THE COMBINED EFFECT OF CEMENT AND LIMESTONE POWDER ON THE STABILIZATION OF SULFATE-BEARING SALINE SOIL IN PAVEMENT CONSTRUCTION

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DECLARATION

I hereby, declare that this manuscript, entitled “The Combined Effect of Cement and Limestone Powder on the Stabilization of Sulfate-Bearing Saline Soil in Pavement Construction”, is the result of my own work except for quotations and citations which have been duly acknowledged. Moreover, some components of this manuscript come from the conference paper, entitled “Potential of Limestone Powder to Improve the Stabilization of Sulfate-contained Saline Soil”, written by me as a part of my graduate studies and published in IOP Conference Series: Materials Science and Engineering. I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

Name: Ayazhan Bazarbekova
Date: April 11, 2021

Abstract

For the modern world with rapidly developing infrastructure, the construction of high-quality roads has always been an issue of primary concern. In this sense, one of the significant factors influencing road pavement's quality and performance is the stability of subgrade material, i.e., soil stability. Therefore, to construct high-quality pavements, the soil must meet specific standards for its mechanical properties and durability parameters. However, the geotechnical properties of soil are determined by soil origin, soil mineralogy, and local environmental conditions, thus, can vary considerably from area to area. For instance, excessive heave occurs in pavements constructed on sulfate-bearing saline soils, the most prevalent soils in Kazakhstan, Central Asia. Salt whiskers in such soils create crystallization pressure that leads to high localized stresses and non-uniform movement of structures in soil. To improve the poor quality of soil and meet the desired end performance criteria in such a pavement construction, stabilization of soil is required, a process that presents the treatment of soil with chemical additives such as cement, lime, fly ash, and calcium chloride, also named as traditional stabilizing agents.

Since soil stabilization is a highly significant issue in constructing both buildings and roads, there has been increasing interest in this topic among researchers. The majority of papers have focused on utilizing the above-mentioned traditional binders and evaluating their effect on soil stabilization. However, less focus has been set on the utilization of recently developed non-traditional stabilizers, such as cement kiln dust, blast furnace slag, and limestone powder. In this research, therefore, limestone powder, an alternative soil stabilizing material, was used in combination with traditional cement, and its potential performance in the stabilization of sulfate-bearing saline soil was evaluated.

For this purpose, silty sand containing high sulfate and chloride levels was stabilized by 4%, 6%, and 8% pure cement contents and 2%, 4%, and 6% cement contents combined with 2%, 4%, and 6% limestone powder contents. Optimal proportions for mix design were chosen, and series of laboratory tests were conducted to evaluate the improvement in materials characteristics and geotechnical properties of the stabilized soil samples. Material characteristics studied in this research are mineralogy, cation and anion analysis, and pH. Geotechnical properties include Atterberg limits, optimum moisture content-dry density relationship, unconfined compressive strength, shear strength, friction angle, cohesion, resilient modulus, California bearing ratio, three-dimensional swelling, and dielectric constant.

Accoroding to experimental results, limestone powder, when added to the cement-treated sulfate-bearing saline soil, improves soil's mechanical properties and enhances soil durability parameters. Mainly, it decreases soil plasticity, improves soil strength parameters, enhances soil stability, and reduces volumetric swelling and soil moisture susceptibility. Along with the stabilization of soil in terms of mechanical properties and durability parameters, limestone powder, as an industrial waste material, also benefits the environment and economy.

DEDICATION

I dedicate my graduate thesis work to my parents, who have nursed me with love and affection, supported my decisions, and encouraged me to strive for my goals.

Acknowledgments

First and foremost, I would like to express my uttermost gratitude to my supervisor, Professor Chang-Seon Shon, and co-supervisor, Professor Jong Ryeol Kim. Their consistent supervision and direction throughout my studies have allowed me to successfully write this graduate thesis and complete the Master of Science program. I am deeply grateful for all the hours of discussion, valuable recommendations, the feedback they have offered me, and the significant financial support they have provided to obtain the necessary laboratory equipment and materials.

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List of Abbreviations

C-A-H	Calcium aluminate hydrate
CBR	California bearing ratio
C-S-H	Calcium silicate hydrate
DC	Dielectric constant
DD	Dry density
DST	Direct shear test
EC	Electrical conductivity
LL	Liquid limit
LSP	Limestone powder
MC	Moisture content
MDD	Maximum dry density
M_R	Resilient modulus
OMC	Optimum moisture content
OPC	Ordinary Portland cement
PI	Plasticity index
PL	Plastic limit
PSD	Particle size distribution
SC	Sulfate concentration
UCS	Unconfined compressive strength
XRD	X-ray diffraction
XRF	X-ray fluorescence

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Chapter 1. Introduction

1.1. Overview and Problem Statement

Soil's geotechnical properties differ from area to area, depending on the origin of soil, environmental conditions of a region, and soil treatment processes. However, in the construction industry, the soil must satisfy specific standards for its engineering properties, such as plasticity, deformability, strength, and durability parameters. It acts as an engineering medium and a foundation for most structures such as buildings, bridges, roads, etc. Mainly, in pavement construction, the soil is at a subgrade level. Depending on soil properties, road pavement can serve well for a long time, or it may fail after a short period with deformation and cracks developing on the surface of the pavement. In Kazakhstan, for example, heavy textured and saline soils occupy about 41% of the national territory [1]. The salt whiskers in sulfate-rich saline soils grow and create crystallization pressure, which leads to an increase in localized stresses and non-uniform movement of structures within the soil matrix. Consequently, they result in eventual defects, such as excessive heave and breaking up of pavements constructed on such soils [2, 3].

To improve the poor quality of soils and meet the desired end performance criteria in pavement construction, soil’s geotechnical properties must be strengthened through the stabilization process; particularly chemical stabilization, in which soil is usually treated with chemical additives such as portland cement, fly ash, and calcium chloride [4, 5]. With lime, fly ash, and calcium chloride, cement is suggested as a traditional binder used for soil stabilization. Cement stabilization of soil is the most common and reliable method for improving soil's mechanical properties such as shear strength and bearing capacity [6]. During the mixing process between soil and stabilizer, strong cations derived from stabilizing agents replace weak cations surrounding soil surface in a cation exchange process. This process leads to the formation of flocculated and agglomerated soil particles, contributing to higher surface tension and increased resistance against compaction. As a result, soil strength is improved [7, 8]. Moreover, in stabilizing soil with traditional calcium-based stabilizing materials, the hydration of cementitious material and pozzolanic reaction produce calcium aluminate hydrate (C-A-H) and calcium silicate hydrate (C-S-H) that continue increasing over time. Eventually, this reaction leads to the long-term improvement of soil's engineering properties [8, 9, 10].

In the past few years, researchers in this area have focused on utilizing industrial solid waste materials, also named by-products, in soil stabilization, such as limestone powder, cement kiln dust, and slag. Particularly, limestone powder is one of the main by-products of the aggregate quarrying industry of Kazakhstan. In this sense, as it has been recently studied, limestone powder increases the bearing capacity and reduces weak soil's deformability [11, 12, 13]. Moreover, alternative stabilizers have positive economic and environmental effects, compared to traditional binders, which have limitations such as higher cost and CO_2 emissions to the atmosphere and landfills [9, 12].

Despite many successful studies on soil stabilization, they have most likely focused on evaluating the physical and mechanical properties of stabilized soil, not durability parameters. Furthermore, existing studies have mainly focused on the effect of a single additive on soil stabilization, particularly traditional agents such as cement, lime, and fly ash. They overlooked the effect of their combination with non-traditional binders such as limestone powder to benefit in economic and environmental aspects. Moreover, little data are available on cement and limestone powder's combined effect on the stabilization of soils containing high salt and sulfate levels. Therefore, the present research aims to study the potential of limestone powder and its combination with cement in the mitigation of salt crystallization, improvement of geotechnical properties, and enhancement of long-term durability of sulfate-bearing saline soils.

1.2. Research Objective and Scopes

First and foremost, this study aims to use limestone powder as a soil stabilizing agent combined with traditional cement. In this sense, limestone powder, which is one of the main by-products of Kazakhstan's aggregate quarrying industry, has positive economic and environmental effects, as it is cheaper industrial waste material and emits less CO_2 to the atmosphere and landfills, comparing to the traditional binders [12]. Moreover, despite many comprehensive studies on soil stabilization and soil stabilizing materials, durability parameters of stabilized soils using limestone powder have not been evaluated as much as physical and mechanical properties. Moreover, little data are available on cement and limestone powder's combined effect on the stabilization of sulfate-bearing saline soils. Therefore, this research's primary objective to evaluate the combined effect of cement-limestone powder blend on the improvement of geotechnical properties and durability parameters of sulfate-bearing saline soil. For this purpose, the singificant tasks covered in this thesis are summarized as the following:

- Literature review: (i) review the concept of soil stabilization, (ii) identify soil stabilizing materials, and limestone powder as an alternative stabilizer, and (iii) review soil stabilization mechanism.

- Development of an integrated experimental program: establish experimental programs to evaluate the combined effect of cement and limestone powder on the stabilization of sulfate-bearing saline soil in pavement construction.
- Test result analysis: (i) conduct essential soil and materials characterization, (ii) evaluation of geotechnical properties of stabilized soil, and (iii) evaluate durability of stabilized soil.

1.3. Thesis Structure

This thesis consists of five chapters. Background information on soil stabilization and its application in pavement construction is presented in Chapter 1. Moreover, it explains the research's novelty, the motivation behind the thesis, and the paper's main objectives and tasks. Further, Chapter 2 presents a literature review, particularly, it collects, reviews, and integrates all relevant information on soil stabilization, its mechanism, and stabilizing agents, including a deeper description of limestone powder. Chapter 3 describes the materials, mix design, and methodology used in this research. This section contains the detailed characterization of materials used in the experiment, notably sulfate-bearing saline soil, cement, and limestone powder. Moreover, it presents the mixtures designed for the investigation and the experimental program itself. Following this, Chapter 4 presents the results of the tests and discusses these findings. Particularly, the effect of cement and limestone powder on the stabilization of sulfate-bearing saline soil in terms of the geotechnical properties and durability parameters of stabilized mixes are analyzed and evaluated. Conclusions regarding the findings described in the previous section are drawn in Chapter 5. Moreover, some recommendations for further studies are given in the last chapter.

Chapter 2. Literature Review

A literature search, as the first step of the research, is completed under this task and presented in this chapter. The focus of this task is to thoroughly collect, review, and integrate all relevant information on the topic of this paper. The information comes from a variety of sources including books, published journals, reports and memos, unpublished reports and memos, a database of industries and agencies, and etc. The compilation of such a comprehensive listing provides a strong foundation for the research on which to formulate and to implement the results of the work.

The following paragraphs present a comprehensive literature review on the following topics: (a) soil stabilization; (b) soil stabilizing materials, including (c) a deeper description of limestone powder as an alternative stabilizer; and (d) soil stabilization mechanism.

2.1. Soil Stabilization

Weak and soft subgrade soils often result in poor performance and a short lifetime of road pavements constructed on these soils. To improve the poor quality of soils and meet the desired end performance criteria in pavement construction, it is necessary to stabilize the soil. The process of soil stabilization aims to enhance soil's engineering properties physically, mechanically, and chemically [14]. Physical stabilization of soil refers to the modification of soil in terms of its particle size distribution or plasticity by adding or subtracting different soil fractions, also named blending to obtain the material meeting the specified soil gradation or soil plasticity, respectively [15]. Mechanical type of soil stabilization includes various techniques, such as compaction, wetting-drying cycles, and fiber reinforcement, applied to achieve the modification of soil porosity, mitigation of free swelling of the soil, and improvement of mechanical properties of soil and soil stability, respectively [8, 10, 15]. Though physical and mechanical types of soil stabilization are essential techniques involved in the material selection and preparation stages, the term “stabilization” in pavement construction mainly refers to soil's chemical treatment [9, 15]. Hence, this paper focuses on chemical stabilization of soil, also named additive or binder stabilization of soil, a process of improving the engineering properties of soil achieved by the addition of chemical stabilizers such as lime, Portland cement, and calcium chloride [4, 5]. In roadway construction, chemical stabilization with calcium-based stabilizing materials (CBSMs) such as lime and cement can enhance many of the subgrade soil's engineering properties. These include compressive strength, bearing capacity, resilient modulus, shear strength, soil stability, plasticity, and long-term durability expressed by mitigation of volumetric swelling and reduction of moisture susceptibility.

The selection criteria for stabilizing sulfate-rich soils have been described by the Texas Department of Transportation [16]. The procedure involves two main steps: (a) risk assessment and (b) soil exploration. Risk assessment addresses the major question about the potential risk for sulfate-induced heave on pavements constructed on the selected area and is performed by identifying soil formation, soil mineralogy, basic soil properties, local climatic characteristics, and drainage features. Soil exploration is a determination of the sulfate concentration of soil. Sulfate concentration is the main criterion for the selection of soil treatment types classified as (a) traditional, (b) modified, and (c) alternative. The precise determination of soil stabilization type is summarized in Figure 2.1.

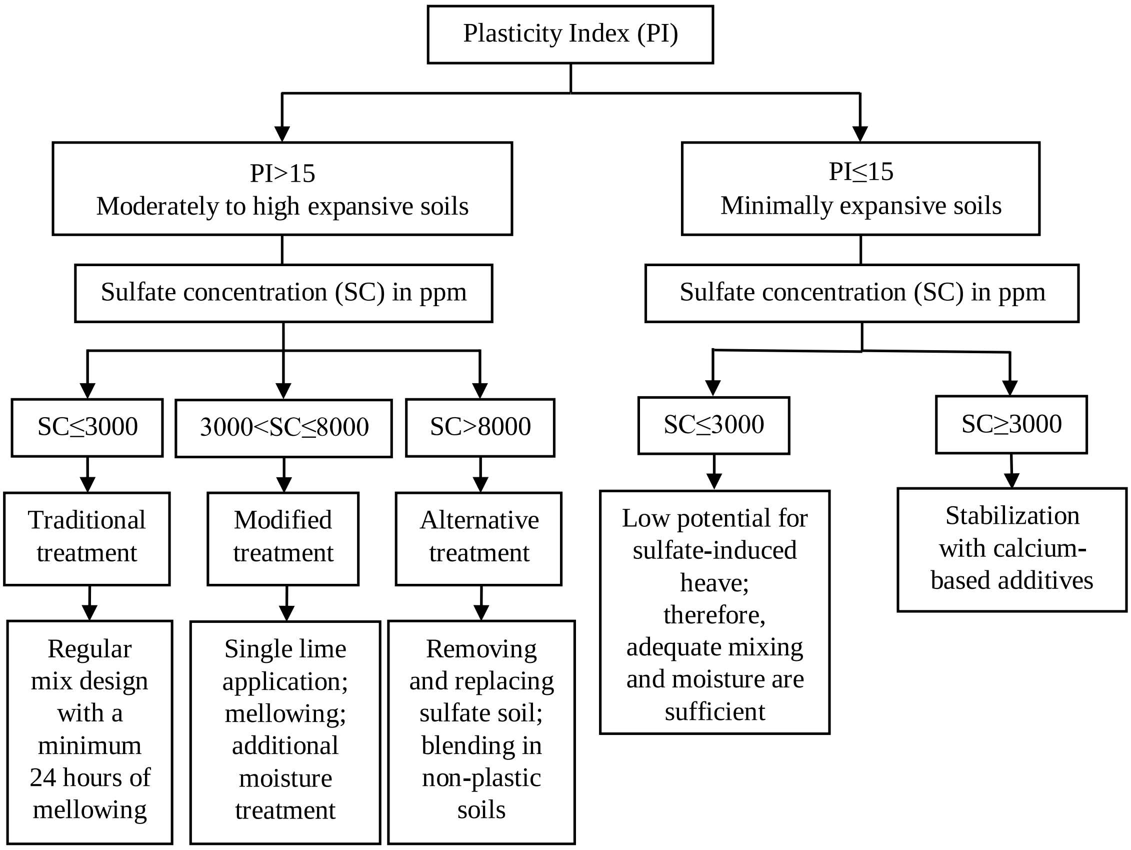

Figure 2.1: Determination of soil stabilization type for varying PI values and sulfate concentrations

2.2. Soil Stabilizing Materials

Chemical stabilization of soil is achieved through the addition of stabilizing materials, which include a wide array of binders such as Portland cement, lime, industrial solid waste materials, polymers, fibers, reagents, bitumen, and etc. Generally, stabilizing agents are classified as traditional and non-traditional additives. As a conventional binder, cement is the most commonly used stabilizing agent for soil treatment, as it allows to achieve the most effective soil strength improvement [6]. Along with cement, examples of traditional binders include calcium-based materials such as lime, fly ash, and calcium chloride. When mixed in an aqueous phase, the soil-additive mixture undergoes immediate chemical reactions, such as cation exchange, flocculation, and agglomeration. These processes contribute to an instant improvement of soil properties and prolonged time-dependent chemical reactions, such as hydration and pozzolanic reaction, which provide a progressive increase of soil strength [8, 9, 17].

The adverse environmental effects of high CO_2 emissions to the atmosphere and landfills, and the high cost of traditional binders, have motivated researchers to propose new economically friendly and cost-effective stabilizing materials. Non-traditional stabilizers, mainly quarry by-product materials, such as cement kiln dust, blast furnace slag, and limestone powder, are the most recently developed materials to stabilize soil stabilization [9]. Like the conventional calcium-based stabilizing materials, the cation exchange, flocculation, agglomeration, hydration, and formation of cementitious materials (C-S-H and C-A-H) are the main mechanisms contributing to the enhancement of the geotechnical properties of stabilized soils.

