

Article

Evaluating the Efficacy of Limestone Powder as a Partial Replacement of Ordinary Portland Cement for the Sustainable Stabilization of Sulfate-Bearing Saline Soil

Ayazhan Bazarbekova ¹, Chang-Seon Shon ^{2,*}, Aizhan Kissambinova ², Dichuan Zhang ² and Jong Kim ^{2,*}

¹ Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843, USA; ayazhan@tamu.edu

² Department of Civil and Environmental Engineering, School of Engineering and Digital Sciences, Nazarbayev University, Astana 010000, Kazakhstan; aizhan.kissambinova@nu.edu.kz (A.K.); dichuan.zhang@nu.edu.kz (D.Z.)

* Correspondence: chang.shon@nu.edu.kz (C.-S.S.); jong.kim@nu.edu.kz (J.K.); Tel.: +7-7172-70-64-22 (C.-S.S.); +7-7172-70-91-36 (J.K.)

Abstract: In today's era of rapid infrastructure development, ensuring the durability and environmental sustainability of soil subgrades in road construction remains a critical concern. With recent advancements in non-traditional soil stabilizing binders, including environmentally friendly industrial waste materials such as fly ash and slag, there is growing recognition of the potential for limestone powder (LSP), a low-carbon alternative soil stabilizing material, to replace traditional calcium-based additives like ordinary Portland cement (OPC) and lime. However, the full extent of LSP's efficacy in soil treatment has yet to be fully explored. Therefore, this paper investigates the partial substitution of cement with LSP for stabilizing sulfate-bearing saline sandy soil and assesses its impact on the treated soil samples' mechanical properties and durability parameters. For this purpose, five stabilized mixes, including a control mix (no stabilizer), were designed, wherein LSP partially replaced 8% of the OPC at 25%, 50%, and 75% substitution levels. A series of laboratory tests were conducted to track the changes in the geochemical properties and the mineralogical compositions and evaluate the stabilized soil samples' improved mechanical performance and durability parameters. The experimental results show that adding LSP to the cement-treated sulfate-bearing saline soil improved the soil's mechanical properties and enhanced the soil's durability parameters. Specifically, it decreased the soil plasticity, improved the soil strength parameters, enhanced the soil stability, and reduced the volumetric swelling and soil moisture susceptibility. In addition to its technical advantages, using LSP, an industrial byproduct, in soil stabilization offers environmental and economic benefits, highlighting its potential as a sustainable solution in engineering practices.

Keywords: soil stabilization; limestone powder; sulfate-bearing saline soil; durability; sustainability



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1. Introduction

Many highways of paved roads (asphalt concrete and Portland cement concrete) are suffering many distresses due to severe weather conditions and the poor stabilization of the sublayers under surface courses in Kazakhstan. In road construction, soil often forms the subgrade layer, playing a critical role in the pavement's longevity and performance. However, soil's geotechnical properties vary depending on its origin, regional environmental conditions, and treatment processes. In the case of saline soils, for example, the presence of salts can lead to the formation of salt whiskers, which create crystallization pressure and result in localized stresses and non-uniform movement within the soil matrix. This can ultimately lead to defects such as excessive heave and pavement deterioration [1–3]. Since the soils in west Kazakhstan contain lots of salt and high sulfate, many heaving issues in the pavement are common. To enhance the soil quality and meet the desired performance

standards in pavement construction, weak and problematic soils are typically modified through a chemical stabilization process involving chemical additives such as ordinary Portland cement (OPC), lime, and fly ash, which are suggested as traditional calcium-based stabilizers [4–6].

The cement stabilization of soil stands out as the most common and reliable technique for enhancing soil's mechanical properties [7,8]. Upon mixing with water, the soil–cement mixture undergoes immediate chemical reactions known as cation exchanges, which induce the flocculation of soil particles and lead to instant improvement in the soil's plasticity and workability. Furthermore, the long-term mechanism of soil stabilization using calcium-based materials involves sustained chemical reactions, specifically cement hydration and pozzolanic reactions. Cement hydration begins with the reaction of water to cement particles, leading to the formation of calcium silicate hydrate (C-S-H) and calcium hydroxide ($\text{Ca}(\text{OH})_2$), which contribute to the initial set and strength of the stabilized soil. Subsequently, pozzolanic reactions occur when the calcium hydroxide released from cement hydration reacts with the dissolved silica (SiO_2) and alumina (Al_2O_3) present in the clay. This series of pozzolanic reactions further produces additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), creating a hardened matrix. These cementing products fill the voids and bind the soil particles together, as depicted in Figure 1, thereby enhancing the soil's mechanical properties and durability over time [4,9,10].

