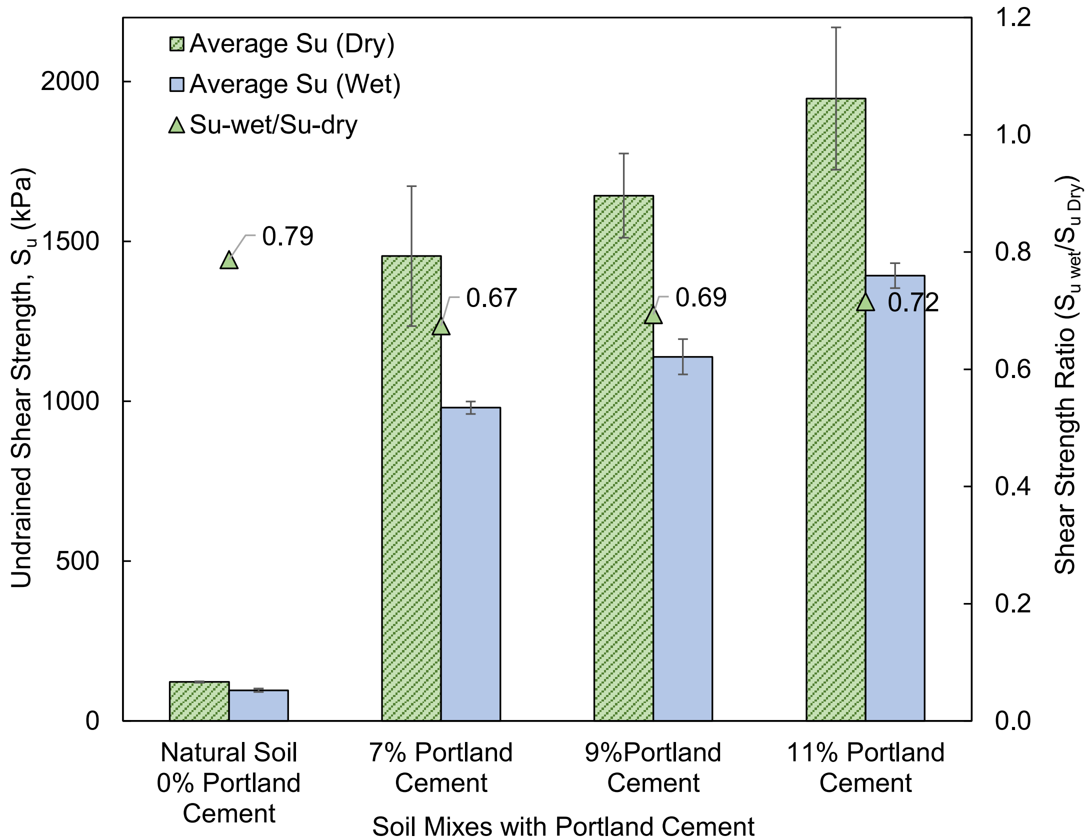

Figure 4.11 Effect of freeze-thaw cycles on shear strength of Portland cement-stabilized soil.

4.7. Semicircular Bend (SCB) Test

Figure 4.12 summarizes the peak loads obtained by testing the SCB samples prepared in the laboratory from natural soil and that stabilized by optimum amounts of hydrated lime and Portland cement, as discussed in section 3.4.7. From Figure 4.12, the peak load recorded for the natural soil tested in dry condition (0.121 kN) increased by 290%, and 878% due to stabilizing it with hydrated lime and Portland cement, respectively. The significance of the peak load at a flexure test is detecting the effect of the tensile stresses developed at the bottom of a stabilized subgrade layer. In other words, the initiation of load-induced cracks in a stabilized subgrade layer is expected to start due to the development of bottom-up tensile cracks. Additionally, from Figure 4.12 it was found that subjecting the soil samples to F-T cycles resulted in a reduction in their recorded peak loads due to decay in their compressive and tensile strengths.

For example, the peak load recorded for natural soil subjected was found to decrease by 7% due to subjecting it to F-T cycles. However, lime-stabilized soil was found to be the most sensitive mix to loss of the peak load (76%) as a result of being subjected to F-T cycles. It is important to note that the peak load of the F-T-conditioned lime-stabilized samples was equal to that of the F-T-conditioned natural soil (0.113 kN). In other words, freeze-thaw cycles have completely neutralized the improvement in the flexural strength after lime stabilization. In contrast, the cement-stabilized soil experienced a 30% loss in its peak load due to the F-T cycles.