Non-calcium-based stabilizing materials, such as polymers and fibers, are also used in the stabilization of soil. Polymers, as it has been reported, mitigate soil liquefication, enhance resistance against moisture susceptibility, and improve soil reaction to weathering actions [18, 19]. Fiber reinforcement, comparing to stabilization using calcium-based binders, provides more ductile behavior of stabilized soil [20]. In addition, the combination of calcium-based and non-calcium-based additives is also a widespread practice implemented in the stabilization of soil.

2.2.1. Limestone Powder as an Alternative Stabilizer

Environmental and economic limitations associated with the traditional stabilizing agents have become a motivation for the researchers to propose the use of non-traditional binders. Particularly, limestone powder, one of Kazakhstan's main by-products from the aggregate quarrying industry, is an environmentally friendly and cost-effective alternative to the traditional stabilizing additives. Generally, as for the calcium-based stabilizing materials, the major mechanisms behind soil properties' improvement are cation exchange, flocculation, agglomeration, hydration, and C-A-H and C-S-H formation. It has been reported that limestone powder, used for stabilizing fine-grained soils, increases soil strength and bearing capacity and reduces deformability of weak soil [11, 12, 13]. Improvement of bearing capacity and reduction of deformability of weak soil leads to a reduction in thickness of pavement layers, which means significant savings in construction materials and, hence, significant savings in construction cost. Furthermore, it has been studied that, when mixed with expansive soil, limestone powder enhances strength parameters, reduces plasticity index and liquid limit, increases liquid limit, and mitigates volumetric swelling of expansive soils [21, 22]. Moreover, along with improving soil properties and saving the construction cost, limestone powder, an industrial waste product, is an environmentally sustainable stabilizing agent due to lower CO_2 emissions to the atmosphere and landfills.

2.3. Soil Stabilization Mechanism

Generally, the primary mechanism of soil stabilization using calcium-based stabilizing agents involves (a) hydration, (b) cation exchange, (c) flocculation and agglomeration, and (d) pozzolanic reaction [8, 9, 17]. Cation exchange, followed by flocculation and agglomeration, occurs immediately after soil and stabilizer are mixed in the aqueous environment. It, thus, contributes to the instant improvement of soil properties such as plasticity and short-term strength. Hydration process and pozzolanic reaction, which result in the formation of C-S-H and C-A-H, lasts longer, months or even years after soil-stabilizer mixing, and provide the long-term enhancement of the geotechnical properties of soil such as continuous improvement of strength parameters, increase in resilient modulus and modulus of elasticity, and reduction of free swell. Moreover, (e) potential carbonation resulting from chemical reactions involved in cement- and lime-treatment of soil has been identified in hot, dry climates with difficult curing control conditions [23]. Strength improvement and plasticity reduction, achieved through soil stabilization, can reverse when stabilized soil is exposed to carbonation. Since carbonation entirely depends on the environmental conditions, stabilized soil specimens are recommended to be cured in sealed containers [24].

The first two processes involved in the stabilization mechanism are cation exchange and formation of flocculated and agglomerated particles, which take place immediately after soil-stabilizer mixing. As a result, they provide instant improvement of soil properties such as plasticity and short-term strength. The surface of sulfate-containing saline soil is negatively charged, and it attracts positively charged ions from the stabilizing agent when soil and stabilizer are mixed in the presence of water. This process provides neutralization of the negative charges surrounding the soil surface. Higher valence cations (e.g., Ca^{2+}) from the stabilizer, particularly cement and limestone powder, replace lower valence cations (e.g., H^+ and Na^+) surrounding soil surface through a phenomenon called cation exchange. This phenomenon leads to the flocculation and agglomeration processes that are associated with the aggregation of soil particles. Moreover, the increased electrolyte concentration in the system due to the cation exchange reduces the thickness of the electrical diffuse double layer (DDL) at the particle-liquid interface. As the thickness of the DDL reduces, the spacing between individual soil particles also reduces, further enhancing the formation of flocculated soil particles. Flocculation and agglomeration of soil particles result in higher surface tension, increased cohesion between soil particles, reduced plasticity, and improved soil strength, particularly at an early age, as the cation exchange occurs instantaneously [8]. The neutralization and cation exchange processes are visualized in Figure 2.2.

The hydration process and pozzolanic reaction last longer, thus, provide progressive improvement of soil strength parameters. Hydration, particularly OH^-, increases soil pH, promoting the dissolution of aluminates and silicates from the soil matrix. Calcium, available from the stabilizing agent, reacts with alumina and/or silica, and free water in pozzolanic reaction, and produces calcium aluminate hydrate (C-A-H) and calcium silicate hydrate (C-S-H). The process is also referred to as solidification. It improves soil strength and stiffness due to the binding nature of the cementation gels produced in the pozzolanic reaction [25]. Moreover, the pozzolanic reaction takes place months and years, as long as sufficiently high pH is obtained for the dissolution of aluminates and silicates from the soil matrix [26]. The amount of these compounds increases over time; therefore, they continuously contribute to the long-term improvement of soil strength [8].

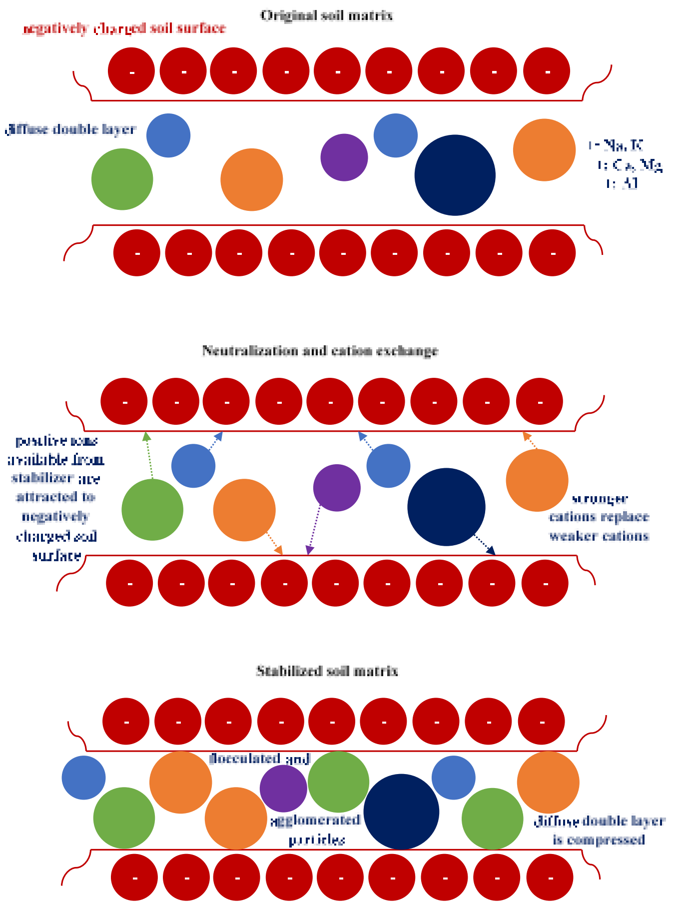

Figure 2.2: Neutralization, cation exchanged, flocculation and agglomeration in soil stabilization mechanism [8, 25]

When sulfate-containing soil is treated with cement and/or lime, its pH increases to above 12.0, promoting the dissolution of soil particles and the release of aluminum and sulfate into the system. Calcium is released from the calcium-based stabilizing material, and water is supplied as a source of soil stabilization and soil mixing. As a result, the aluminum-sulfate-calcium-water reaction produces the ettringite minerals, which can hold a large amount of water within the material, resulting in its expansion [27]. The stabilization with low-calcium-based additives, such as cement, fly ash, ground granulated blast furnace slag, is recommended to reduce the selling potential in sulfate-bearing saline soils over the use of high-calcium-based benders, such as lime [28, 29]. In addition, the use of a non-calcium-based stabilizer, particularly metakaolin-based geopolymer, is proposed for the mitigation of free swelling in sulfate-rich soils [30].

Chapter 3. Materials, Mixtures, and Methods

Based on the comprehensive literature review, an adequate selection of materials, design of optimum mixtures, and development of the experimental program has been performed and described in this chapter.

3.1. Materials

3.1.1. Soil

In the current research, a sulfate-bearing saline soil collected from West Kazakhstan was studied. According to the AASHTO classification system, the tested soil is classified as silty or clayey gravel and sand [31]. The tested soil's gradation is obtained according to the TxDOT specification and is shown in Figure 3.1 [32]. Basic soil properties, including AASHTO soil classification, Atterberg limits, and optimum moisture content-maximum dry density relationship, were determined as summarized in Table 3.1. Moreover, the tested soil's chemical properties, particularly cation and anion analysis, performed by the Dionex ICS-600 Ion Chromatography System, and pH of the soil, measured by the Tex-128-E test method, are also presented in the Table 3.1 [33]. Atterberg limits test results (liquid limit, plastic limit, plasticity index) show low plasticity value for the soil, resulting in lower volumetric swelling compared to that of clayey soil. However, high sulfate and chloride concentrations in the tested soil are expected to promote salt crystallization in the soil matrix, which results in pavement failure due to sulfate-induced heave.

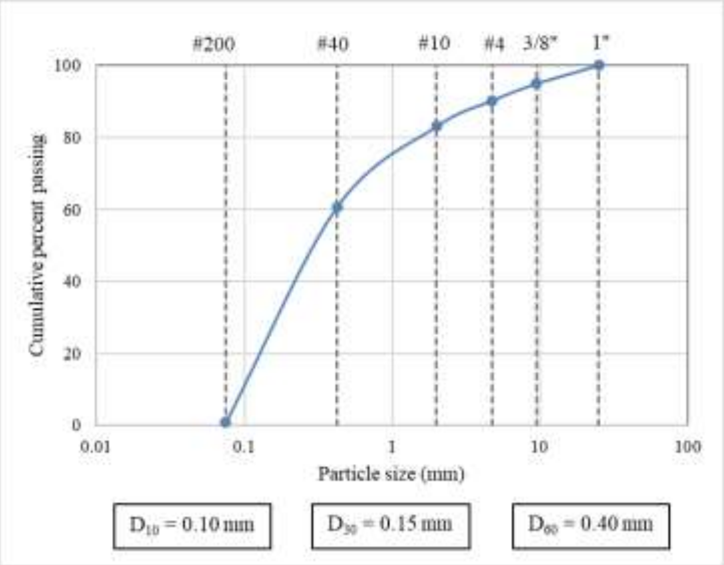

Figure 3.1: Soil gradation

Table 3.1: Basic soil characterization

<table>
<tr><td colspan="5">Geotechnical properties</td></tr>
<tr><th>Property</th><th>Value</th><th colspan="2">Property</th><th>Value</th></tr>
<tr><td>AASHTO classification</td><td>A-2-4(0)</td><td colspan="2">Liquid limit (%)</td><td>19.16</td></tr>
<tr><td>Optimum moisture content (%)</td><td>10.80</td><td colspan="2">Plastic limit (%)</td><td>16.67</td></tr>
<tr><td>Maximum dry density (kg/m^3)</td><td>1941.00</td><td colspan="2">Plasticity index (%)</td><td>2.49</td></tr>
<tr><td colspan="5">Chemical properties</td></tr>
<tr><td rowspan="2">Cations (ppm)</td><td>Calcium</td><td>Sodium</td><td>Potassium</td><td>Magnesium</td></tr>
<tr><td>6983.81</td><td>6682.37</td><td>801.37</td><td>664.87</td></tr>
<tr><td rowspan="2">Anions (ppm)</td><td colspan="2">Sulfate</td><td colspan="2">Chloride</td></tr>
<tr><td colspan="2">16931.00</td><td colspan="2">10681.98</td></tr>
<tr><td>pH</td><td colspan="4">6.32</td></tr>
</table>

The mineralogical analysis performed using XRD is shown in Figure 3.2. Particularly, the soil mainly consists of quartz (SiO_2), gypsum ($CaSO_4H_2O$), and calcite ($CaCO_3$). The presence of gypsum provides high sulfate concentration in the soil, which is expected to result in salt crystallization, causing poor soil performance and damage due to sulfate-induced heave.

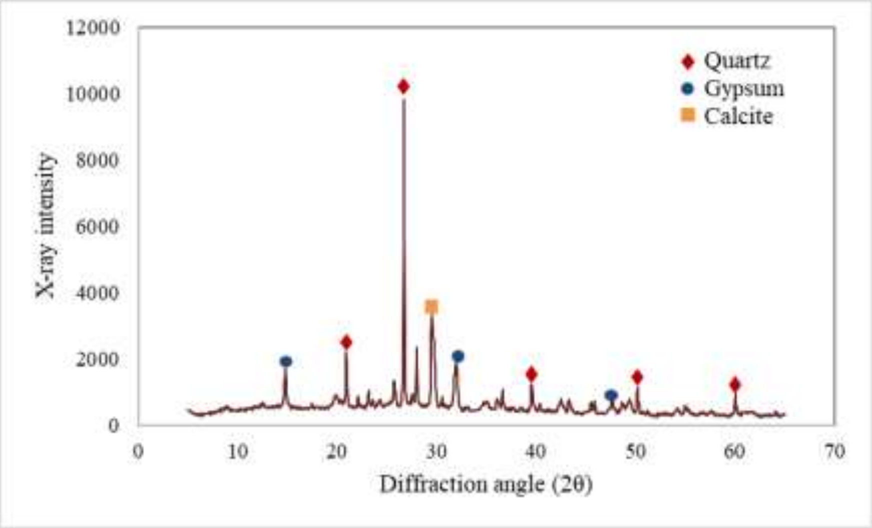

Figure 3.2: XRD patterns for the tested soil

3.1.2. *Stabilizers*

Ordinary Portland cement and its combination with limestone powder were used as stabilizing agents for the experimental work. Particularly, limestone powder was obtained by crushing locally collected limestones using a jaw crusher and then ground the material using a ball mill. The particle size distribution of the stabilizers is shown in Figure 3.3. According to it, LSP is relatively well-graded, thus, has coarser particles with 73% fines content, passing sieve No. 325 (45 μm), comparing to relatively uniformly graded OPC with 95% fines content. Moreover, due to its poor uniform gradation, OPC has a lower content of very fine particles than well-graded LSP, which has approximately the same content of coarser and finer particles. Grain size distribution of stabilizing agents, particularly, predominant fine particles, comparing to sand, allow these stabilizers to act as a filling material and contribute to binding of particles in the soil-stabilizer matrix, which is expected to result in increased cohesion, reduced plasticity, and improved strength at an early age.

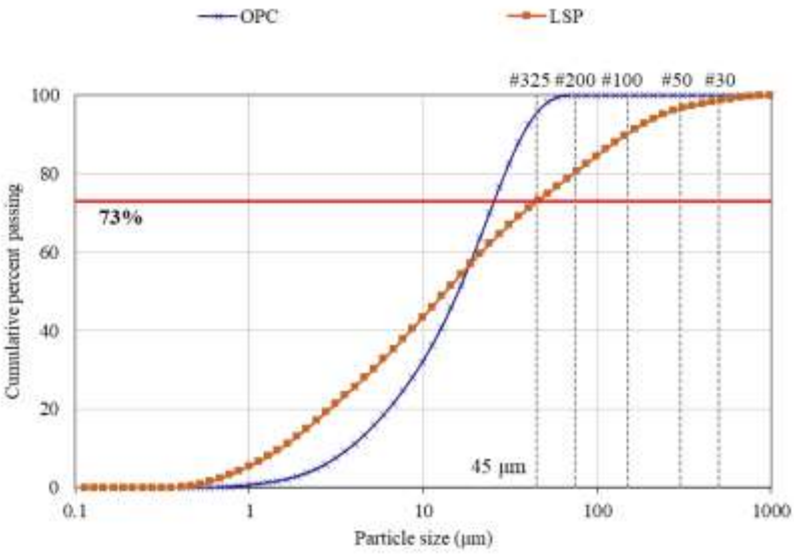

Figure 3.3: PSD for OPC and LSP

The mineralogical analysis of cement and limestone powder obtained by XRD and chemical composition of the tested soil and stabilizers obtained by XRF are presented in Figures 3.4 and 3.5 and Table 3.2, respectively. The presence of calcium silicate oxide and calcium silicate in OPC and calcite in LSP is expected to promote the pozzolanic reaction in soil-stabilizer mixing, thus contributing to prolonged strength improvement.