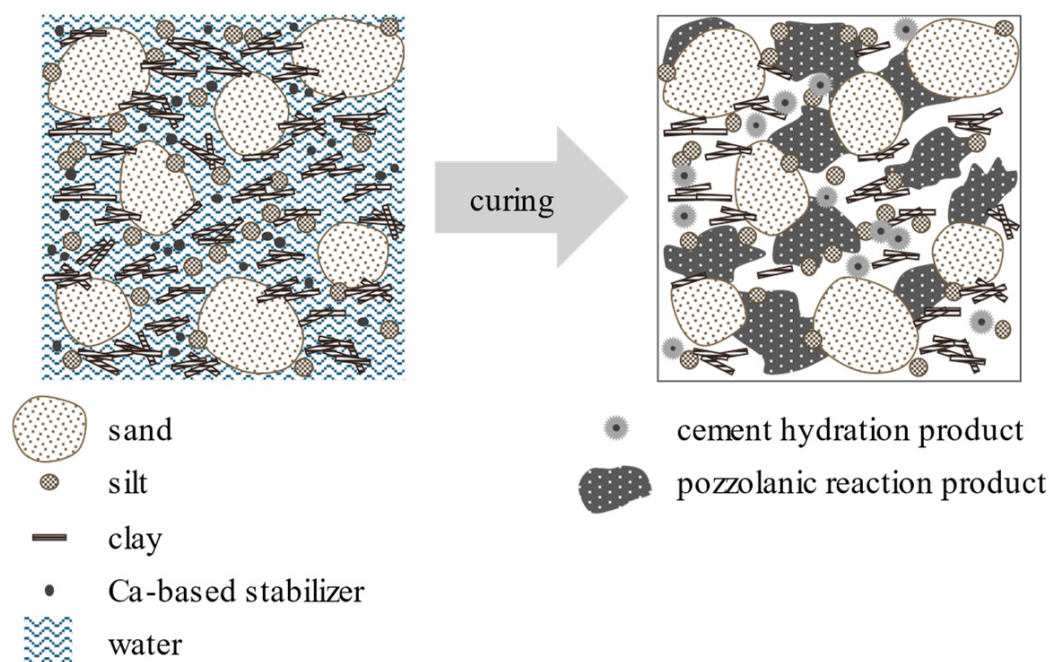


Figure 1. Stabilization mechanism of soil treated with calcium-based additives.

Despite the effectiveness of cement, its widespread use in the construction industry has posed challenges to environmental sustainability, including high CO_2 emissions, increased energy consumption, and elevated costs. In response, low-carbon non-traditional stabilizers, primarily industrial byproduct materials such as cement kiln dust, slag, and limestone powder, have emerged as promising alternatives for soil stabilization. Like traditional calcium-based stabilizing binders, using industrial waste materials like limestone powder (LSP) involves cation exchange, resulting in soil particle agglomeration and pozzolanic reactions, forming strength-bearing cementing gels. Previous findings have indicated that LSP, when used to stabilize weak fine-grained soils, enhances soil strength and bearing capacity, reduces soil plasticity, and improves soil durability parameters, including moisture susceptibility and volumetric swelling [11–15]. Moreover, a couple of researchers studied the effect of stone powder on coarse-grained soils. Al-Joulani [16] reported that

incorporating stone powder with high calcium content into coarse-grained sandy soil (SP and A-3) decreased the maximum dry density and the optimum moisture content. The addition of stone powder increased the friction angles, reduced the cohesion in the direct shear, and increased the California bearing ratio (CBR) values. Shat et al. [17] investigated the effect of limestone powder on the geotechnical properties of soils with coarse particles (GP and A-1). Like Al-Joulani's test results, adding LSP to such soils decreased their optimum moisture content (OMC), cohesion, and liquidity indices while increasing their CBR value, unconfined compressive strength (USC), and internal friction angles. They concluded that reactive calcium content in SLP might work as lime (stabilizer) and improve and modify the properties of soils.

However, despite the promising results observed in earlier studies, the full extent of LSP's efficacy in soil treatment has yet to be fully explored. Further investigation is suggested to comprehensively understand the mechanisms underlying LSP's impact on soil stabilization, including its long-term performance and durability aspects. Additionally, ongoing research efforts are needed to optimize the utilization of LSP as a partial substitute for traditional cement across different soil types and environmental conditions, specifically sulfate-bearing saline sandy soils subjected to wetting and drying cycles. This allows for the practical application of LSP as a sustainable solution for soil stabilization in the construction industry.

The treatment of sulfate-bearing saline soils with calcium-based additives poses distinctive challenges, particularly concerning the formation of ettringite, a mineral compound formed through a series of chemical reactions within the soil–binder–water system [18–20]. When sulfate-containing soil is mixed with cement and/or lime in the presence of water, the pH of the system increases to above 12.0, promoting the dissolution of the soil phases and the release of alumina and sulfate. These compounds react with the calcium released from the stabilizer and the water supply as a source of soil stabilization and soil mixing. As a result, the calcium–alumina–sulfate–water reaction produces ettringite minerals, which can hold a large amount of water within their material, leading to their expansion [21–24]. Among the several methods to mitigate the swelling potential of sulfate-bearing saline soils, stabilization with low-calcium additives such as fly ash, slag, and LSP is recommended as an environmentally friendly and comparatively cheap approach [25–27]. LSP contains calcium carbonate (CaCO_3) containing reactive lime, which, when introduced into the soil–binder–water system, can interact with sulfate ions to form less expansive compounds compared to ettringite. Additionally, the incorporation of LSP can help buffer the pH of the soil–binder–water system, reducing the alkalinity that promotes ettringite formation. Further studies are required to comprehensively understand the effectiveness of low-calcium additives such as LSP in mitigating ettringite formation and reducing the swelling potential of sulfate-bearing saline soils.