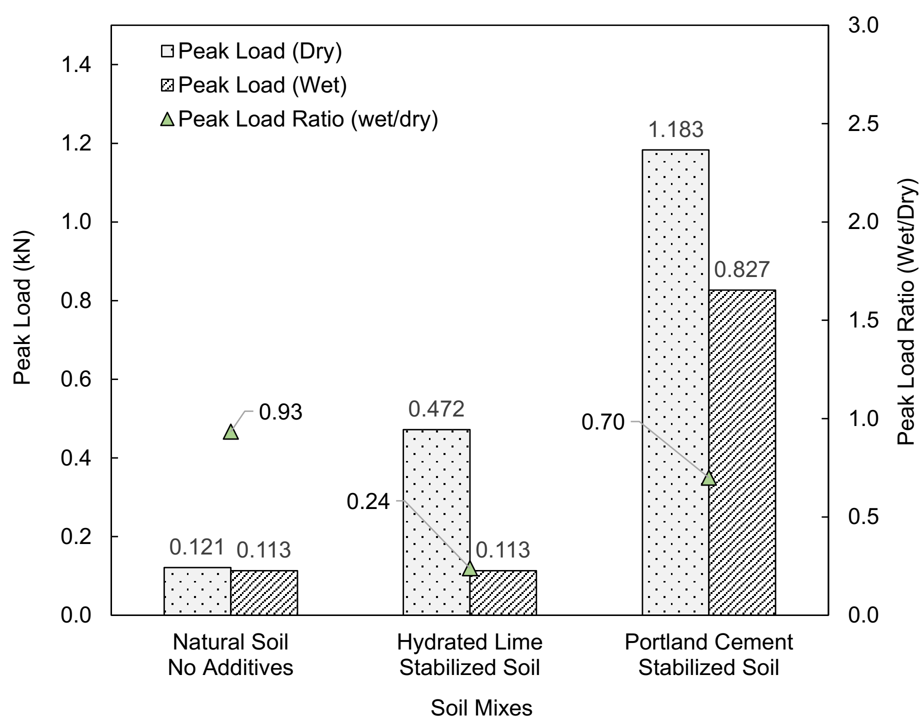

Figure 4.12 Effect of additive type and freeze-thaw cycles on peak load in SCB test.

Figure 4.13 summarizes the secant stiffness modulus values of the tested SCB samples. From Figure 4.13 it is evident that the secant modulus of the natural soil tested in dry condition (0.9 kN/mm) increased by 80% and 377% as a result of stabilizing it with hydrated lime and Portland cement, respectively. In other words, the pre-peak behavior of the natural soil shifted from soft to moderate and stiff due to stabilizing it with lime and cement, respectively. A reduction in flexural deformation under the same load indicates a higher load-bearing capacity before the initiation of the cracks. Additionally, from Figure 4.13, it was observed that subjecting the soil samples to F-T cycles resulted in a reduction in their moduli. For example, the secant modulus recorded for natural soil was found to undergo a 47% reduction due to subjecting it to F-T cycles. In a similar way, lime-stabilized soil was found to experience a 43% reduction in its secant modulus as a result of being subjected to F-T cycles. One can conclude that the F-T cycles can form microcracks inside the material, resulting in a ductile behavior.

In contrast, the cement-stabilized soil experienced only a 20% reduction in its secant stiffness modulus due to the F-T cycles.