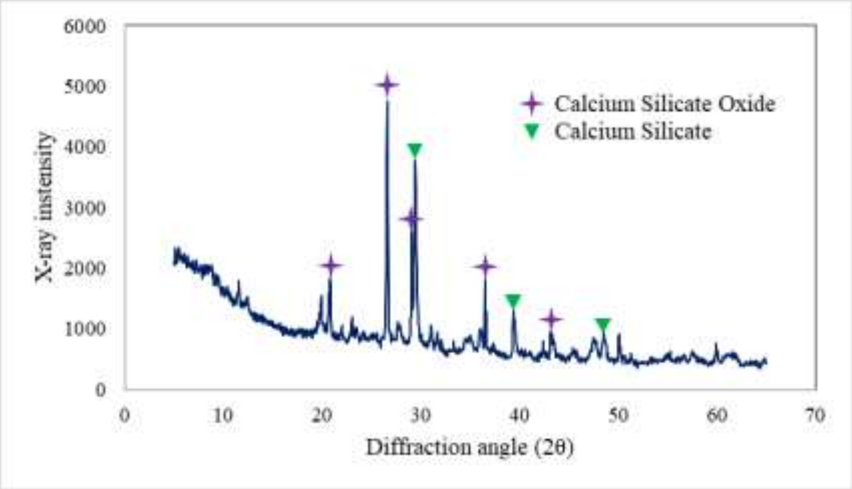

Figure 3.4: XRD patterns for OPC

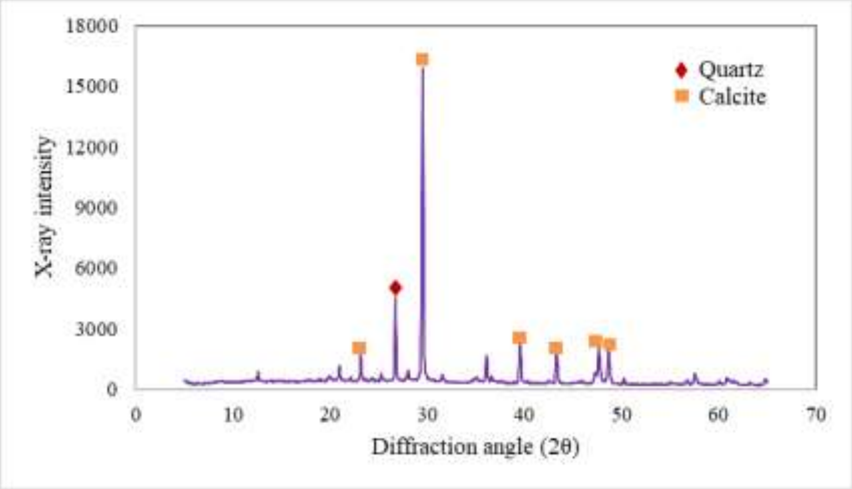

Figure 3.5: XRD patterns for LSP

Table 3.2:Chemical composition of the tested soil, OPC, and LSP

Compound	Soil (%)	OPC (%)	LSP (%)
SiO_2	20.22	21.05	11.16
Al_2O_3	4.55	3.79	3.62
Fe_2O_3	11.68	4.47	9.44
Na_2O	0.84	0.43	0.60
K_2O	4.16		2.58
MgO	1.66	1.77	1.00
CaO	39.78	64.48	68.54
TiO_2	1.61	-	1.23
SO_3	10.60	2.88	0.70
MnO	0.66	-	0.62
Cl	3.70	0.01	0.59

3.2. Mixtures

A total of 10 mixtures, including a control sample (soil only), were set up to achieve the research objectives. Stabilizers contents were determined using the Edges-Grim test method described in TxDOT specification [34]. The Edges-Grim test calculates the recommended percentage of stabilizing agents. The minimum percentage of additive required to achieve the pH of soil-stabilizer mixture equal to 12.4 indicates a sufficient pH value for pozzolanic reaction to take place. According to test results, shown in Figure 3.6, the minimum recommended cement and limestone powder contents are 4% and 2%, respectively. Four different cement contents (2, 4, 6, and 8%) and three different limestone powder contents (2, 4, and 6%) were selected. Different combinations of cement and limestone powder contents were designed in order to evaluate the effect of each additive on the stabilization of sulfate-bearing saline soil. Based on the evaluation, select the optimum stabilizer content and mixture. Mixtures were designed as follows:

Table 3.3: Mix design

No.	OPC	LSP	Notes
1	-	-	Control (soil only)
2	2%	2%	
3	2%	4%	
4	2%	6%	
5	4%	-	
6	4%	2%	
7	4%	4%	
8	6%	-	
9	6%	2%	
10	8%	-	

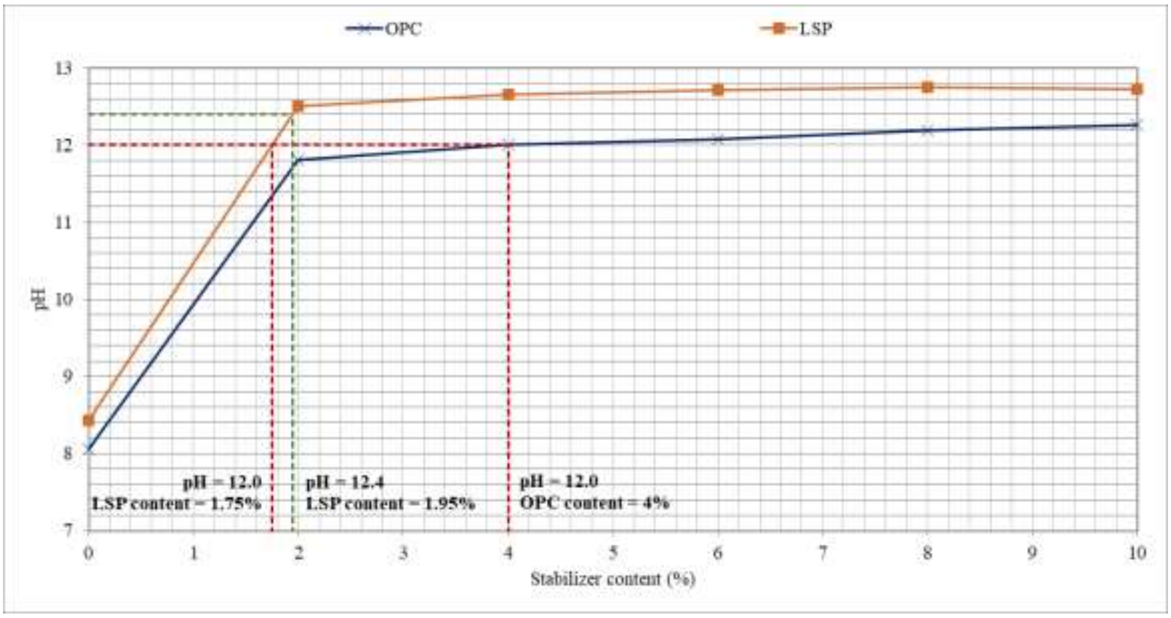

Figure 3.6: Edge-Grim test results for OPC and LSP

3.3. Methods

The study's experimental program can be categorized into basic material characterization, mix design and sample preparation, determination of the material characterization of the stabilized soil samples, evaluation of the geotechnical properties, and the durability of soil-cement-limestone powder mixtures. The detailed procedure with specified tests and test methods is presented in Figure 3.7.

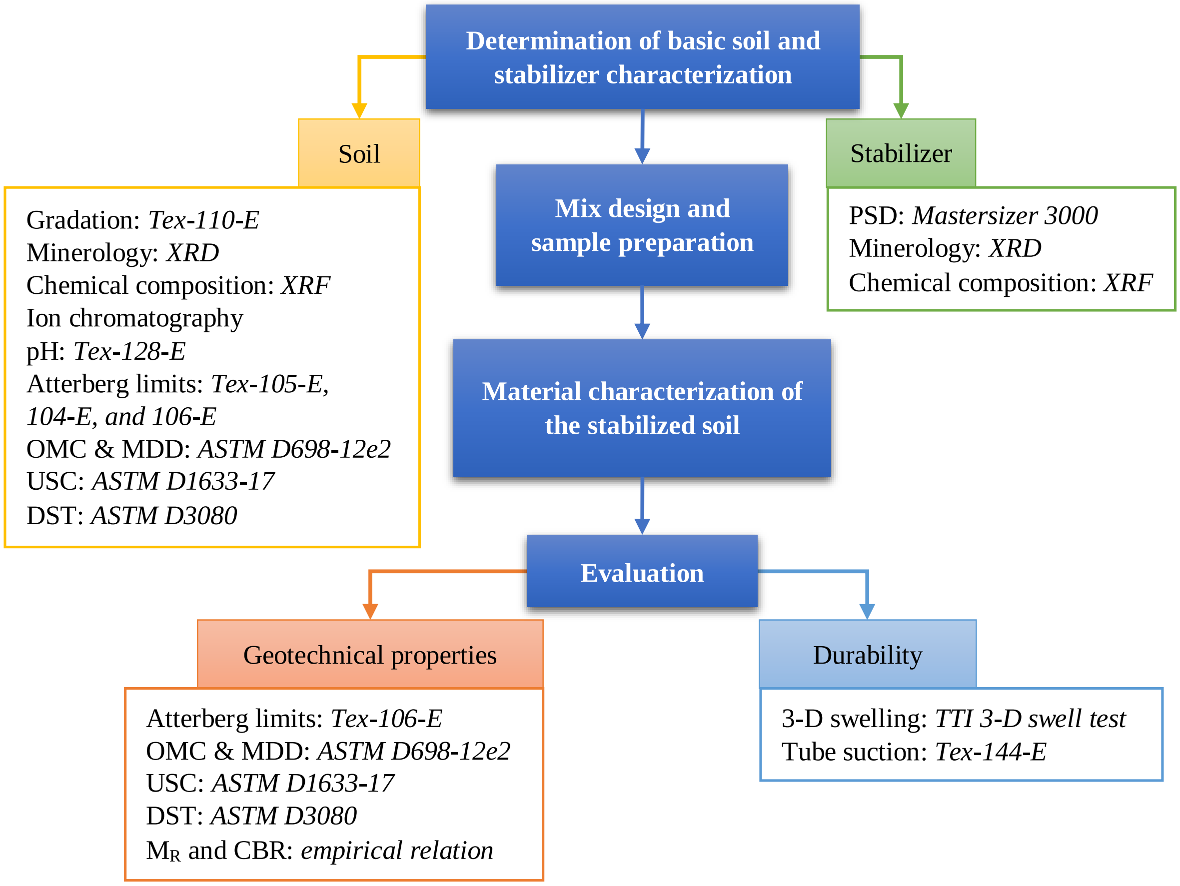

Figure 3.7: The experimental program to evaluate the effect of OPC and LSP on the stabilization sulfate-bearing saline soil

3.3.1. Determination of Basic Material Characterization

Soil gradation was performed in accordance with the Tex-110-E specification. Based on it, the following grain sizes are included in the analysis: 1 in, 3/8 in, sieve No. 4, sieve No. 10, sieve No. 60, and sieve No. 200. The Atterberg limits (LL, PL, and PI) of the tested soil were determined as described in the Tex-104-E, Tex-105-E, and Tex-106-E specifications and shown in Figures 3.8 and 3.9 [35, 36, 37]. The optimum moisture content-maximum dry density relationship for the soil was obtained, according to the procedure provided in the ASTM D698-12e2 specification [38]. The chemical analysis of the tested soil, particularly cation and anion analysis, was conducted by the Dionex ICS-6000 Ion Chromatography System. Moreover, the pH of the natural soil was measured based on the Tex-128-E test method [33].

The mineralogical compositions of both the tested soil and the additives were obtained by means of XRD patterns, which were determined using Rigaku SmartLab and analyzed using MDI Jade 6. The chemical compositions of the soil, OPC, and LSP were determined using AxiosmAX XRF spectrometer by PANalytical.

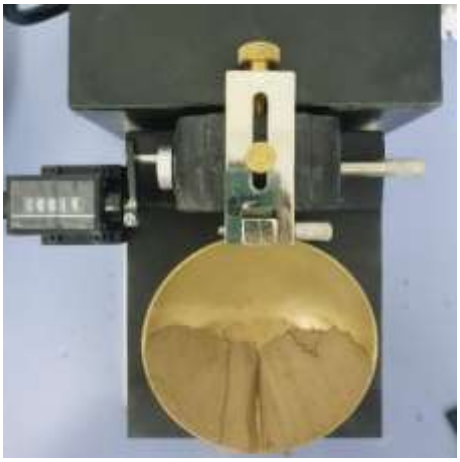

Figure 3.8: Determination of LL

Figure 3.9: Determination of PL

3.3.2. Mix Design and Sample Preparation

A total of 10 mixtures, including a plain soil sample and nine soil mixtures containing different amounts and types of stabilizer, were designed as described in the previous sections. As presented in Figure 3.10, the soil samples were mixed thoroughly with the different cement and limestone powder percentages at their corresponding optimum moisture contents. Determination of OMC for varying stabilizer contents is described in the following sections. After thoroughly mixing soil-stabilizer mixtures at their corresponding OMC, the cylindrical specimens (4 in. × 4.5 in. and 50 mm × 100 mm) were compacted with the standard Proctor compaction energy and cured in the sealed conditions for further testing, as shown in the Figure 3.11.

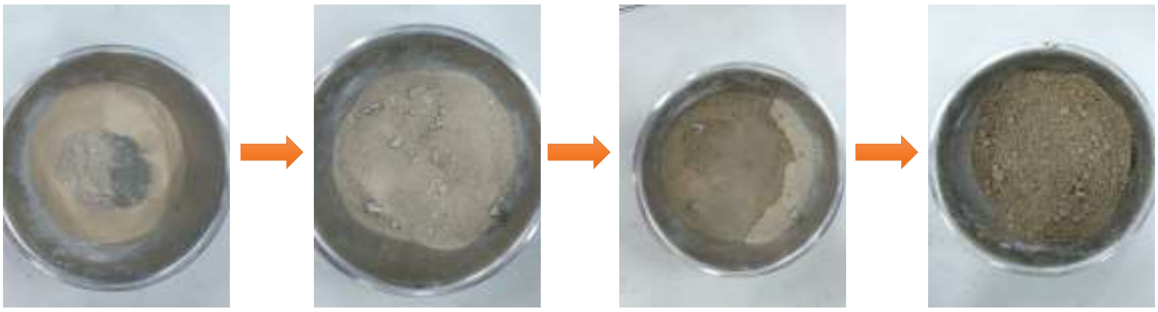

Figure 3.10: Soil-stabilizer mixing at the OMC

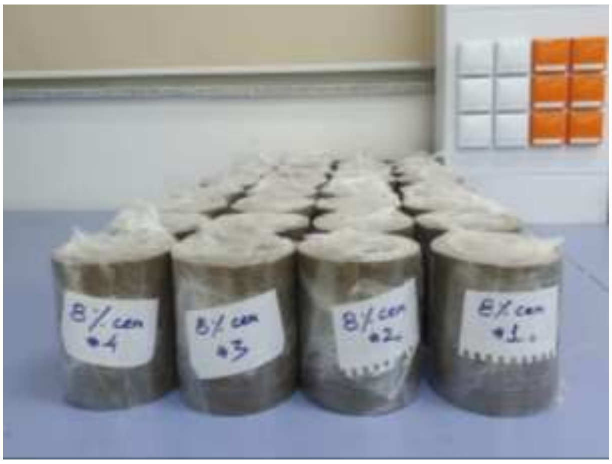

Figure 3.11: The cylindrical soil specimen cured in the sealed conditions

3.3.3. Determination of the Material Characteristics of the Stabilized Soil

The stabilized soil's material characteristics include cation and anion analysis, performed by the Dionex ICS-6000 Ion Chromatography System, pH, measured in accordance with the Tex-128-E test specification, mineralogical composition of the cement- and limestone powder-treated soil mixtures associated with XRD patterns of the samples [33]. The stabilized samples were cured for 7-days, and the samples exposed to 58-days volumetric swelling under capillary soak conditions were tested for the material characteristics. The 7-days cured samples represent the instant effect of the soil stabilization that indicates cation exchange and formation of flocculated and agglomerated particles, while the samples after 58-days volumetric swelling provide the realistic long-term durability assessment.

3.3.4. Determination of the Geotechnical Properties of the Stabilized Soil

Geotechnical properties determined in this study include Atterberg limits (LL, PL, PI), optimum moisture content, maximum dry density, 7-days and 28 days unconfined compressive strength, shear strength parameters such as friction angle and cohesion. Moreover, resilient modulus and California bearing ratio of stabilized mixtures were obtained through the empirical relation.

The Atterberg limits (LL, PL, and PI) were measured for both the plain and the stabilized soil samples. The optimum moisture content-maximum dry density relationship (M-D curve) of the natural soil was obtained as described in the previous section, and then OMC for the stabilized mixtures was calculated according to the soil-cement testing proposed by TxDOT in the Tex-120-E specification[39]. Equation 3.1 allows calculating nearer OMC for stabilized soil samples without running a new OMC-MDD relationship determination for each stabilizer content. % cement increase is considered as the total stabilizer content (%OPC + %LSP).

$$\%\ molding\ water = \%\ OMC\ from\ M - D\ curve + 0.25 \times (\%\ cement\ increase) \tag{3.1}$$

Maximum dry densities of soil-cement-limestone powder mixtures were calculated as shown in Equation 3.2. The moist density of specimen is a density of soil stabilized with cement or its combination with limestone powder, mixed at the corresponding optimum moisture content, and compacted with standard Proctor compaction energy.

$$Dry\ density = \frac{Moist\ density}{1 + \frac{OMC}{100}} \tag{3.2}$$

$$Moist\ density = \frac{Wet\ mass}{Volume} \tag{3.3}$$

As presented in Figure 3.12, the 7- and 28-day UCS of the natural soil and the stabilized mixtures were measured as described in the ASTM D1633-17 specification [40]. The 7- and 28-days cured cylindrical soil specimens of 50 mm diameter and 100 mm height were compressed at a loading rate equal to 1 mm/min under unconfined conditions, and the maximum load that the tested samples could withstand was determined as UCS. Shear strength, friction angle, and cohesion of the plain and the stabilized soil samples were determined through the Direct Shear Test according to the ASTM D3080 specification [41]. The 7-days cured samples and the samples exposed to 58-days volumetric swelling, including 28-days persistent swelling and 30-days wetting-drying cycles, were tested in the DST as shown in Figure 3.13.