2. Research Scope and Objectives

This study investigates low-calcium additives' effectiveness and long-term performance, specifically LSP, in stabilizing sulfate-bearing saline soils. While many previous studies have successfully assessed stabilized soils' physical and mechanical properties, they often overlook durability parameters. To address this gap, a comprehensive series of experimental tests, ranging from geochemical characterization to mechanical evaluation and durability assessments, was designed to understand the stabilization mechanisms, evaluate the long-term performance, and assess the durability aspects of incorporating LSP into soil treatment. Moreover, this research aims to optimize the use of LSP in combination with cement. For this purpose, limestone powder was employed as a partial substitute for OPC, particularly at 25%, 50%, and 75% substitution levels. Through systematic investigation, the present study evaluates the potential of LSP and its combination with cement in mitigating salt crystallization, improving geotechnical properties, and enhancing the long-term durability of sulfate-bearing saline soils.

3. Materials and Methods

3.1. Materials

3.1.1. Soil

In this study, sulfate-bearing saline soil collected from West Kazakhstan was investigated. The soil's gradation is shown in Figure 2. The basic geotechnical properties of the tested soil, including the Unified Soil Classification System (USCS) and the American Association of Highway and Transportation Officials (AASHTO) soil classifications, the Atterberg limits, the optimum moisture content, and the maximum dry density, are summarized in Table 1. The soil was classified into poorly graded sand with silt (SP-SM) based on the USCS and silty or clayey gravel and sand (A-2-4) based on the AASHTO soil classification. The chemical properties, particularly the cation and anion analysis results and the pH measurements, are also presented in Table 1. The mineralogical analysis revealed that the soil mainly consisted of quartz, albite, calcite, and gypsum phases, as seen in the XRD pattern provided in Figure 3. The gypsum and halite in the tested soil contributed to high sulfate and chloride concentrations. This is expected to promote salt crystallization in the stabilized soil matrix under unstable environmental conditions, potentially leading to pavement failure due to sulfate-induced heave.

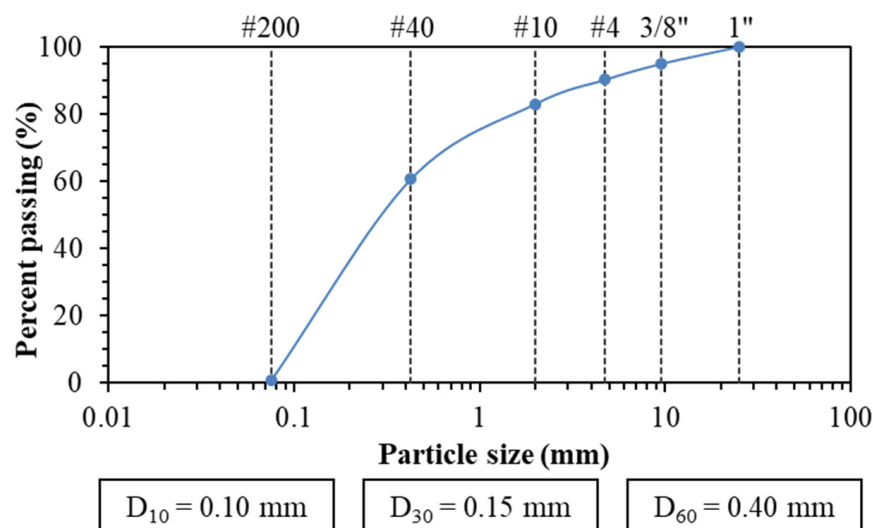


Figure 2. Particle size distribution curve of tested soil.

Table 1. Basic soil characterization data.

| Geotechnical Properties | | | | | | | | | | | |
|--------------------------------|----------------------|------------------|--------------------------------|--------------------------------|-----------------|------|-------------------|------------------|------------------|-------|------|
| USCS and AASHTO Classification | Atterberg Limits (%) | | | | | | Compaction Data | | | | |
| | LL | | PL | | PI | | OMC (%) | | MDD (kg/m³) | | |
| SP-SM, A-2-4 | 19.16 | | 16.67 | | 2.49 | | 10.80 | | 1941.00 | | |
| Chemical concentration | | | | | | | | | | | |
| Concentration (ppm) | | | | | | | | pH | | | |
| Sulfate | | | | Chloride | | | | | | | |
| 16,931.00 | | | | 10,681.98 | | | | 6.32 | | | |
| Chemical compositions | | | | | | | | | | | |
| Oxide (wt.%) | CaO | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | SO ₃ | MgO | Na ₂ O | K ₂ O | TiO ₂ | Other | LOI |
| | 39.78 | 20.22 | 4.55 | 11.68 | 10.6 | 1.66 | 0.84 | 4.16 | 1.61 | 4.36 | 0.54 |

Note: LL—liquid limit; PL—plastic limit; PI—plasticity index; OMC—optimum moisture content; MDD—maximum dry density; LOI—loss of ignition.