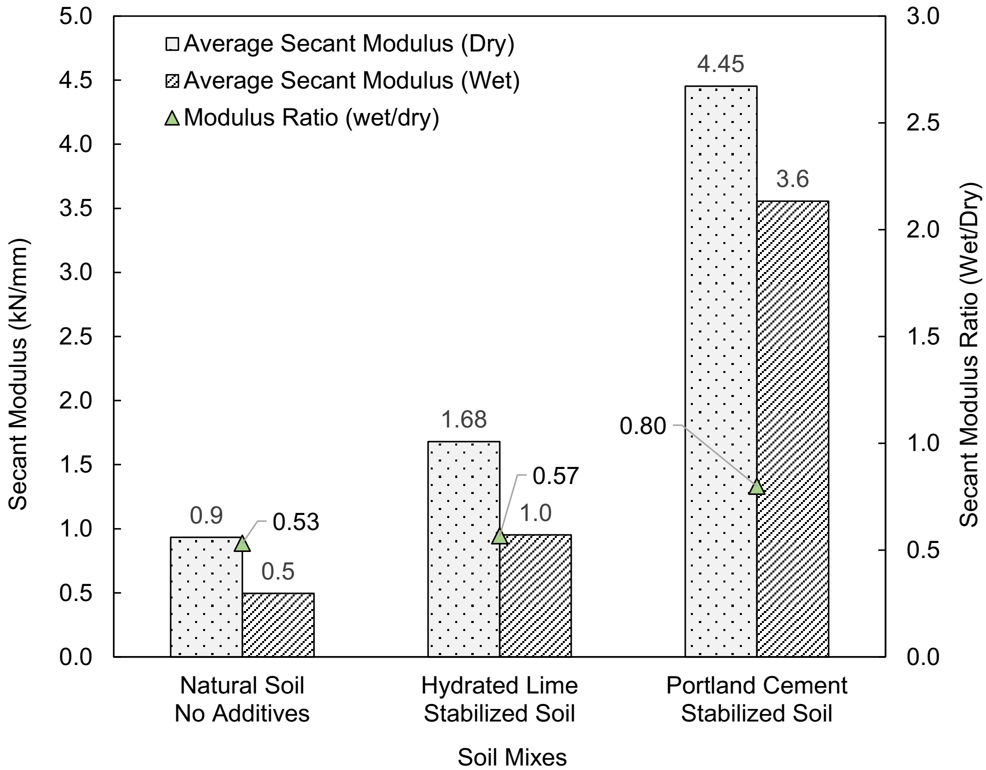

Figure 4.13 Effect of additive type and freeze-thaw cycles on secant modulus in SCB test.

Figure 4.14 summarizes the flexural fracture energies determined by testing the SCB samples. Fracture energy (G_f) captures the pre-peak as well as the post-peak behavior of the sample under the bending test. While there is no consensus regarding the significance of the flexural fracture energy in predicting the cracking potential of the specimens, it is expected to increase the resistance of the subgrade layer to fatigue cracking under low traffic loads. From Figure 4.14, it is evident that the fracture energy determined for the natural soil tested in dry condition (9,1 J/m^2) increased by 231% and 422% as a result of stabilizing it with hydrated lime and Portland cement, respectively. As observed, Portland cement was more effective in increasing the fracture energy of the tested samples. In other words, fatigue crack initiation under repeated small loads might be delayed as a result of using cement. Additionally, from Figure 4.14, subjecting the soil samples to F-T cycles resulted in a reduction in their recorded fracture energy values due to decay in their structural integrity due to the formation of the micro-cracks.

For example, the fracture energy calculated for natural soil was found to decrease by 64% due to subjecting it to F-T cycles. However, lime-stabilized soil was found to be the most sensitive mix to decay in its fracture energy (88%) as a result of being subjected to F-T cycles. It is important to note that the fracture energy of the F-T-conditioned lime-stabilized samples (3.5 J/m^2) was almost equal to that of the F-T-conditioned natural soil (3.3 J/m^2). In other words, freeze-thaw cycles have neutralized the improvement in the flexural fracture energy after lime stabilization. In contrast, the cement-stabilized soil experienced only a 38% loss in its fracture energy due to the F-T cycles.