Figure 3.12: UCS test of the soil specimen

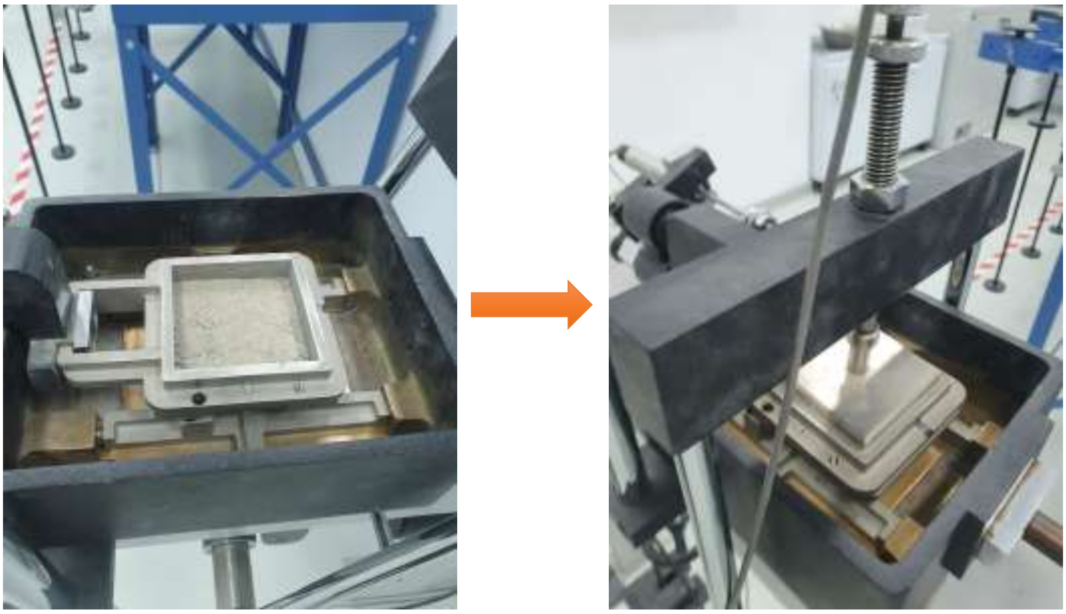

Figure 3.13: DST of the soil specimen

Resilient modulus and California bearing ratio of the stabilized mixtures were obtained using the empirical relations provided in Equations 3.4, 3.5, and 3.6. CBR is a function of % particles passing No. 200 sieve (P200) and PI.

$$M_R(psi) = 2555 \times CBR^{0.64} \tag{3.4}$$

$$M_R(psi) = 1500 \times CBR, \ where \ CBR < 20 \tag{3.5}$$

$$CBR(\%) = \frac{75}{1 + 0.728 \times P200 \times PI} \tag{3.6}$$

3.3.5. Determination of the Durability of the Stabilized Soil

Durability assessment was performed by measuring the three-dimensional (3-D) swelling and dielectric constant of the plain and stabilized soil samples. The 3-D swelling test was conducted as described by Texas Transportation Institute in order to assess the volumetric expansion of the sample associated with the formation of ettringite minerals when cement- and limestone powder-treated sulfate-bearing saline soil is exposed to prolonged capillary suction [42]. The 3-D swell test was performed, as shown in Figures 3.14 and 3.15, by covering the 4-inch diameter and 4.5-inch height specimen with a wet towel and rubber membrane, placing filter paper and porous stone on the bottom and filter paper, plastic sheet, porous stones on the top of the sample. The specimen was placed in a container with deionized water, letting the water to soak through the sample for a particular period. The volumetric expansion of the sample was measured periodically. After the 28-days of continuous capillary soak, the samples were exposed to wetting-drying conditions, performed by drying the samples for two days and placing them back in the container with water for three days, total in a 30-days period.

The residual unconfined compressive strength of the stabilized soil samples after the 3-D swell test was also determined. The residual UCS of the samples exposed to the volumetric swelling under capillary suction assesses the moisture susceptibility of the soil. The obtained strength value is considered as a more realistic approach since it imitates in-situ conditions and provides an assessment of long-term durability of the soil.

Figure 3.14: 3-D swell test preparation

Figure 3.15: 3-D swell measurements

The dielectric constant quantifies the moisture susceptibility of material and categorizes the material as “good, marginal, and poor”. DC value is determined in the Tube Suction test, described in the Tex-144-E test method [43]. The 4-inch diameter and 4.5-inch height specimen was covered with a rubber membrane, placed filter paper and porous stone on the bottom and filter paper, plastic sheet, and porous stone on the top, and exposed to continuous capillary suction conditions in the container. DC values for each sample were measured using a percometer, as shown in Figure 3.16. Similar to the 3-D swelling test, the samples were exposed to wetting-drying cycles, total 30-day, after 28-days of continuous capillary suction. The effect of wetting-drying cycles is presented in Figure 3.17.

Figure 3.16: DC measurement

Figure 3.17: Development of salt crystallization during drying in wetting-drying cycles

Chapter 4. Test Results and Discussion

The results of the tests described in the previous sections are presented in this Chapter. Mainly, Chapter 4 evaluates OPC and LSP's effect on the material characteristics of the stabilized soil, improvement of the geotechnical properties, the enhancement of its long-term durability of the soil-stabilizer mixtures.

4.1. Material Characterization of the Stabilized Soil

Material characterization of the stabilized soil samples includes cation and anion analysis, pH, and mineralogical composition of the soil-stabilizer mixtures. The 7-day cured samples and the samples exposed to 58-days volumetric swelling were tested in order to determine the short-term and the long-term effect of the soil stabilization, respectively. Cation and anion concentrations in the natural and the stabilized samples are shown in Table 4.1.

Table 4.1: Cation and anion analysis of the stabilized soil

	Cation (ppm)				**Anion (ppm)**	
	Ca^{2+}	**Na^{+}**	**K^{+}**	**Mg^{2+}**	**SO_4^{2-}**	**Cl^{-}**
Control	6983.81	6682.37	801.37	664.87	16931.00	10681.98
7-days						
2%OPC+2%LSP	5740.32	5001.21	260.40	9.05	11712.34	7538.38
2%OPC+4%LSP	4841.45	4460.50	215.54	7.12	10098.22	6696.80
2%OPC+6%LSP	4936.73	4227.02	236.06	6.24	10221.67	6469.27
4%OPC	6710.86	6765.66	394.59	12.59	12951.56	10276.09
4%OPC+2%LSP	5030.45	4643.48	419.31	7.17	10404.88	7047.44
4%OPC+4%LSP	5259.05	4763.29	356.42	5.60	10519.02	7208.32
6%OPC	5684.40	4760.15	398.79	5.63	10143.65	7334.04
6%OPC+2%LSP	5893.82	4384.49	431.67	6.70	11064.09	6705.38
8%OPC	6264.56	4952.64	474.76	22.28	11631.59	7526.07
58-days						
2%OPC+2%LSP	4859.41	1509.97	223.90	20.49	5628.18	1623.66
2%OPC+4%LSP	5451.18	3474.75	189.51	14.44	8262.55	3598.50
2%OPC+6%LSP	6795.18	3135.18	201.87	25.63	11833.37	3635.28
4%OPC	5900.93	4070.65	293.37	20.30	11286.48	4868.86
4%OPC+2%LSP	6152.33	3630.45	342.48	49.26	11038.46	4610.68
4%OPC+4%LSP	6031.01	3611.80	326.64	48.00	11145.30	4700.59
6%OPC	6569.17	3755.78	377.06	19.35	11596.63	5166.02
6%OPC+2%LSP	6552.37	3761.40	439.17	42.09	12062.76	5152.18
8%OPC	5666.99	3457.90	469.04	46.74	10647.34	4670.22

According to cation and anion analysis, OPC- and LSP-stabilization of sulfate-bearing saline soil reduce sulfate and chloride concentrations in the tested soil. As a result, the originally acidic soil with a pH value of 6.32 transforms into the alkaline material with a pH value almost twice the original one when stabilized with calcium-based OPC and LSP. pH values above 12.0 achieved in the 7-days cured samples stabilized with 4% OPC + 2% LSP, 4% OPC + 4% LSP, 6% OPC, 6% OPC + 2% LSP, and 8% OPC are sufficient to promote pozzolanic reaction in these mixtures, which contributes to the long-term strength improvement. However, pH values of the samples exposed to the 58-days volumetric swelling under capillary suction are slightly lower, comparing to those of the 7-days cured samples. The slight drop in pH value can be attributed to the potential carbonation of the OPC- and LSP-treated soil samples when the samples reacted with CO_2 in the room during drying periods in the wetting-drying cycles. The results of the pH measurements performed for the 7-days cured samples and the 58-days swelling samples are illustrated in Figure 4.1.

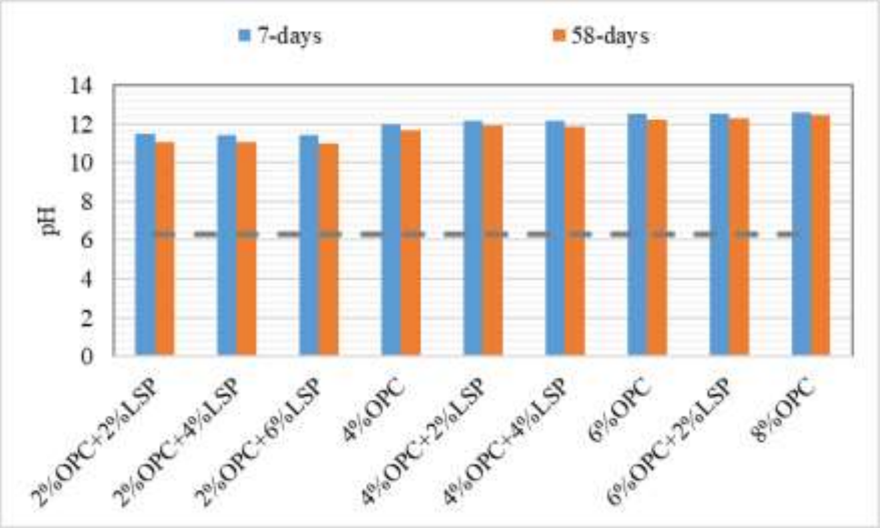

Figure 4.1: pH of the control and the stabilized soil

The mineralogical composition of the stabilized soils is presented in Figure 4.2. According to the XRD patterns of the stabilized soils, ettringite was formed in all samples due to the reaction of calcium available from the calcium-based stabilizing material, aluminum and sulfate available from the sulfate-bearing saline soil, and water provided as the source for soil-stabilizer mixing. Ettringite is capable of storing large amounts of water within the material, thus promoting the volumetric swelling of the OPC- and LSP-stabilized soil. As the tested soil is a low plasticity soil, and plasticity is expected to reduce after the stabilization, the expansion is expected to be not as high as for clayey soil.

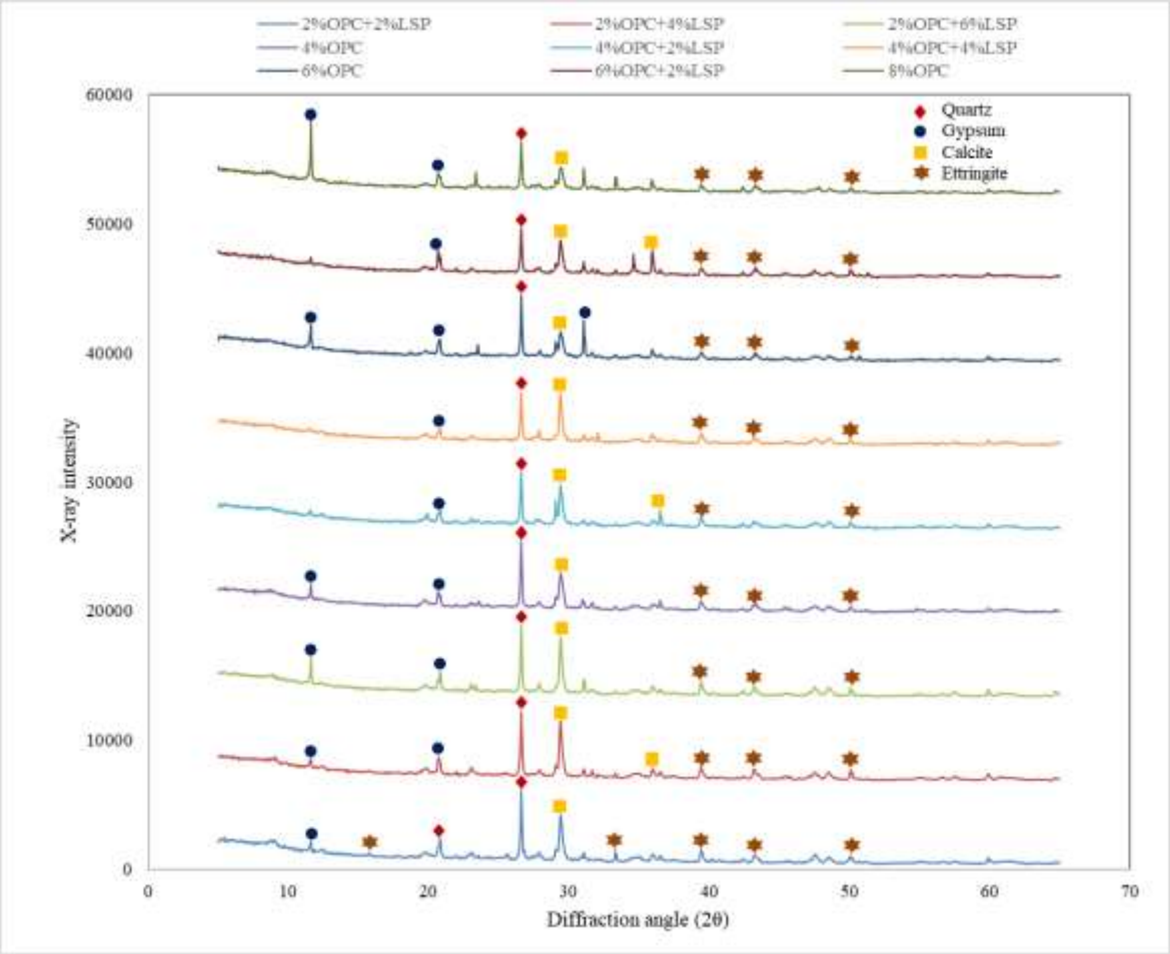

Figure 4.2: XRD patterns for the stabilized soil

4.2. Evaluation of the Geotechnical Properties of the Stabilized Soil

The geotechnical properties of the cement- and limestone powder-stabilized sulfate-bearing saline soil, including Atterberg limits, optimum moisture content, maximum dry density, unconfined compressive strength, shear strength, particularly, cohesion and friction angle, resilient modulus, and California bearing ratio are discussed. Changes in these properties associated with the soil stabilization mechanism and soil chemistry are analyzed and explained in this section.

4.2.1. Atterberg Limits

The soil stabilization mechanism that induces cation exchange and formation of flocculated and agglomerated particles at an early age aims to reduce soil plasticity. Indeed, as Atterberg limits test results show, stabilization of sulfate-bearinf saline soil with pure cement and its combination with limestone powder provides a reduction of soil plasticity except for one case. As presented in Figure 4.3, except for the sample stabilized with 2% OPC + 2% LSP, all other mixtures show a decrease in soil PI, with the maximum 91% reduction achieved in the 8% OPC treated soil sample.

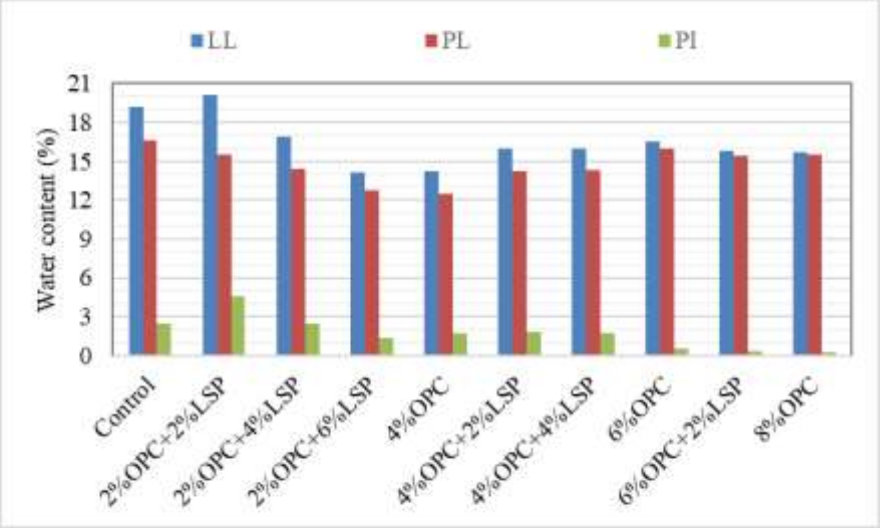

Figure 4.3: Atterberg limits of the control and the stabilized soil samples

The maximum PI reduction of 91% in 8% OPC treated soil can be compared to the 86% decrease in PI of the soil mixture containing 6% OPC content combined with 2% LSP content. It shows that cement and limestone powder's combined effect is almost as strong as the effect of cement used in a higher percentage. Moreover, it was recorded that 2% OPC content in combination with 2% and 4% LSP contents was not efficient in reducing soil plasticity, with the former combination resulting in the plasticity increase of about 84.5%. This behavior may be attributed to the introduction of the finer particles with OPC and LSP, which are sufficient to change the gradation of the soil-stabilizer mixture and not sufficient to promote the stabilization mechanism, particularly, cation exchange in the soil-stabilizer matrix and flocculation and agglomeration of the mixture particles. However, the soil sample treated with the combination of 2% OPC and 6% LSP has lower PI, comparing to the samples stabilized with 4% OPC and its combination with 2% and 4% LSP. This again shows that higher cement content can be replaced by lower cement content with the addition of limestone powder, as the mixtures stabilized with the combination of lower OPC content and LSP result in the same or even lower soil plasticity as the ones treated with higher OPC content. Moreover, an increase in LSP content provides a more significant reduction in soil PI, except for the 4% OPC + 2% LSP treated soil sample. Nevertheless, the 30% PI reduction associated with 4% OPC content is almost similar to the plasticity decrease of 29% associated 4% OPC + 2% LSP content. Thus, the trend, shown in Figure 4.4, may be generalized as stated above.