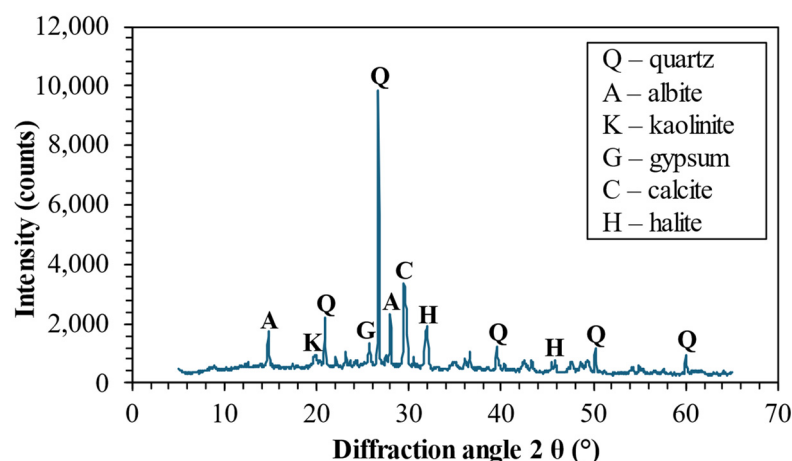


Figure 3. XRD pattern of tested soil.

3.1.2. Chemical Stabilizers

OPC and its combination with LSP were used as stabilizing agents for this experimental study. The LSP was obtained by crushing locally collected limestone using a jaw crusher and then grinding the material with a ball mill. The particle size distributions of the stabilizers are shown in Figure 4. The grain size distribution of the stabilizing agents, particularly the predominant fine particles compared to the tested sand, allowed these stabilizers to act as filling materials and contribute to the binding of the particles in the stabilized soil matrix. This is expected to increase cohesion, reduce plasticity, and improve strength at an early curing age. Table 2 presents the chemical oxide compositions of the tested soil, and the chemical additives used in this study. The XRD patterns in Figure 5 suggest that the LSP had abundant quartz and calcite phases, while the OPC predominantly consisted of quartz, Portlandite, and alite phases, which contributed to forming calcium aluminate silicate hydrate (C-A-S-H) or calcium silicate hydrate (C-S-H) upon their dissolution and activation.

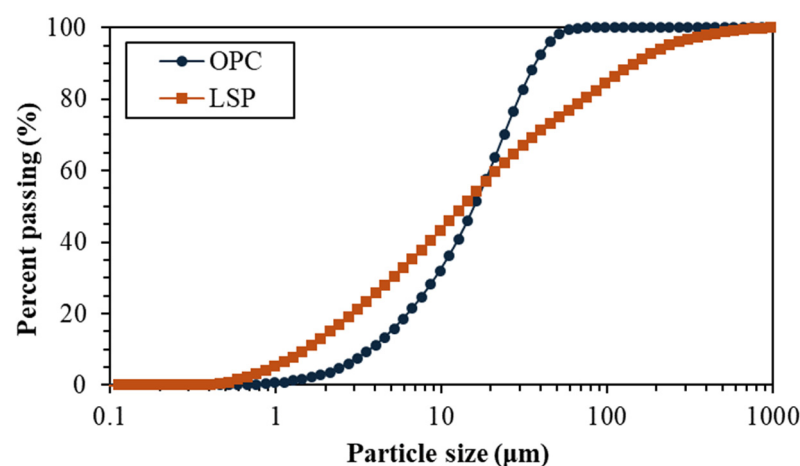


Figure 4. Particle size distribution of stabilizers.

Table 2. Chemical compositions of tested soil and chemical stabilizers.

| Oxide | OPC (wt.%) | LSP (wt.%) |
|--------------------------------|------------|------------|
| CaO | 64.48 | 68.05 |
| SiO ₂ | 21.05 | 11.16 |
| Al ₂ O ₃ | 3.79 | 3.62 |

Table 2. Cont.

| Oxide | OPC (wt.%) | LSP (wt.%) |
|--------------------------------|------------|------------|
| Fe ₂ O ₃ | 4.47 | 9.44 |
| SO ₃ | 2.88 | 0.7 |
| MgO | 1.77 | 1 |
| Na ₂ O | 0.11 | 0.6 |
| K ₂ O | 0.32 | 2.58 |
| TiO ₂ | NA | 1.23 |
| Other | 0.58 | 1.21 |
| LOI | 0.55 | 0.41 |

Note: OPC—ordinary Portland cement; LSP—limestone powder; LOI—loss of ignition, NA—not available.

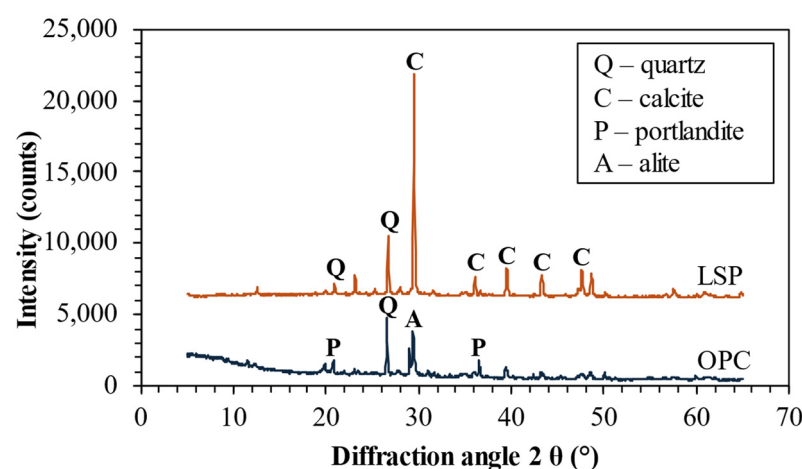


Figure 5. XRD patterns of stabilizers.