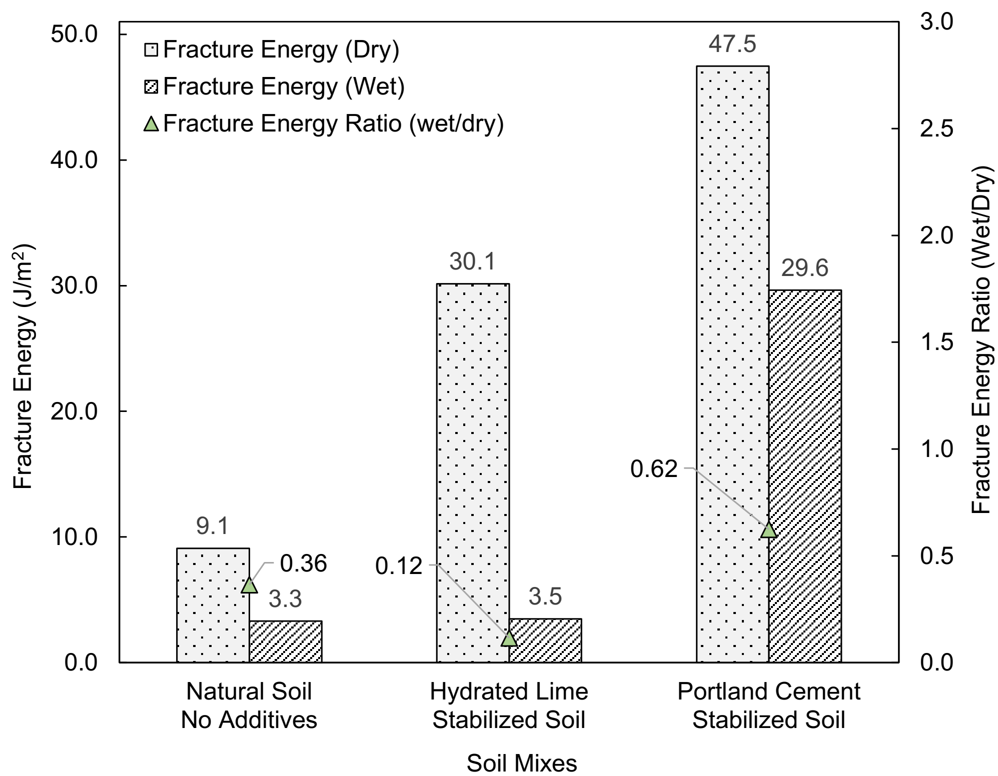

Figure 4.14 Effect of additive type and freeze-thaw cycles on fracture energy in SCB test.

Figure 4.15 presents a summary of the flexibility index (FI) values obtained by testing the SCB samples and applying the methodology discussed in section 4.4.7. For this purpose, fracture energy (G_f) and slope at the post-peak inflection point (m) were determined, and FI values were calculated for each specimen using Equation 3.9. The flexibility index captures the post-peak behavior of the sample under the bending test and indicates the crack propagation rate with time. Higher the FI value for a given sample, the higher the resistance to crack propagation. From Figure 4.15, it is evident that the flexibility index of the natural soil tested under dry condition (0.16) significantly increased and became 4.55 due to stabilizing it with hydrated lime. It should be noted that an increase in FI value indicates an improvement in the resistance of the stabilized soil to crack propagation. Therefore, it can be concluded that the addition of hydration lime with the amount used in this study is expected to lead to a substantial improvement in the resistance of the subgrade soil to crack propagation.

In contrast, Figure 4.15 revealed that there was no post-peak resistance to cracking when the soil was stabilized by mixing it with Portland cement (FI = 0). This finding is consistent with the lab observations, as while conducting the SCB test on cement-stabilized soil, a sudden (almost vertical) decline in the applied load was observed as soon as the peak load was reached. As it can be seen, while Portland cement was effective in increasing the fracture energy, it resulted in almost zero post-peak cracking resistance, an indication of a brittle failure, and sudden post-peak crack propagation. In other words, while fatigue crack initiation under repeated small loads might be delayed as a result of using cement, after the formation of a crack, it is expected to propagate at a high rate. Additionally, from Figure 4.15, it was found that subjecting the soil samples to

F-T cycles resulted in a significant reduction of the FI values (to almost zero) in soil samples stabilized with both types of stabilizing agents. This observation was attributed to decay in samples' structural integrity due to the formation of the micro-cracks and increased discontinuity pockets in the material.

Application of the SCB test for characterization of the cracking properties of the soil samples was pursued with limited scope as a novel approach utilized in this study. More studies, including field observations and modeling, should be conducted to determine the necessary criteria and acceptance thresholds for stabilized subgrade soils based on overall pavement structure, loading, and environmental parameters.