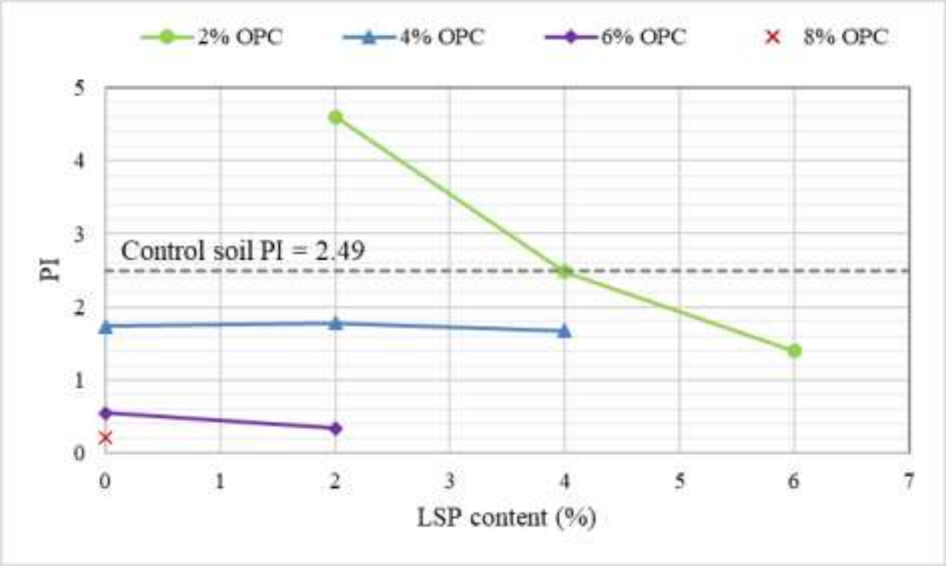

Figure 4.4: Effect of LSP content on PI

4.2.2. Optimum Moisture Content-Dry Density Relationship

The moisture content-dry density relation (M-D curve) of the natural soil was obtained, and the optimum moisture content at which the tested soil exhibits the highest dry density was determined as shown Figure 4.5. Further, the values of OMC and MDD for the OPC- and LSP-treated samples were obtained using the empirical relationship (Equations 3.1, 3.2, and 3.3) described in the previous sections. The effect of OPC and LSP addition on the stabilization of sulfate-bearing saline soil, in terms of OMC and MDD, is illustrated in Figure 4.6.

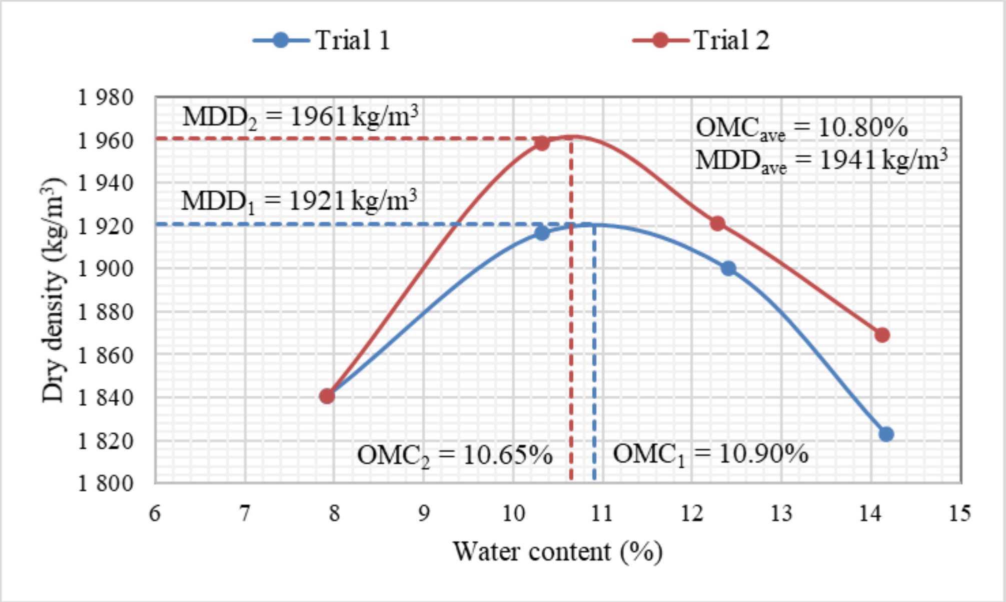

Figure 4.5: OMC-MDD determination for the tested soil

Generally, the stabilization of soil is required to increase MDD and decrease OMC of soil. The soil samples treated with 2% OPC + 2% LSP and 4% OPC lead to the significant MDD increase, while the samples treated with 2% OPC + 4% LSP, 4% OPC+ 2% LSP, and 6% OPC have almost the same MDD as the control sample. The other mixtures show a significant drop in MDD values. The combination of 2% OPC and 2% LSP contents act as a filling material due to the small particle sizes of the binders, thus, contribute to the MDD increase. This behavior can also be linked to the behavior of the same additive combination in changing Atterberg limits described in the previous section, particularly increasing soil plasticity (instead of reducing it). The reduced MDD, corresponding to the majority of the stabilized soil samples, may be explained by the increased soil resistance against compaction due to the formation of flocculated and agglomerated soil-stabilizer particles during cation exchange. Based on the mathematical equation (Equation 3.1) provided in the previous sections, OMC is a linear function of the stabilizer content. Thus, the value increases when the total stabilizer content rises. The increased OMC may also be attributed to the flocculation and agglomeration of soil-stabilizer particles during cation exchange: the flocculated and agglomerated particles occupy larger spaces, which, in turn, contributes to an increase in void ratio in soil-stabilizer matrix

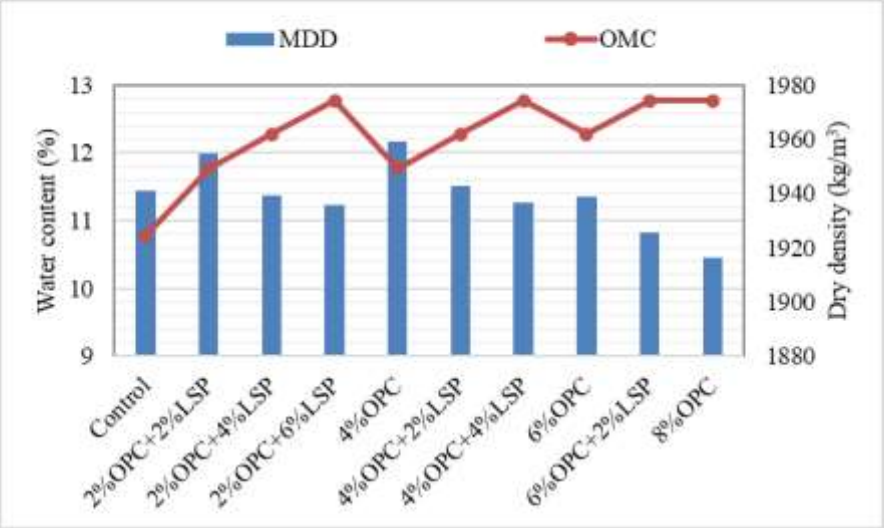

Figure 4.6: OMC and MDD of the control and the stabilized soil samples

As stated in Equation 3.1 provided by the TxDOT, the higher stabilizer content corresponds to the higher OMC value. Accordingly, the increased additive content leads to the reduced MDD value. Thus, an increase in LSP content causes a decrease in MDD value, as shown in Figure 4.7.

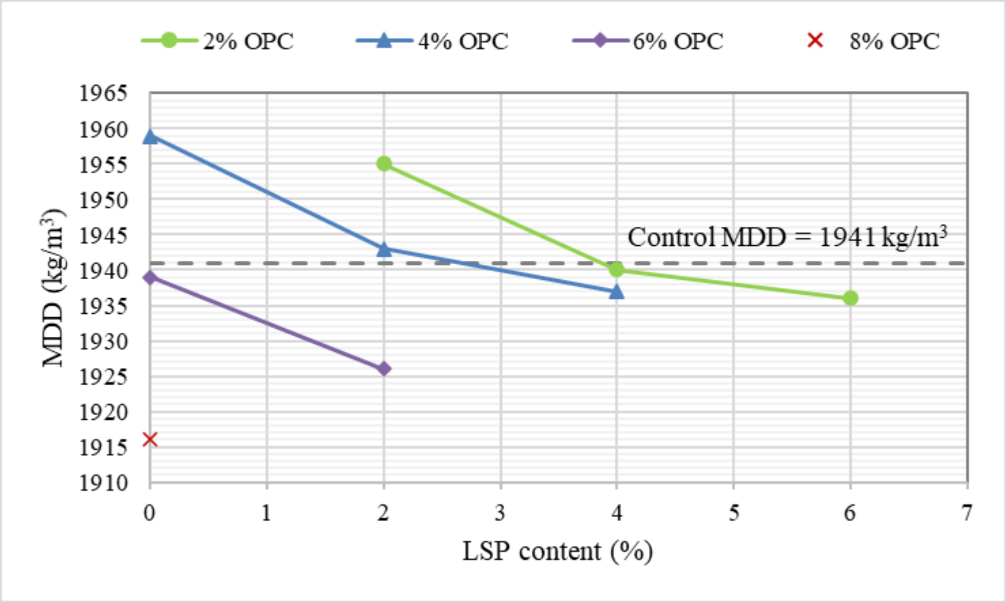

Figure 4.7: Effect of LSP on MDD

4.2.3. Unconfined Compressive Strength

The stabilization of soil aims to achieve both the short-term and the long-term strength improvements through the stabilization mechanism, particularly cation exchange, flocculation and agglomeration soil-stabilizer particles, and pozzolanic reaction, resulted in the formation of C-A-H and C-S-H. As shown in Figure 4.7, the stabilized mixtures have considerably higher UCS than the untreated soil, which reflects the main purpose of the stabilization process. The highest increase in UCS of about 171% corresponds to the 8% OPC-treated soil sample.

Figure 4.8: UCS of the control and the stabilized soil

In general, the cement content increase correlates with the instant and prolonged strength improvement, whereas the limestone powder content increase from 2% to 4 reduces soil strength, regardless of curing age, as illustrated in Figures 4.9 and 4.10. The LSP content increase from 4% to 6% at fixed 2% OPC content slightly enhances both short- and long-term strength. Interestingly, while the LSP content increase from 0% to 2% for the 6% OPC-treated soil increases the 7-days and the 28-days UCS significantly, the similar increase in LSP content for the 4% OPC-treated soil shows the opposite trend. Overall, the addition of LSP in the 2% OPC-treated and the 4% OPC-treated soil samples is not efficient in promoting bot instant and prolonged strength improvement. This behavior may be attributed to the gradation of the binders, particularly, the fact that LSP has well-graded grain size distribution, comparing to uniformly-graded OPC. The introduction of coarse particles together with fine particles, when LSP is added to the system, especially at higher contents than OPC, results in the poor binding of the soil-stabilizer particles and insufficient surface tension, that together lead to the reduction of the soil compressive strength, as it can be seen from the UCS test results.

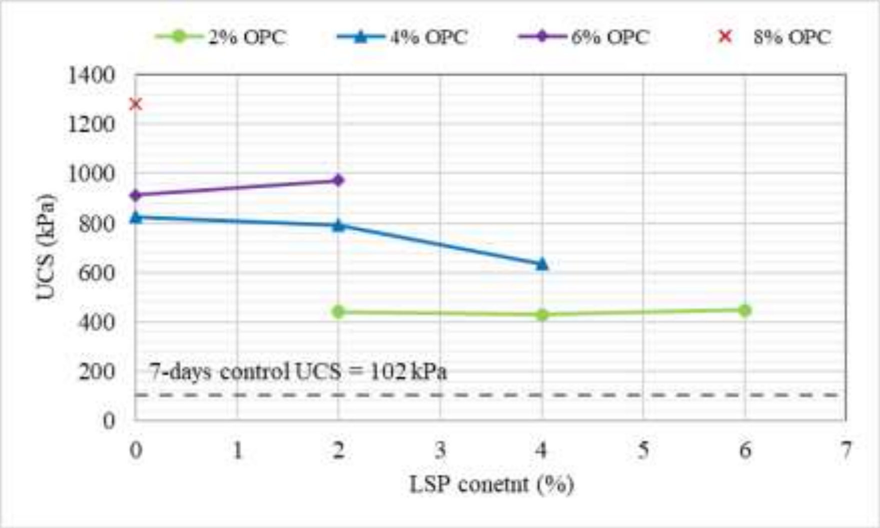

Figure 4.9: Effect of LSP on 7-days UCS

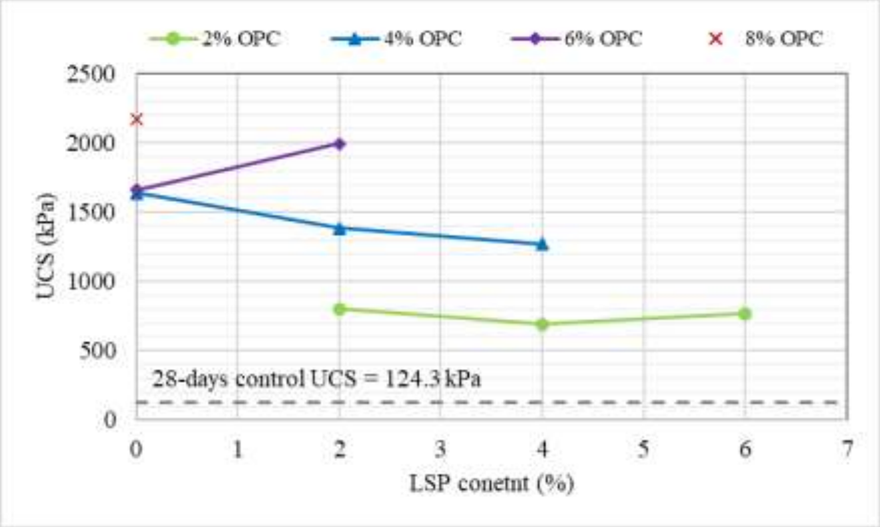

Figure 4.10: Effect of LSP on 28-days UCS

4.2.4. Shear Strength

The stabilization of soil aims to increase shear strength of soil. Namely, the flocculation and agglomeration of soil-stabilizer particles during cation exchange and the formation of cementation gel, a product of the pozzolanic reaction, result in the increased surface tension of soil-stabilizer matrix, thus, higher cohesion and friction angle of stabilized soil. Along with the effect of stabilizers, the shear strength parameters also rise under the effect of curing age. Accordingly, the DST results, illustrated in Figure 4.11, show a significant increase in soil cohesion due to the addition of stabilizers and curing age. Initially, the tested soil is cohesionless sand, and after mixing it with cement and limestone powder, the cohesion of the soil-stabilizer mixture rises, with the maximum increase up to 62 kPa and 63 kPa associated with the 7-days and 58-days 8% OPC-treated soil sample, respectively.