3.2. Mix Design, Sample Preparation, and Test Methods

The experimental program of this study can be categorized into the basic material characterization of natural sandy soil and selected stabilizers, mix design and sample preparation, geochemical and mineralogical analysis, mechanical evaluation, and the assessment of the durability parameters of the stabilized soil under simulated in situ conditions.

3.2.1. Mix Design and Sample Preparation

One untreated mix and four mixes were designed, where 8% of the OPC was partially replaced by LSP at 25%, 50%, and 75% substitution levels, as summarized in Table 3. The minimum LSP content was determined based on the Eades–Grim test method [28], which calculates the recommended percentage of stabilizing agents to achieve a pH of 12.4 in the soil–stabilizer mixture (Figure 6). The OPC dosage of 8% by dry weight of soil was selected based on a review of the existing literature [27–30], findings from preliminary laboratory tests, and practical considerations for field applications. Three different OPC-to-LSP ratios were designed to evaluate the effect of partially substituting conventional OPC with the non-traditional low-carbon stabilizer LSP. This approach aimed to determine the optimum combination of OPC and LSP.

The soil was thoroughly mixed with different dosages of stabilizing additives in the corresponding moisture contents to ensure the uniform distribution of the stabilizers. After mixing, the samples were compacted into cylindrical shapes (4.0 inches (101.6 mm) in diameter and 4.5 inches (114.3 mm) in height) using a standard Proctor compaction procedure to achieve the desired densities presented in Table 3. The specimens with this sample size were used for unconfined compressive strength and the three-dimensional (3-D) volumetric swelling test. Later, the residual strength of the stabilized soil samples

was determined after the durability experiment. The compacted samples were then cured under sealed conditions for 7 and 28 days to allow the hydration and pozzolanic reactions to develop the stabilized soil's mechanical properties.

Table 3. Soil stabilizing mix design.

| Mix No. | Dosage (%) | | | Compaction Data | | Curing Period (Days) |
|---------|------------|-----|-------|-----------------|--------------------------|----------------------|
| | OPC | LSP | Total | OMC (%) | MDD (kg/m ³) | |
| 1 | 0 | 0 | 0 | 10.78 | 1941.00 | 7 and 28 days |
| 2 | 8 | - | 8 | 12.78 | 1916.37 | |
| 3 | 6 | 2 | | 12.78 | 1925.65 | |
| 4 | 4 | 4 | | 12.78 | 1936.80 | |
| 5 | 2 | 6 | | 12.78 | 1935.56 | |

Note: OPC—ordinary Portland cement; LSP—limestone powder; OMC—optimum moisture content; MDD—maximum dry density.

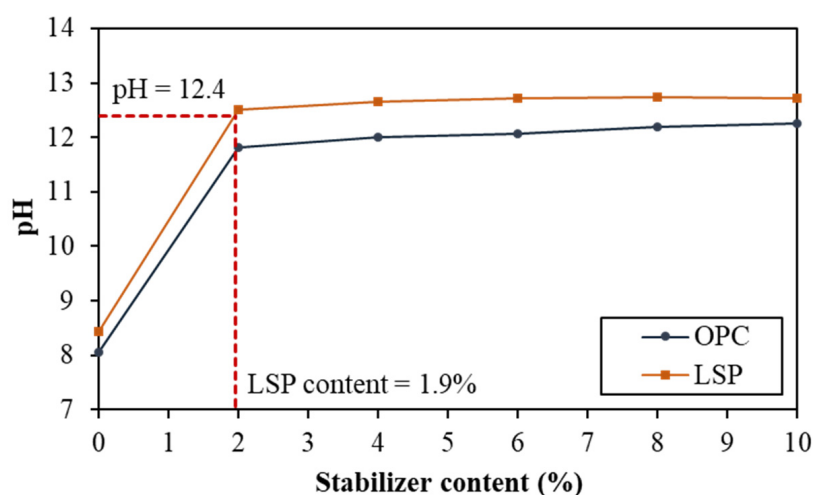


Figure 6. Eades–Grim test results.

3.2.2. Determination of Durability Parameters of Stabilized Soil

A durability assessment was performed by measuring the three-dimensional (3-D) volumetric swelling of both natural sandy soil (untreated) and stabilized soil mixes. The 3-D swelling test, conducted as per the Texas Transportation Institute's guidelines [20], aimed to evaluate the volumetric expansion due to ettringite formation when OPC- and LSP-treated sulfate-bearing saline soil is exposed to prolonged capillary suction [21,22]. The 3-D swelling test, illustrated in Figure 7, involved the following procedure:

- (1) The cylindrical soil sample (cured for 7 days) was covered with a rubber membrane;
- (2) Filter paper and a porous stone were placed at the bottom, and filter paper, a plastic sheet, and porous stones were placed on the top of the sample;
- (3) The specimen was then placed in a container filled with deionized water, which allowed the water to soak through the porous stone from the bottom of the sample for a specified period.