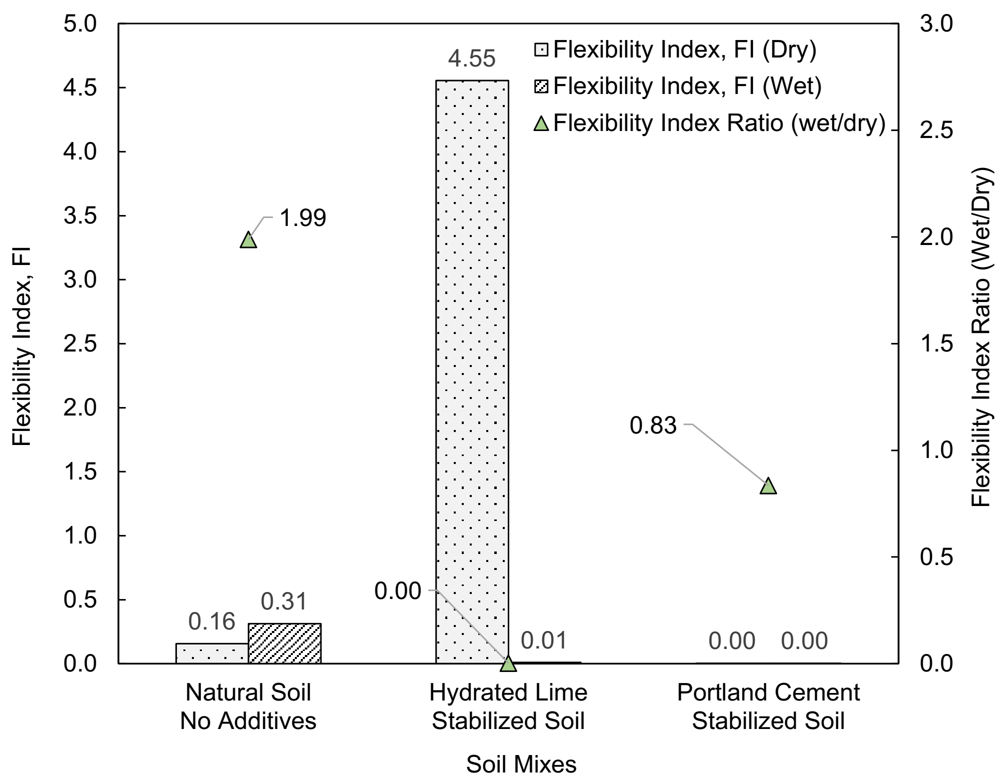

Figure 4.15 Effect of additive type and freeze-thaw cycles on peak load in SCB test.

4.8 Summary of the Results and Discussions

It was found that Portland cement and hydrated lime were both effective stabilizer agents in controlling CL soil's plasticity. The optimum hydrated lime content was found as 2% which resulted in the soil pH value of 12.4. Also, the UCS tests indicated that the shear strength of the soil increased with an increase in Portland cement or hydrated lime content. In fact, the addition of 1% of Portland cement was more effective compared to 1% of hydrated lime in improving the shear strength of the soil. The SCB test results indicated that by stabilizing the natural soil with both hydrated lime and Portland cement the flexural stiffness and fracture energy of the soil increased.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the tests conducted on the materials, applied methodology, and the analyses, conclusions as follows were drawn.

1. Soil's plasticity was effectively controlled by the addition of both hydrated lime and cement. However, lime was found to be more effective, as a lower dosage of hydrated lime resulted in a similar change in the pH with a higher amount of Portland cement.

2. Correlations were developed for the prediction of undrained-unconfined shear strength of the CL soil before and after the F-T cycles. It was also concluded that the addition of 1% cement to the tested CL soil was more effective than 1% lime in improving the shear strength.

3. Undrained-unconfined shear strength of the natural soil was found to become more sensitive to F-T cycles with increasing the lime content. An approximately similar trend was also observed for cement-stabilized soil.

4. The peak load of the soil samples in flexure was observed to improve as a result of both lime and cement stabilization. This increase was more pronounced when Portland cement was used in the mix. The F-T cycles were found to neutralize the effect of lime stabilization while resulting in a 30% reduction in peak load recorded for cement stabilized soil.

5. The flexural stiffness and fracture energy of the natural soil were found to improve by stabilizing it with both lime and cement. This improvement was more pronounced when Portland cement was used in the mix than lime. Reduction in the

flexural stiffness and fracture energy of the lime-stabilized soil was found to be more sensitive to F-T cycles than cement-stabilized soil.

6. The only stabilizing agent found to be capable of improving the flexibility index of the natural soil was hydrated lime. Cement-stabilized soil was concluded to be highly brittle and may result in instantaneous propagation of the crack in the whole section after reaching the peak load. Therefore, the use of cement stabilization should be carried out more cautiously to avoid premature cracks.

The use of cyclic loading in conducting the SCB test is recommended to be pursued in future studies. Additionally, it is recommended to conduct resilient modulus tests on soil samples to precisely determine the soil properties required for mechanistic pavement design. Application of the SCB test for characterization of the cracking properties of the soil samples was pursued with limited scope as a novel approach utilized in this study. More studies, including field observations and modeling, should be conducted to determine the necessary criteria and acceptance thresholds for stabilized subgrade soils based on overall pavement structure, loading, and environmental parameters.

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