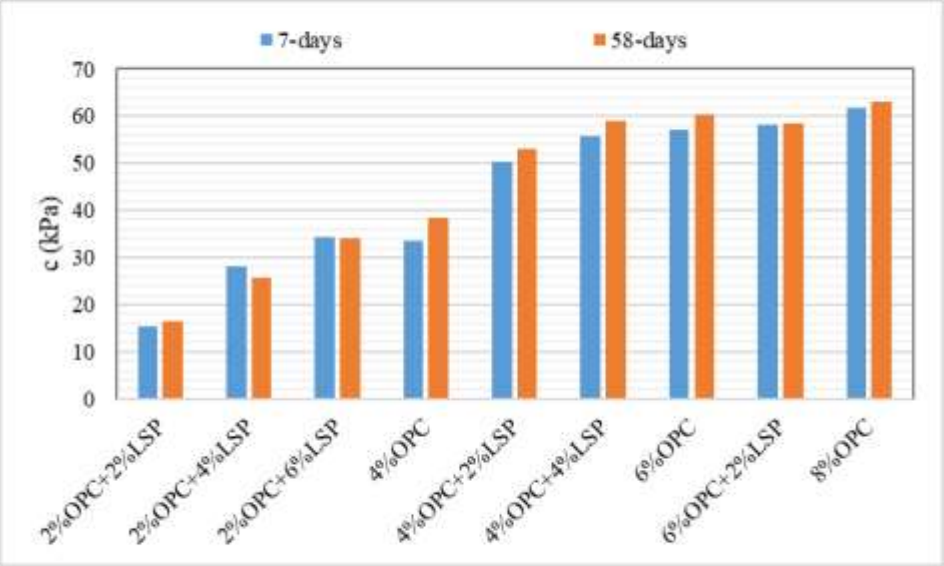

Figure 4.11: Cohesion of the stabilized soil

Generally, the increased stabilizer content, both OPC and LSP, results in increased soil cohesion. However, the effect of LSP is more moderate, comparing to that of OPC, as provided in Figures 4.12 and 4.13. Particularly, for the 7-days cured samples, the LSP content increase from 0% to 2% has a more significant effect in increasing soil cohesion for the 4% OPC-stabilized sample rather than 6% OPC-stabilized one. Similarly, increasing LSP content from 2% to 4% is more effective in promoting soil cohesion for the samples treated with 2% OPC rather than the ones treated with 4% OPC, for both 7-days and 58-days samples. This trend may be explained by the particle size distribution of the stabilizers: while OPC is uniformly graded and mainly consists of particles between 10 μm and 45 μm, LSP has more particles coarser than 45 μm and more particles finer than 10 μm. The introduction of both coarse and fine particles, when LSP is added to the soil-cement mixture, changes the overall gradation of the system, and coarse particles weaken the effect of the stabilizer in promoting cohesion of the stabilized mixture. Interestingly, however, for the 6% OPC-stabilized soil samples exposed to the 58-days volumetric swelling, the increase in LSP content from 0% to 2% results in the reduction of soil cohesion, though not significant. In this sense, the sample treated with 4% OPC + 4% LSP can be compared to the samples treated with 6% OPC + 2% LSP. It can be concluded that, in the long-term perspective, the combination of lower cement and higher limestone powder contents can be more effective in enhancing shear strength parameters, namely cohesion, rather than the combination of higher cement and lower limestone powder contents. Decreasing OPC and increasing LSP contents is not only efficient technique in terms of shear strength improvement, but also an environmentally-friendly and cost-effective solution for soil stabilization.

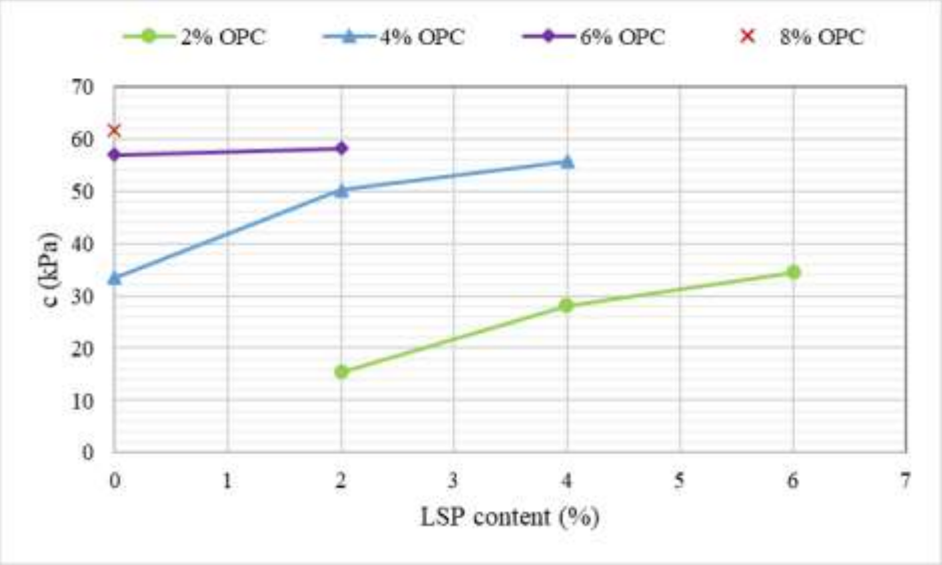

Figure 4.12: Effect of LSP on 7-days cohesion

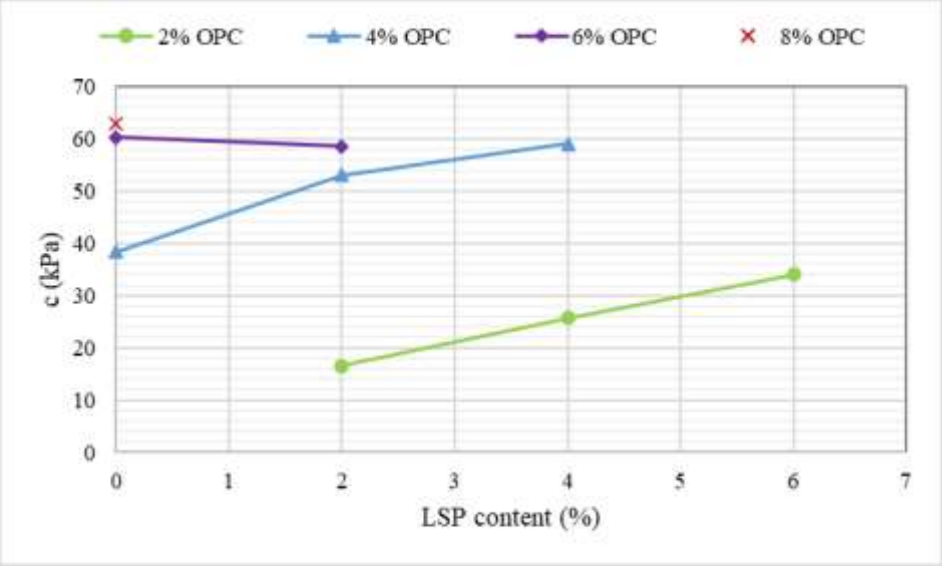

Figure 4.13: Effect of LSP on 58-days cohesion

The internal friction angle of the soil was not subjected to significant changes under the effect of the stabilization. As presented in Figure 4.14, friction angle values for the treated samples remain almost constant. This behavior may be attributed to the fact that cement and limestone powder do not affect the interlocking stress between soil-stabilizer particles.

Figure 4.14: Friction angle of the control and the stabilized soil

4.2.5. Resilient Modulus and California Bearing Ratio

Resilient modulus, M_R, and California bearing ratio, CBR, are the key parameters used for the assessment of pavement performance. In this paper, M_R and CBR were obtained using the empirical relation provided in the previous chapter, and the calculated values are presented in Figure 4.15. Usually, the unit for M_R is pound per square inch (psi), however, for convenience, the values were converted to MPa. In general, the soil stabilization mechanism promotes an increase in both M_R and CBR, thus, contribute to improved pavement performance and the prolonged road lifetime. The beneficial effect of the soil stabilization is evidential for all soil-stabilizer mixtures, except for the 2% OPC + 2% LSP treated sample. Based on Equation 3.6, the CBR of the treated soil depends on its plasticity, therefore, as PI of the 2% OPC + 2% LSP treated sample increased significantly, as described in the previous sections, CBR for the mixture decreased. The CBR reduction led to the M_R reduction of the same sample, according to Equation 3.4. The other stabilized samples show an increase in both M_R and CBR due to the positive effect of OPC and LSP on soil plasticity. The most significant increase in M_R and CBR is experienced in 6% OPC and 8% OPC treated samples. The addition of LSP to the 2% OPC + 2% LSP stabilized soil samples increases both M_R and CBR values, the same trend is applicable for the 4% OPC + 2% LSP treated samples, though the M_R and CBR increase in relatively low. Moreover, the stabilization of soil with 2% OPC + 6% LSP leads to the more effective M_R and CBR improvement, comparing to the stabilization with 4% OPC + 2% LSP. In this sense, the use of lower cement content in combination with higher limestone powder content is more beneficial in terms of enhancing M_R and CBR values rather than the use of higher cement and lower limestone powder contents. However, the addition of 2% LSP content to the 4% OPC and 6% OPC treated samples leads to the reduction of M_R and CBR values. This shows that the introduction of LSP to the individual OPC-treated system negatively correlates with the M_R and CBR of the system.

Figure 4.15: MR and CBR of the control and the stabilized soil

4.3. Evaluation of the Durability of the Stabilized Soil

The durability assessment of the stabilized soil samples was performed by conducting a three-dimensional (3-D) swelling test and tube suction test. The former provides volumetric swelling of the compacted sample under capillary soak conditions, while the latter obtains moisture susceptibility of the sample. Both tests were conducted during 58-days, including 28-day continuous capillary suction and 30-day wetting-drying cycles, which represent a more realistic approach. The residual strength of the samples exposed to the 3-D swelling was obtained in order to perform the long-term durability evaluation.

4.3.1. Three-Dimensional Swelling

Figure 4.16 shows the volumetric expansion results over time obtained from the 3-D swelling test for the designed soil mixtures. All soil mixtures, including the control and the stabilized soil, experienced rapid volumetric swelling at an early stage. The steep increase in volumetric expansion during the first 4 days may be attributed to the moisture capillary suction of the dried samples. That was then followed by the steady volumetric expansion at a slower rate for all stabilized soil samples. Such behavior may be caused by ettringite minerals formed during the reaction of aluminum and sulfate available from the sulfate-bearing saline soil, calcium derived from OPC and LSP, and water provided as a source for soil-cement and soil-cement-limestone powder miffing. In this sense, ettringite minerals can store large amounts of water within the stabilized soil sample resulting in its expansion.

The untreated soil sample resulted the highest volumetric expansion of about 5.4% during first 10 days and then exhibited a a shrinking behavior for the remaining testing period. Rapid volumetric swelling at the beginning stage of the expansion may be explained by the high solubility of sulfate ions. However, at a later age, sodium chloride, prevalent in the naturally saline soil, significantly lowers the solubility of sulfate ions, which, in turn, provides the mitigation of crystallization of sodium sulfate. In addition, the collapse of the structural system of soil matrix caused by the ettringite formation under prolonged moist conditions may also cause the shrinkage of soil sample after 10 days.

In general, OPC- and LSP-treatement lowers the volumetric expansion of sulfate-bearing saline soil. Comparing the treated samples, the 2% OPC + 6% LSP sample and the samples stabilized with 2% and 4% LSP contents at fixed 4% OPC content experienced relatively high expansion during 28-days continuous swelling. Further, these samples kept increasing up to 43 days, though the increase was not as significant as previously due to the effect of wetting-drying cycles described later in this section. The 2% OPC + 2% LSP soil sample, which exhibited the relatively low increase in volumetric expansion at an earlier age, gained the highest swelling at a later age. Similar behavior is associated with the 2% OPC + 4% LSP soil sample. Consequently, it can be concluded that the addition of LSP at the fixed 2% OPC content is not effective in the improvement of the long-term durability of the sulfate-bearing saline soil. Interestingly, the sample stabilized with the combination of 6% OPC and 2% LSP exhibited better performance in terms of free swelling rather than the 8% OPC treated sample, which shows that the higher cement content can be replaced with the lower cement content in combination with limestone powder to promote the same or even better soil performance. Finally, according to the 3-D swell test results illustrated in Figure 4.16, the 4% OPC treated sample had the highest resistance against the volumetric increase for the entire period of swelling, including 28-days continuous capillary suction and 30-days alternating wetting-drying cycles.

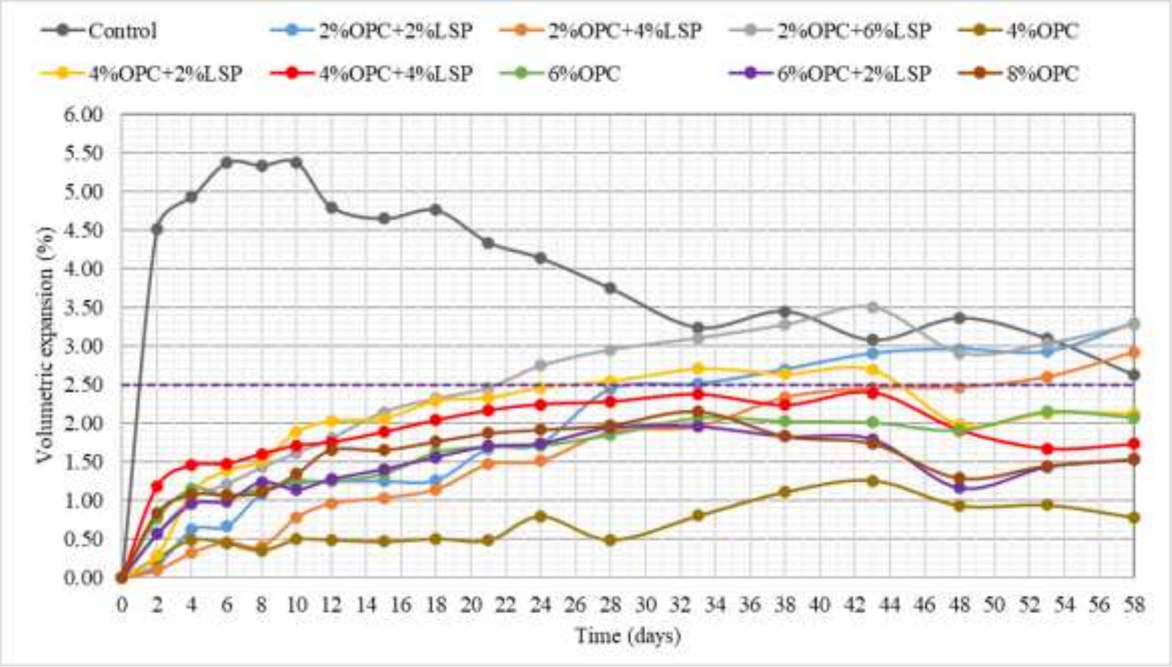

Figure 4.16: 3-D swelling of the control and the stabilized soil

The effect of wetting-drying cycles is shown in Figures 4.17 and 4.18. Wetting-drying cycles are implemented to evaluate the long-term performance of stabilizing binders under realistic field conditions, which is achieved by alternatinfg wetting and drying of the stabilized soil samples. Moreover, wetting-drying cycles allow achieving an equilibrium state for water content in the stabilized soil samples under capillary soak conditions. Indeed, after the rapid increase in the first 4 days followed by the steady increase up to 28 days, MC of the designed mixtures achieve the equilibrium state during 30-days wetting-drying cycles, as illustrated in Figure 4.17.

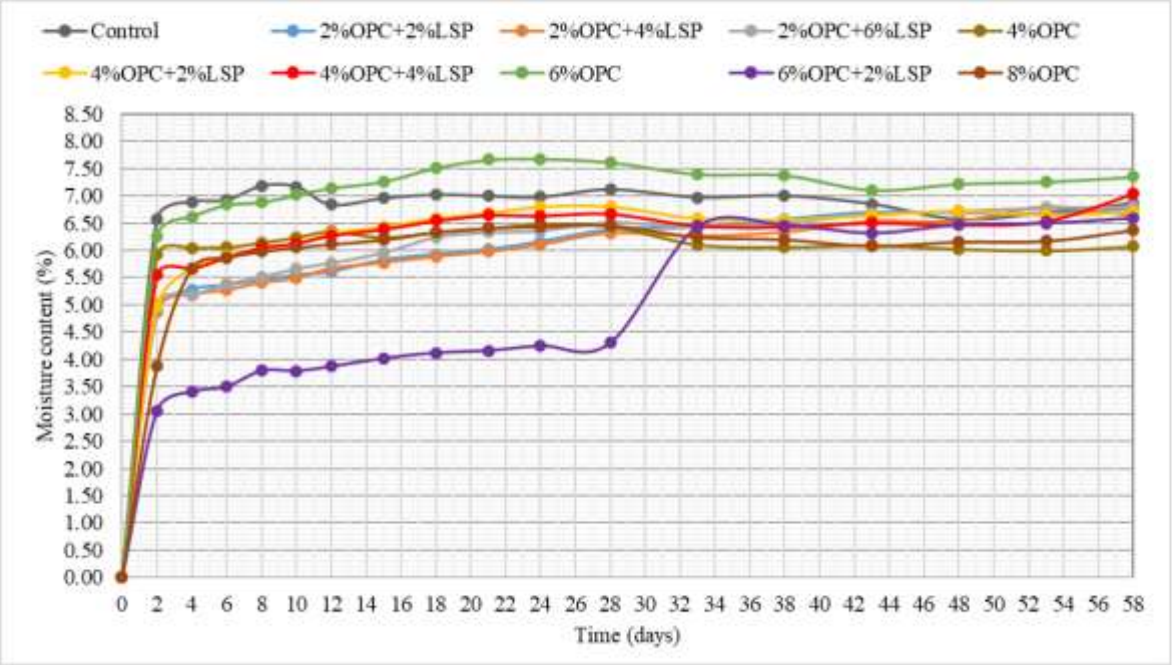

Figure 4.17: Moisture content of the control and the stabilized soil during 3-D swelling

Regarding volumetric expansion exhibited during wetting-drying cycles, it shows varying trends for the varying stabilizer contents. The samples stabilized with 4% OPC + 2% LSP, 4% OPC + 4% LSP, 6% OPC + 2% LSP, and 8% OPC resulted in the lower 3-D swelling after 30-days wetting-drying cycles, which corresponds to the purpose of wetting-drying technique. As moisture content achieves its equilibrium state during alternating wetting and drying of the samples, volumetric expansion of the treated soil decreases. However, the samples treated with the combination of 2% OPC and varying LSP contents, the 4% OPC and the 6% OPC treated samples exhibited the opposite behavior. This may be attributed to the continuous formation of ettringite minerals in the soil-stabilizer mixtures, which further promotes volumetric swelling. Nevertheless, the increase in volumetric swelling during 30-days wetting-drying cycles is not as high as during 28-days continuous capillary soak. This again shows the beneficial effect of wetting-drying cycles and, most importantly, the enhancement of long-term durability of the stabilization of sulfate-bearing saline soil with cement and limestone powder.