The change in moisture content and the volumetric expansion of the sample were measured periodically. After 28 days of continuous capillary suction, the samples were subjected to wetting-and-drying (W/D) cycles. These cycles were performed by drying the samples under ambient conditions for two days and then re-wetting them in the container with water (capillary suction) for three days. This process was repeated for a total period of 30 days, equivalent to 6 W/D cycles, to simulate real-world environmental conditions with alternating moisture levels.

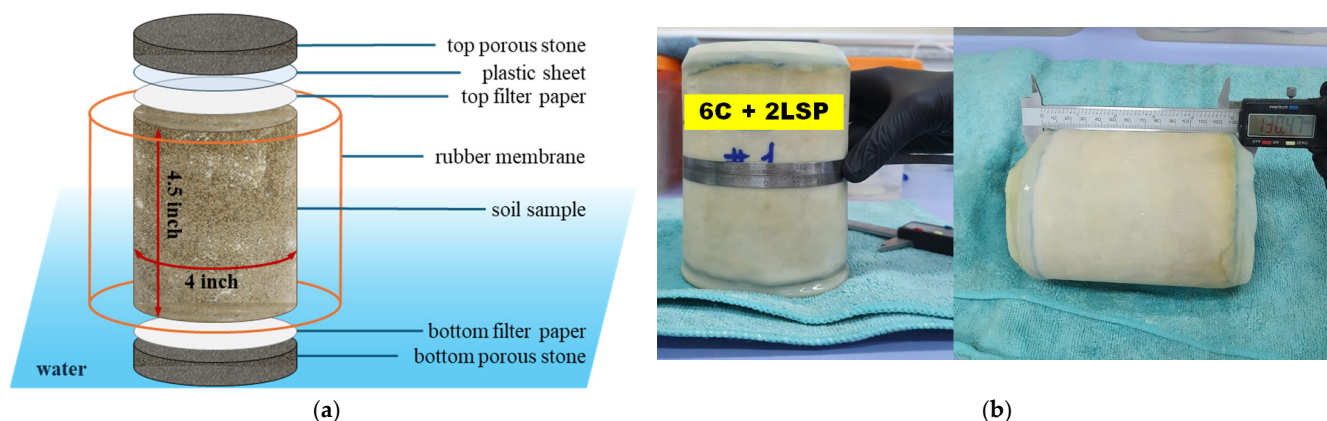


Figure 7. Schematic of testing setup for a 3-D swelling test: (a) components for the specimen and (b) radial and vertical measurements.

3.2.3. Determination of Geochemical and Mineralogical Characteristics of Stabilized Soil

The geochemical properties and mineralogical compositions of both the natural sand and stabilized soil mixes were evaluated before and after the durability experiments.

The geochemical characterization included pH measurement and ion analysis. A liquid soil–stabilizer solution was prepared for pH testing by mixing one part of dry stabilized soil with five parts of water. The pH measurements were taken within 15 min after the sample preparation process, maintaining a constant temperature of 25 ± 1 °C.

Cation and anion quantification was conducted using the Dionex ICS-6000 Ion Chromatography System by Thermo Scientific (Waltham, MA, USA). For this analysis, the liquid solution used for the pH measurement was further diluted with deionized water and filtered to remove particulates. The clear solution was then used for ion chromatography to determine the concentrations of various cations and anions.

The mineralogical compositions of the natural sand and stabilized soil mixes were obtained through an X-ray diffraction (XRD) analysis. Samples were prepared by grinding the soil samples (before and after durability testing) to a particle size of 0.075 mm using a mortar and pestle. The Rigaku SmartLab XRD System (Osaka, Japan) was employed to obtain the diffraction measurements. Raw XRD data were then processed, and Rietveld refinement was conducted using Profex software (version 5.3.0) for phase identification and quantification.

3.2.4. Determination of Mechanical Properties of Stabilized Soil

A mechanical evaluation of the effects of the designed stabilizing mixes was performed through the unconfined compressive strength (UCS) test and the direct shear strength test. The UCS test was performed using a Matest compression testing machine (Italy), in which the soil samples were compressed at a constant strain rate of 0.5%/min under unconfined conditions until failure. The shear strength of the soil was evaluated in the direct shear test using the Matest SHEARLAB testing machine.

In addition to the samples cured for 7 days, the residual strength properties of the stabilized soil samples were determined after the durability assessment. These residual UCS and shear strength evaluations were performed on samples exposed to capillary suction and moisture fluctuations to assess their moisture susceptibility and provide a realistic approach to assessing the long-term durability of the soil under in situ conditions.

4. Results and Discussion

4.1. Plasticity

As seen with the Atterberg limits test results that are summarized in Figure 8, the stabilization of sulfate-bearing saline soil with the designed stabilizing mixes reduces soil plasticity, with a maximum 91% reduction achieved in the purely 8% OPC-treated soil

sample. The reduced plasticity and improved workability of the stabilized sandy soil samples can be attributed to the formation of flocculated and agglomerated soil–stabilizer particles during mixing and compaction processes. A 25% OPC replacement (6% OPC + 2% LSP) resulted in a comparable 86% decrease in the plasticity of the tested soil, implying that the combined effect of OPC and LSP is almost as strong as the effect of OPC alone at a higher percentage. However, partial OPC replacement with LSP at a 75% substitution level (2% OPC + 6% LSP) was not effective in reducing the soil’s plasticity. The lower percentage of the OPC might result in insufficient reactive calcium availability for effective soil stabilization and the formation of flocculated structures. This highlights the need to select a minimum recommended dosage of OPC to achieve an optimum combination with LSP, ensuring proper soil stabilization.

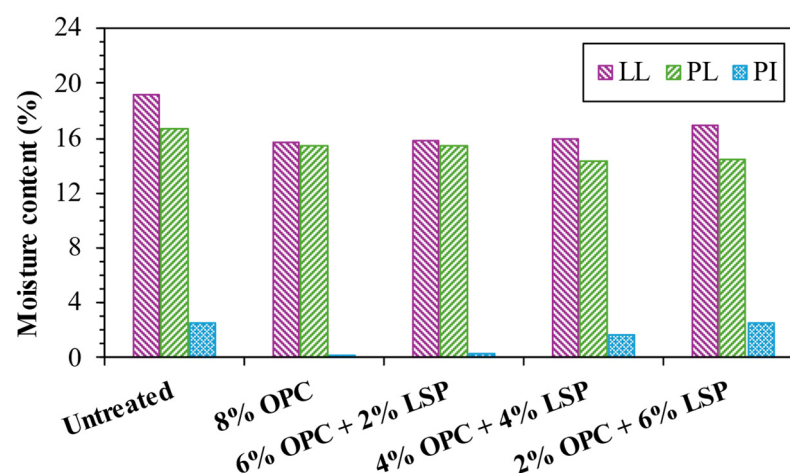


Figure 8. Atterberg limits of untreated and stabilized soil samples.

4.2. Swelling Characteristics

The changes in the moisture content and volume of the untreated and stabilized soil samples were measured throughout the durability experiment and are summarized in Figure 9. At an early stage of the capillary suction test, all the soil samples experienced rapid water intake and associated volumetric swelling. This steep increase in volume during the first 4 days of wetting can be attributed to the soil’s initial water absorption capacity, leading to the quick hydration and swelling of the soil matrix. Following this initial phase, all the stabilized soil samples observed a steady increase in their moisture content and volumetric expansion at a slower rate. In contrast, the untreated soil sample quickly obtained the moisture content and swelling behaviors and remained at an almost constant moisture content of 7.1% and a constant volumetric swelling of about 5.7%, higher than the chemically stabilized samples. This behavior can be explained by the lack of binding agents in the untreated soil, which results in a limited capacity to absorb water further and expand. On the other hand, the stabilized soil samples exhibited continued expansion due to ongoing hydration, pozzolanic reactions, and ettringite formation facilitated by stabilizing agents and continuous moisture uptake.

In general, OPC and LSP treatments lowered the volumetric expansion of sulfate-bearing saline soil. The best-performing mixes were the purely 8% OPC and a combination of 6% OPC and 2% LSP. This indicates that the partial substitution of OPC with LSP can be effective and exhibit comparable results to pure OPC treatment. In the Ca-based treatment of the sulfate-bearing soil, ettringite formation played a crucial and complex role in soil stabilization: ettringite, comprising needle-like crystals, is a hydrated mineral that incorporates water molecules into its structure. As ettringite forms, it expands and causes initial swelling in the soil. This phenomenon is accelerated by high sulfate content and moisture availability conditions. However, ettringite may reduce swelling in sandy soil by involving several interconnected mechanisms. First, ettringite crystals fill the pores within the sandy soil structure and grow there. As a result, they physically block the voids that

would allow water to enter and cause swelling. Also, as ettringite continues to hydrate, it can consume excess water. Secondly, ettringite may act as a binding agent, which cements soil particles and induces a more cohesive structure. This increased cohesion in the sandy soil can lower the permeability of the soil and make it less susceptible to water infiltration, subsequently reducing swelling. Moreover, ettringite formation in the soil can disrupt natural soil particle arrangement, potentially producing more stable structures that are less prone to swelling. Finally, ettringite may chemically interact with other minerals in the sandy soil, leading to ion exchanges and influencing the soil's pH. These chemical interactions can affect the soil's swelling behaviors and contribute to reducing soil swelling. Therefore, ettringite can help the soil matrix's solidification and reduce soil swelling by filling pores, cementing soil particles, modifying soil structure, and chemically interacting with other minerals [29–38].