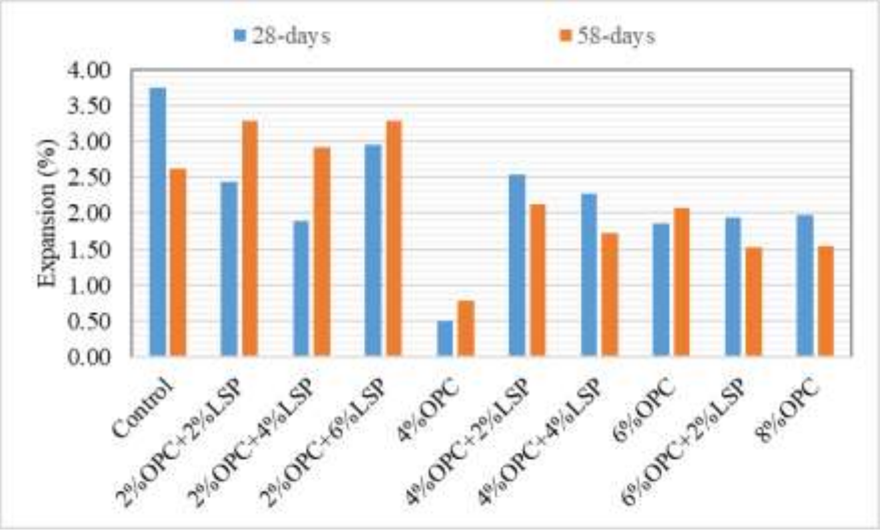

Figure 4.18: 28-days and 58-days 3-D swelling of the control and the stabilized soil

The residual strength provides a realistic approach for the long-term improvement evaluation for the stabilized soil samples. Thus, the samples exposed to 58-days volumetric swelling were tested to determine the unconfined compressive strength values. The UCS of the samples after the 3-D swelling test were compared to the UCS of the 7-days cured samples, as illustrated in Table 4.2. The residual strength values of all designed mixtures exceeded the threshold value of 80% recommended by the TxDOT. The high UCS values of the stabilized soil samples after the 3-D swelling test may be attributed to the hydration of cementitious material and the pozzolanic reaction between calcium and silica and alumina.

Table 4.2: Residual strength of the control and the stabilized soil after 3-D swelling test

Sample	**UCS (kPa)**		**Residual strength (%)**
	7-days	***58-days***	
Control	102.0	97.0	95.0
2%OPC+2%LSP	440.5	768.4	174.4
2%OPC+4%LSP	429.2	534.2	124.5
2%OPC+6%LSP	449.3	503.2	112.0
4%OPC	835.4	1237.2	148.1
4%OPC+2%LSP	790.9	1128.7	142.7
4%OPC+4%LSP	635.6	935.2	147.1
6%OPC	913.9	1450.0	158.7
6%OPC+2%LSP	971.2	1325.5	136.5
8%OPC	1281.8	2408.1	187.9

4.3.2. Dielectric Constant

As stated earlier, the dielectric constant value represents the moisture susceptibility of material and obtained in the tube suction test. The DC value is most sensitive and directly related to the amount of unbound water that exists within the soil-stabilizer matrix. The stabilized soil sample with the final DC value less than 10 is considered as of a good performance, while that with the DC value above 16 is expected to provide poor performance. The soil-stabilizer mixture having final DC values between 10 and 16 is expected to be marginally moisture-susceptible. Similar to the 3-D swell test, the over 58-days tube suction test was divided into 28-days continuous tube suction and 30-days wetting-drying cycles.

Figure 4.19 shows DC values of the designed soil-cement-limestone powder mixtures changing over time. As with the 3-D swelling results, there was a rapid increase in DC at an early age. This behavior is also explained by the intensive moisture capillary suction of the dried samples. The control soil mixture and the one treated with 6% cement exhibited the highest DC values at the 28-day, followed by the 2% OPC + 2% LSP and 2% OPC + 6% LSP soil samples, while the other mixtures stayed between 10 and 16, showing the marginal performance, at the same age. The lowest DC value at the 28-day is observed in the soil samples stabilized with 8% OPC and the combination of 2% and 4% LSP at the fixed 4% OPC content.

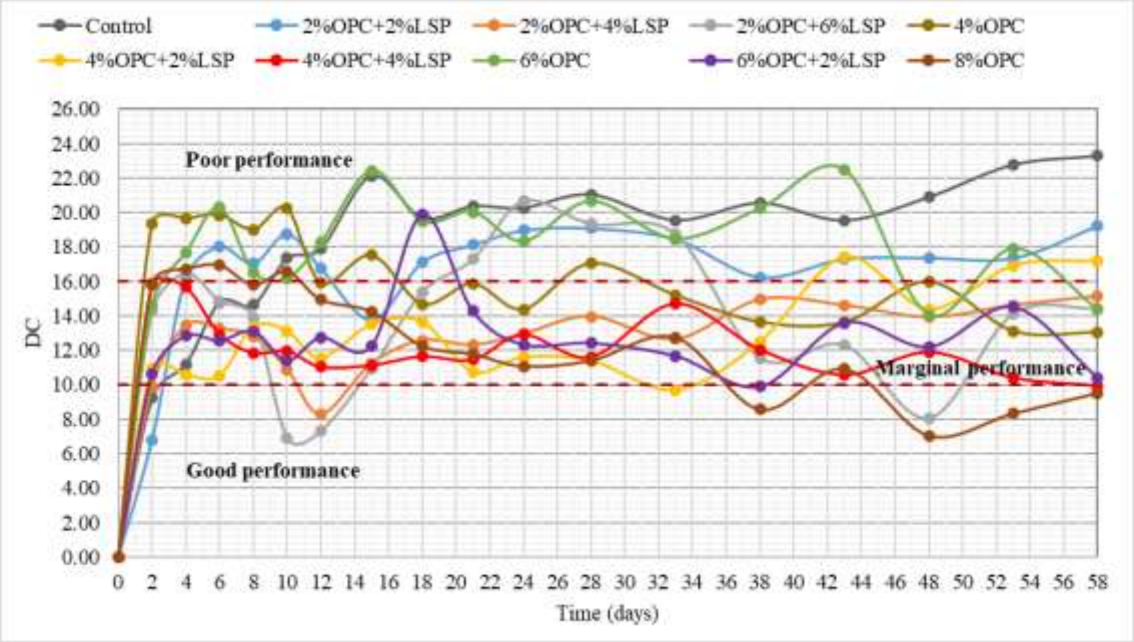

Figure 4.19: Dielectric constant of the control and the stabilized soil

The effect of wetting-drying cycles on the moisture susceptibility of soil is illustrated in Figure 4.20. After alternating wetting and drying of the samples for 30 days, 4% OPC + 4%

LSP soil sample and 8% OPC soil sample achieved DC reduction to below 10, which corresponds to the good performance of the material. The positive effect of the wetting-drying technique is also evidential for the majority of the designed mixtures, namely, the samples treated with 2% OPC + 6% LSP, 4% OPC, 6% OPC, and 6% OPC +2% LSP. While for the mixture stabilized with a combination of 2% OPC and 2% LSP the effect of wetting-drying cycles is not much significant, the sample stabilized with the combination of 4% OPC and 2LSP exhibits more moisture susceptible behavior after 30-days wetting-drying cycles. Consequently, the samples treated with 2% OPC + 2% LSP and 4% OPC + 2% LSP, along with the control sample, result in a high DC value at the 58th day, particularly, above 16, which is associated with the poor performance of the material due to the risk of moisture damage caused by high moisture susceptibility. Other mixtures exhibit marginal performance with final DC values lower or equal to the initial values when the samples were exposed to capillary soak conditions and the 28-days values before the samples were exposed to wetting-drying cycles.

Figure 4.20: 28-days and 58-days dielectric constant of the control and the stabilized soil

Generally, the increased stabilizer content deteriorates the moisture susceptibility of the soil-stabilizer mixture. Moreover, the 4% OPC + 4% LSP soil sample can be compared to the 6% OPC + 2% LSP and the 8% OPC soil samples, as they result in the same lowest DC values, hence, same resistance against moisture susceptibility and the same performance. Therefore, the utilization of the lower cement content in combination with higher LSP content again proves to be as effective in the enhancement of the long-term durability as the use of higher cement content combined with lower limestone powder content or used alone.

Chapter 5. Conclusion and Recommendations

The primary objective of this research was to improve mechanical properties and mitigate deleterious volume expansion in sulfate-bearing saline soil using the cement-limestone powder blend. After the comprehensive literature review on the soil stabilization, the stabilization mechanism, and the stabilizing materials, particularly the deep description of cement and limestone powder, was conducted, the integrated experimental program was developed to evaluate the combined effect of cement and limestone powder on the stabilization of sulfate-bearing saline soil in terms of the improvement of geotechnical properties and the enhancement of long-term durability. The successful completion of the tests provided necessary data, which was used for further analysis and interpretation. Based on the findings, the main conclusions of the study are drawn in this chapter. In addition, few recommendations regarding the research and future work are given at the end of the chapter.

Firstly, the combined effect of cement-limestone powder blend was evaluated in terms of the materials characterization of the stabilized soil. Ion chromatography shows a significant decrease in sulfate and chloride concentrations due to the effect of the stabilization. Moreover, the mineralogical analysis of the stabilized soil shows the formation of ettringite mineral, which corresponds to the limitation of the stabilization of sulfate-bearing saline soil with calcium-based stabilizing material, as described in the literature review.

Secondly, the geotechnical properties of the stabilized soil, including Atterberg limits, moisture-density relationship, unconfined compressive strength, shear strength parameters, namely, cohesion and friction angle, resilient modulus, and California bearing ratio, were assessed. Particularly, the effect of single cement and the effect of its combination with limestone powder were compared in order to evaluate the potential of limestone powder in soil stabilization. Based on the analysis of the findings, the following conclusions are drawn:

- The combined use of cement and limestone powder (6% OPC + 2 % LSP) is as effective in decreasing soil plasticity as the single cement use at higher content (8% OPC).
- There is an increase in optimum moisture content and corresponding decrease in maximum dry density with increase in total stabilizer content.
- The introduction of limestone powder to the cement-stabilized soil system is not effective in promoting both the instant and prolonged strength of the stabilized sample.
- The cohesion of the stabilized soil rises significantly, as the stabilizer content increases. In the long-term perspective, the combination of lower cement and higher limestone

powder contents can be more effective in enhancing shear strength parameters, namely cohesion, rather than the combination of higher cement and lower limestone powder contents.

- The introduction of LSP to the single OPC-treated system negatively correlates with the resilient modulus and California bearing ratio of the system.

Finally, the long-term durability assessment was performed by measuring volumetric expansion and moisture susceptibility if the stabilized soil samples were exposed to the prolonged capillary soak conditions. The altering wetting and drying cycles were also implemented to simulate a more realistic approach. Based on the test results and analysis, the following conclusions are drawn:

- The use of cement and limestone powder in the sulfate-bearing saline soil inhibited volumetric expansion due to ettringite minerals formed in the alumina-sulfate-calcium-water reaction.
- The use of cement as of single additive promotes the lower volumetric expansion of the soil compared to the use of its combination with limestone powder.
- The residual strength values of all designed mixtures exceeded the threshold value of 80% recommended by the TxDOT.
- Cement and limestone powder stabilization increases the moisture susceptibility resistance of sulfate-bearing saline soil. The utilization of the lower cement content in combination with higher limestone powder content (4% OPC + 4% LSP) is as effective in deteriorating moisture susceptibility of soil as the use of higher cement content combined with lower limestone powder content (6% OPC + 2% LSP) or used alone (8% OPC).

Overall, based on the combined analysis of the geotechnical properties and the durability parameters of the stabilized soil samples, the soil mixture stabilized with 4% cement and 4% limestone powder has the best performance for the mechanical and durability properties of sulfate-bearing saline soil. Moreover, the decrease in cement and the increase in limestone powder contents are a more environmentally sustainable and cost-effective method used for the chemical stabilization of soil.

In addition, few recommendations regarding the research and future work are summarized as follows:

- To perform the full comparison of cement and limestone powder as of stabilizing materials, the mixtures of the same fixed and alternating stabilizers contents can be designed: for example, 2% OPC + 2% LSP, 2% OPC + 4% LSP, 2% OPC + 6% LSP can be better compared with 4% OPC + 2% LSP, 4% OPC + 4% LSP, 4% OPC + 6% LSP.
- The introduction of the triaxial test into the experimental procedure can allow to obtain more accurate data and perform a more comprehensive analysis of strength parameters of the tested soil mixtures.
- The relationship between the stabilizer content and the improvement of soil properties can be investigated more deeply to derive the mathematical model.
- The addition of alternative stabilizers, such as waste glass powder, fly ash, and blast furnace slag, can be proposed and studied.

References

[1] Borovskii, V.M. 1982. “Formation of saline soils and haologeochemical regions of Kazakhstan”. Nauka publ., Alma-Ata, pp. 256. [in Russian]

[2] Carteret, R. D., Buzzi, O., & Fityus, S. 2010. “A Review of the Effects of Salinity on Road Pavements and Bituminous Surfacings”. 24th ARRB Conference – Building on 50 years of road and transport research, Melbourne.

[3] Horpibulsuk, S., Phojan, W., Suddeepong, A., Chinkulkijniwat, A., & Liu, MD. 2012. “Strength Development in Blended Cement Admixed Saline Clay”. Appl Clay Sci, 55, pp. 44–52.

[4] Cheng, Y., Wang, S., Li, J., Huang, X., Li, C., & Wu, J. 2018. “Engineering and Mineralogical Properties of Stabilized Expansive Soil Compositing Lime and Natural Pozzolans”. Construction and Building Materials, pp. 1031–1038.

[5] Saylak, D., Mishra, S.K., Mejeoumov, G.G., & Shon, C.-S. 2008. “Fly Ash–Calcium Chloride Stabilization in Road Construction”. Transportation Research Record: Journal of the Transportation Research Board, 2053-04, pp. 23–29.

[6] Mola-Abasi, H., & Shooshpasha, I. 2016. “Influence of Zeolite and Cement Additions On Mechanical Behavior of Sandy Soil”. Journal of Rock Mechanics and Geotechnical Engineering, 8(5), pp. 746-752. doi:10.1016/j.jrmge.2016.01.008

[7] Kumar, A., Walia, B. S., & Bajaj, A. 2007. “Influence of Fly Ash, Lime, and Polyester Fibers on Compaction and Strength Properties of Expansive Soil”. Journal of Materials in Civil Engineering, 19(3), pp. 242-248. doi:10.1061/(asce)0899-1561(2007)19:3(242)

[8] Shon, C.-S., Saylak, D., & Mishra, S. K. 2010. “Combined Use of Calcium Chloride and Fly Ash in Road Base Stabilization”. Transportation Research Record: Journal of the Transportation Research Board, 2186, pp. 120–129. doi: 10.3141/2186-13

[9] Behnood, A. (2018). “Soil and Clay Stabilization with Calcium- and Non-calcium-based Additives: a State-of-the-art Review of Challenges, Approaches and Techniques”. Transportation Geotechnics, 17, pp. 14-32. doi:10.1016/j.trgeo.2018.08.002

[10] Ikeagwuani, C. C., & Nwonu, D. C. 2019. “Emerging Trends in Expansive Soil Stabilisation: a Review”. Journal of Rock Mechanics and Geotechnical Engineering, 11(2), pp. 423-440. doi:10.1016/j.jrmge.2018.08.013

[11] Al-Joulani. 2012. “Effect of Stone Powder and Lime on Strength, Compaction and CBR Properties of Fine Soils”. Jordan Journal of Civil Engineering, 6(1).

[12] Pastor, J., Tomás, R., Cano, M., Riquelme, A., & Gutiérrez, E. 2019. “Evaluation of the Improvement Effect of Limestone Powder Waste in the Stabilization of Swelling Clayey Soil”. Sustainability, 11(3), pp. 679. doi: 10.3390/su11030679

[13] Routhu, B. 2019. “Stabilization of Soil by using Limestone Powder”. International Research Journal of Engineering and Technology, 6(3).

[14] Burroughs, V. S. 2001. “Quantitative Criteria for the Selection and Stabilization of Soils for Rammed Earth Wall Construction”. Unpublished doctoral dissertation. http://unsworks.unsw.edu.au/fapi/datastream/unsworks:468/SOURCE02?view=true

[15] Hall, M., Najim, K., & Keikhaei Dehdezi, P. 2012. “Soil Stabilisation and Earth Construction: Materials, Properties and Techniques”. Modern Earth Buildings, pp. 222-255. doi:10.1533/9780857096166.2.222

[16] TxDOT 09/2005. 2005. “Guidelines for Treatment of Sulfate-rich Soils and Bases in Pavement Structures”. Texas Department of Transportation, Construction Division, Materials & Pavements Section, Geotechnical, Soils & Aggregates Branch, Austin, TX.

[17] Soltani, A., Taheri, A., Khatibi, M., & Estabragh, A. R. 2017. “Swelling Potential of a Stabilized Expansive Soil: a Comparative Experimental Study”. Geotechnical and Geological Engineering, 35(4), pp. 1717-1744. doi:10.1007/s10706-017-0204-1

[18] Mirzababaei, M., Arulrajah, A., & Ouston, M. 2017. “Polymers for Stabilization of Soft Clay Soils”. Procedia Engineering, 189, pp. 25-32. doi:10.1016/j.proeng.2017.05.005

[19] Rezaeimalek, S., Huang, J., & Bin-Shafique, S. 2017. “Evaluation of Curing Method and Mix Design of a Moisture Activated Polymer for Sand Stabilization”. Construction and Building Materials, 146, pp. 210-220. doi:10.1016/j.conbuildmat.2017.04.093

[20] Kumar, A., & Gupta, D. 2016. “Behavior of Cement-stabilized Fiber-reinforced Pond Ash, Rice Husk Ash–soil Mixtures”. Geotextiles and Geomembranes, 44(3), pp. 466-474. doi:10.1016/j.geotexmem.2015.07.010

[21] Sabat, A.K.; & Muni, P.K. 2015. “Effects of Limestone Dust on Geotechnical Properties of an Expansive Soil”. Int. J. Appl. Eng. Res., 10, pp. 37724–37730.

[22] Ogila, W.A.M. 2016. “The Impact of Natural Ornamental Limestone Dust on Swelling Characteristics of High Expansive Soils”. Environ. Earth Sci., 75, pp. 1493.

[23] Bargonza, S., Peete, J. M., Freer-Hewish, R., & Newill, D. 1987. “Carbonation of Stabilised Soil-cement and Soil-lime Mixtures”. In: P-TRC. Proc of Seminar H, MTC Transport and Planning, Summer Annual Meeting, University of Bath. London: P-TRC Education and Research Services, pp. 29-48

[24] Guyer, J. P. 2011. “Introduction to Soil Stabilization in Pavements”. Independently published.

[25] Jung, C., & Bobet, A. 2008. “Post-construction Evaluation of Lime-treated Soils”. doi:10.5703/1288284313443

[26] Singh Pundir, V., & Prakash, V. 2015. “Effect of Soil Stabilizers on the Structural Design of Flexible Pavements”. Advances in Applied Science Research, 6(8), pp. 134-147.

[27] Harris, P., Scullion, T., & Sebesta, S. 2004. “Hydrated Lime Stabilization of Sulfate-Bearing Soils in Texas (Rep. No. FHWA/TX-04/0-4240-2)”. Texas Transportation Institute, College Station.

[28] McCarthy, M. J., Csetenyi, L. J., Sachdeva, A., & Dhir, R. K. 2014. “Engineering and Durability Properties of Fly Ash-treated Lime-stabilised Sulphate-bearing Soils”. Engineering Geology, 174, pp. 139-148. doi:10.1016/j.enggeo.2014.03.001

[29] Seco, A., Miqueleiz, L., Prieto, E., Marcelino, S., García, B., & Urmeneta, P. 2017. “Sulfate Soils Stabilization with Magnesium-based Binders”. Applied Clay Science, 135, pp. 457-464. doi:10.1016/j.clay.2016.10.033

[30] Zhang, M., Zhao, M., Zhang, G., Nowak, P., Coen, A., & Tao, M. 2015. “Calcium-free Geopolymer as a Stabilizer for Sulfate-rich Soils”. Applied Clay Science, 108, pp. 199-207. doi:10.1016/j.clay.2015.02.029

[31] ASTM D3282-15. 2015. “Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes”. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.
[32] Tex-110-E. 1999. “Particle Size Analysis of Soils”. Texas Department of Transportation, Construction Division, Austin, TX.
[33] Tex-128-E. 1999. Determining Soil pH. Texas Department of Transportation, Construction Division, Austin, TX.
[34] Tex-121-E. 2002. “Soil-Lime Testing”. Texas Department of Transportation, Construction Division, Austin, TX.
[35] Tex-104-E. 1999. “Determining Liquid Limits of Soils”. Texas Department of Transportation, Construction Division, Austin, TX.
[36] Tex-105-E. 1999. “Determining Plastic Limits of Soils”. Texas Department of Transportation, Construction Division, Austin, TX.
[37] Tex-106-E. 1999. “Determining Plasticity Index of Soils”. Texas Department of Transportation, Construction Division, Austin, TX.
[38] ASTM D698-12e2. 2012. “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort”. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.
[39] Tex-120-E. 2013. “Soil-Cement Testing”. Texas Department of Transportation, Construction Division, West Conshohocken, PA.
[40] ASTM D1633-17. 2017. “Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders”. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.
[41] ASTM D 3080-11. 2011. “Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions”. Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.
[42] Texas A&M Transportation Institute. “3-D Swell Test.” College Station, TX.
[43] Tex-144-E. 2020. “Tube Suction Test”. Texas Department of Transportation, Materials and Tests Division, Austin, TX.

Appendices

Table A.1: Sieve analysis of the tested soil

Sieve Size		Individual Weight Retained (g)	Individual % Retained	Cummulative % Retained	% Passing
mm	**No.**				
25	**1''**	0.00	0.00	0.00	100.00
9.5	**3/8''**	83.00	5.06	5.06	94.94
4.75	**No. 4**	77.00	4.69	9.75	90.25
2	**No. 10**	118.00	7.19	16.94	83.06
0.425	**No. 40**	367.00	22.36	39.31	60.69
0.075	**No. 200**	984.00	59.96	99.27	0.73
Pan		12.00	0.73	100.00	0.00
Total		1641	0.55% loss		
Initial Mass		1650			

Table A.2: pH of the control and the stabilized soil

	7-days	58-days
Control	6.32	
2%OPC+2%LSP	11.51	11.06
2%OPC+4%LSP	11.45	11.03
2%OPC+6%LSP	11.44	11.01
4%OPC	11.96	11.65
4%OPC+2%LSP	12.17	11.89
4%OPC+4%LSP	12.14	11.88
6%OPC	12.51	12.19
6%OPC+2%LSP	12.51	12.27
8%OPC	12.57	12.44

Table A.3: Atterberg limits of the control and the stabilized soil

	LL	PL	PI
Control	19.16	16.67	2.49
2%OPC+2%LSP	20.08	15.48	4.60
2%OPC+4%LSP	16.92	14.45	2.48
2%OPC+6%LSP	14.19	12.79	1.40
4%OPC	14.26	12.52	1.74
4%OPC+2%LSP	16.01	14.23	1.78
4%OPC+4%LSP	15.97	14.29	1.68
6%OPC	16.54	15.99	0.55
6%OPC+2%LSP	15.80	15.46	0.34
8%OPC	15.70	15.49	0.22

Table A.4: OMC and MDD of the control and the stabilized soil

	OMC (%)	**MDD (kg/m^3)**
Control	10.8	1941
2%OPC+2%LSP	11.8	1955
2%OPC+4%LSP	12.3	1940
2%OPC+6%LSP	12.8	1936
4%OPC	11.8	1959
4%OPC+2%LSP	12.3	1943
4%OPC+4%LSP	12.8	1937
6%OPC	12.3	1939
6%OPC+2%LSP	12.8	1926
8%OPC	12.8	1916

Table A.5: UCS of the control and the stabilized soil

	UCS (kPa)	
	7-days	**28-days**
Control	102.0	124.3
2%OPC+2%LSP	440.5	801.3
2%OPC+4%LSP	429.2	689.0
2%OPC+6%LSP	449.3	764.8
4%OPC	835.4	1640.3
4%OPC+2%LSP	790.9	1383.7
4%OPC+4%LSP	635.6	1270.7
6%OPC	913.9	1661.2
6%OPC+2%LSP	971.2	1993.1
8%OPC	1281.8	2172.2

Table A.6: Cohesion and friction angle of the control and the stabilized soil

	7-days		**58-days**	
	c (kPa)	**φ (°)**	**c (kPa)**	**φ (°)**
Control	0	84.40829	0	84.71284
2%OPC+2%LSP	15.366	83.92754	16.547	83.85921
2%OPC+4%LSP	28.099	83.48544	25.728	82.7268
2%OPC+6%LSP	34.439	82.50512	34.06	83.03948
4%OPC	33.543	83.03939	38.397	83.54898
4%OPC+2%LSP	50.259	81.94247	53.138	82.33964
4%OPC+4%LSP	55.782	81.31017	59.081	81.69181
6%OPC	57.032	82.74467	60.267	82.73579
6%OPC+2%LSP	58.185	82.79656	58.57	83.22158
8%OPC	61.686	83.00413	62.986	83.01219

Table A.7: CBR and M_R of the control and the stabilized soil

	P200	PI	wPI	CBR (%)	M_R (psi)	M_R (MPa)
Control	0.73	2.49	1.82	32.22	23582	162.59436
2%C+2%LP	0.73	4.60	3.36	21.74	18334	126.40754
2%C+4%LP	0.73	2.48	1.81	32.36	23647	163.03972
2%C+6%LP	0.73	1.40	1.02	43.04	28382	195.68987
4%OPC	0.73	1.74	1.27	38.97	26634	183.6352
4%C+2%LP	0.73	1.78	1.30	38.53	26442	182.30994
4%C+4%LP	0.73	1.68	1.23	39.55	26890	185.40017
6%C	0.73	0.34	0.25	63.37	36359	250.68449
6%C+2%LP	0.73	0.55	0.40	57.98	34346	236.80457
8%C	0.73	0.22	0.16	67.27	37774	260.44054

Table A.8: Average 3-D swelling of the control and the stabilized soil during 28 days

	0	2	4	6	8	10	12	15	18	21	24	28
Control	0.00	4.52	4.92	5.37	5.33	5.37	4.80	4.65	4.76	4.34	4.14	3.74
2%OPC+2%LSP	0	0.17	0.62	0.67	1.09	1.22	1.25	1.25	1.27	1.67	1.74	2.44
2%OPC+4%LSP	0.00	0.10	0.33	0.46	0.41	0.78	0.96	1.04	1.15	1.47	1.51	1.89
2%OPC+6%LSP	0.00	0.57	1.03	1.21	1.43	1.62	1.80	2.15	2.32	2.46	2.74	2.95
4%OPC	0.00	0.26	0.50	0.45	0.36	0.50	0.49	0.47	0.51	0.49	0.80	0.49
4%OPC+2%LSP	0.00	0.29	1.11	1.39	1.51	1.89	2.03	2.06	2.29	2.33	2.46	2.54
4%OPC+4%LSP	0.00	1.19	1.46	1.48	1.60	1.71	1.75	1.89	2.04	2.17	2.24	2.28
6%OPC	0.00	0.77	1.15	1.07	1.16	1.26	1.25	1.35	1.63	1.70	1.71	1.86
6%OPC+2%LSP	0.00	0.57	0.96	0.99	1.24	1.14	1.28	1.41	1.56	1.71	1.74	1.94
8%OPC	0.00	0.84	1.08	1.07	1.11	1.35	1.66	1.66	1.77	1.87	1.92	1.98

Table A.9: Average 3-D swelling of the control and the stabilized soil during 30 days wet-dry cycles

	33	38	43	48	53	58
Control	3.24	3.45	3.08	3.36	3.10	2.62
4%OPC	0.80	1.11	1.26	0.93	0.94	0.78
6%OPC	2.07	2.03	2.01	1.91	2.15	2.08
8%OPC	2.16	1.83	1.74	1.29	1.45	1.54
2%OPC+2%LSP	2.51	2.70	2.91	2.96	2.93	3.29
2%OPC+4%LSP	1.96	2.33	2.45	2.46	2.60	2.92
2%OPC+6%LSP	3.10	3.27	3.50	2.91	3.03	3.28
4%OPC+2%LSP	2.70	2.64	2.69	1.98	2.13	2.12
4%OPC+4%LSP	2.37	2.24	2.40	1.91	1.67	1.73
6%OPC+2%LSP	1.96	1.83	1.79	1.16	1.44	1.53

Table A.10: Average moisture content change of the control and the stabilized soil during 28 days of 3-D swelling test

	0	2	4	6	8	10	12	15	18	21	24	28
Control	0.00	6.57	6.89	6.92	7.18	7.17	6.84	6.96	7.02	6.99	6.98	7.12
2%OPC+2%LSP	0	4.85	5.28	5.36	5.46	5.54	5.61	5.82	5.92	6.01	6.16	6.38
2%OPC+4%LSP	0.00	4.90	5.18	5.27	5.41	5.49	5.67	5.77	5.89	5.97	6.10	6.31
2%OPC+6%LSP	0.00	5.01	5.17	5.39	5.51	5.67	5.77	5.96	6.25	6.33	6.36	6.51
4%OPC	0.00	5.92	6.04	6.06	6.15	6.24	6.35	6.24	6.34	6.40	6.48	6.45
4%OPC+2%LSP	0.00	4.97	5.67	5.90	6.05	6.13	6.31	6.44	6.59	6.68	6.80	6.81
4%OPC+4%LSP	0.00	5.54	5.66	5.87	6.05	6.13	6.27	6.39	6.54	6.64	6.64	6.67
6%OPC	0.00	6.26	6.62	6.84	6.88	7.02	7.14	7.26	7.51	7.66	7.68	7.62
6%OPC+2%LSP	0.00	3.06	3.41	3.50	3.79	3.79	3.87	4.02	4.12	4.16	4.25	4.30
8%OPC	0.00	3.87	5.67	5.87	5.98	6.05	6.11	6.19	6.34	6.41	6.44	6.46

Table A.11: Average moisture content change of the control and the stabilized soil during 30 days wet-dry cycles of 3-D swelling test

	33	38	43	48	53	58
Control	6.97	7.00	6.85	6.57	6.69	6.87
2%OPC+2%LSP	6.42	6.56	6.69	6.68	6.67	6.77
2%OPC+4%LSP	6.26	6.33	6.53	6.53	6.79	6.63
2%OPC+6%LSP	6.43	6.50	6.67	6.72	6.78	6.80
4%OPC	6.11	6.06	6.10	6.03	6.00	6.08
4%OPC+2%LSP	6.59	6.56	6.65	6.72	6.65	6.71
4%OPC+4%LSP	6.45	6.43	6.51	6.47	6.54	7.04
6%OPC	7.40	7.38	7.11	7.22	7.26	7.35
6%OPC+2%LSP	6.43	6.46	6.31	6.46	6.49	6.59
8%OPC	6.25	6.20	6.08	6.16	6.17	6.37

Table A.12: Dielectric constant of the control and the stabilized soil during 28 days of tube suction test

	0	2	4	6	8	10	12	15	18	21	24	28
Control	13.10	22.32	24.26	27.88	27.74	30.44	30.99	35.24	32.79	33.46	33.37	34.14
2%OPC+2%LSP	14.01	20.83	30.20	32.06	31.06	32.78	30.79	27.80	31.13	32.14	32.99	33.10
2%OPC+4%LSP	13.50	23.39	26.93	26.75	26.31	24.39	21.79	24.73	26.06	25.81	26.45	27.47
2%OPC+6%LSP	19.88	34.16	36.39	34.75	33.79	26.81	27.20	30.84	35.27	37.19	40.57	39.24
4%OPC	20.65	40.01	40.30	40.51	39.66	40.88	36.57	38.17	35.34	36.52	35.03	37.70
4%OPC+2%LSP	14.51	25.43	25.08	25.03	27.87	27.61	26.06	28.01	28.15	25.26	26.10	25.90
4%OPC+4%LSP	21.10	36.88	36.76	34.04	32.93	33.05	32.12	32.22	32.74	32.54	34.00	32.71
6%OPC	12.50	27.09	30.14	32.78	29.05	28.68	30.76	34.93	31.98	32.52	30.81	33.15
6%OPC+2%LSP	19.98	30.61	32.82	32.55	33.09	31.39	32.73	32.24	39.88	34.26	32.31	32.40
8%OPC	21.53	37.41	38.26	38.50	37.34	38.13	36.49	35.79	33.79	33.31	32.61	32.94

Table A.13: Dielectric constant of the control and the stabilized soil during 30 days wet-dry cycles of tube suction test

	0	**33**	**38**	**43**	**48**	**53**	**58**
Control	13.10	32.66	33.65	32.64	34.00	35.88	36.39
2%OPC+2%LSP	14.01	32.48	30.27	31.32	31.39	31.37	33.24
2%OPC+4%LSP	13.50	26.15	28.44	28.11	27.42	28.12	28.63
2%OPC+6%LSP	19.88	38.66	31.44	32.19	27.94	34.01	34.33
4%OPC	20.65	35.84	34.29	34.28	36.63	33.76	33.68
4%OPC+2%LSP	14.51	24.19	27.01	31.93	28.90	31.42	31.71
4%OPC+4%LSP	21.10	35.81	33.13	31.67	32.99	31.50	31.04
6%OPC	12.50	30.96	32.72	34.97	26.55	30.39	26.86
6%OPC+2%LSP	19.98	31.65	29.87	33.58	32.18	34.50	30.40
8%OPC	21.53	34.29	30.09	32.46	28.57	29.86	31.05