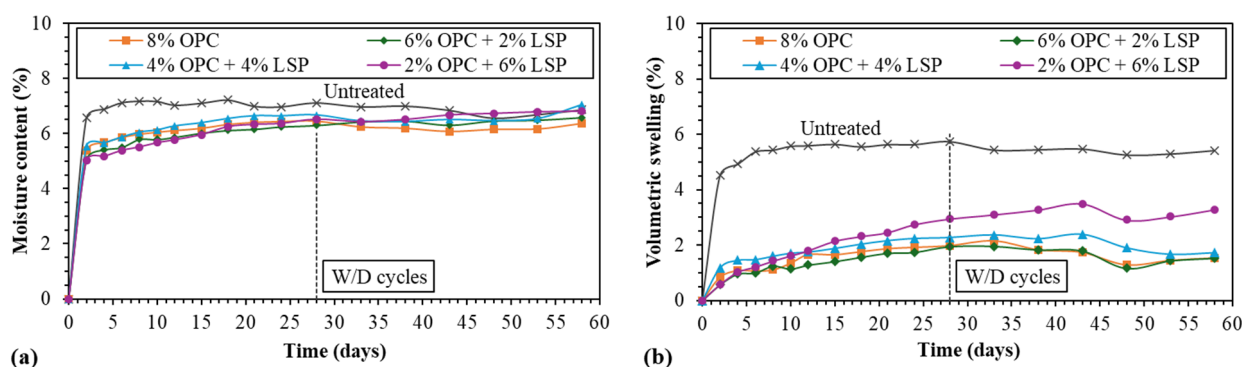


Figure 9. (a) Moisture content change and (b) volumetric swelling of untreated and stabilized soil samples subjected to durability testing.

Wetting–drying cycles were implemented to evaluate the long-term performances of stabilizing binders under realistic field conditions by alternating wetting and drying of the soil samples. These cycles also help achieve an equilibrium state for water content in the stabilized soil samples under capillary soak conditions. Indeed, after the rapid increase within the first 4 days followed by a steady increase up to 28 days, the moisture content of the designed mixtures reached equilibrium during the 30 days of wetting–drying cycles, as shown in Figure 9a. A side-view and top-view of a stabilized soil sample after durability testing, provided in Figure 10, shows a layer of salt crystallization and efflorescence on the surface, which occurs due to moisture fluctuations during the wetting–drying cycles. As the soil dries, dissolved salts are brought to the surface by capillary action, precipitating and forming visible crystals. This process highlights the impact of cyclic moisture changes on the soil's surface properties and indicates the ongoing movement of water and salts within the soil matrix. These internal movements can lead to the strength degradation of the soil–stabilizer matrix due to its exposure to repeated moisture fluctuations [39,40].

Regarding volumetric expansion exhibited during wetting–drying cycles, varying trends were observed for the different stabilizer contents (Figure 9b). Overall, as the moisture content achieved its equilibrium state during the alternating wetting and drying of the samples, the volumetric expansion of most of the treated soil mixes decreased, except for the mix treated with 2% OPC + 6% LSP. This indicates that higher levels of LSP substitution might not provide sufficient stabilization, resulting in continued swelling even after repeated wetting and drying. This finding matches previous research that shows that there is an optimum LSP content to control and reduce the swell potential [15,41].

Again, partial OPC replacement with LSP at a 75% substitution level (2% OPC + 6% LSP) was the least effective treatment for the sulfate-bearing soil studied. This underscores the importance of selecting a minimum recommended dosage of OPC to ensure effective stabilization and minimize swelling. Ensuring adequate calcium availability is crucial for forming stable soil structures and reducing the soil's moisture susceptibility.

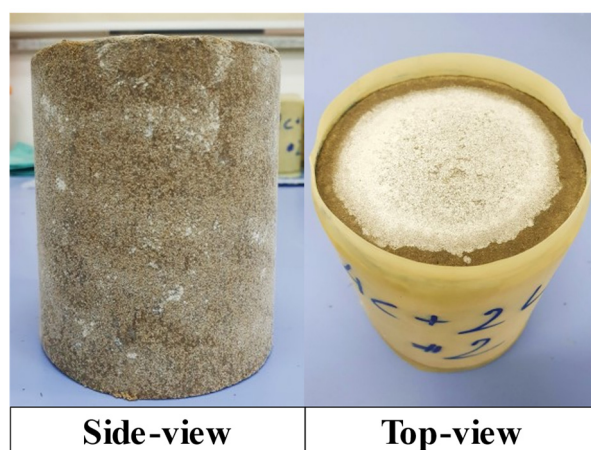


Figure 10. Surface view of a stabilized soil sample post-durability testing.

4.3. Geochemical Properties

Upon chemical treatment, the originally acidic soil with a pH value of 6.32 transformed into an alkaline material with a pH value nearly twice the original, as seen in Figure 11. pH values above 12.0 in the 7-day cured samples were sufficient to promote pozzolanic reactions in the stabilized mixes and improve long-term strength. However, the pH values of the samples exposed to the 58-day durability assessment under capillary suction were slightly lower than those of the 7-day cured samples. This pH reduction can be attributed to C-A-S-H leaching due to moisture intrusion and the potential carbonation of the OPC- and LSP-treated soil samples when they reacted with CO_2 in the room during drying periods in the W/D cycles. Similar to other material properties described in previous subsections, the mix stabilized with 2% OPC and 6% LSP showed the least improvement in its pH levels.

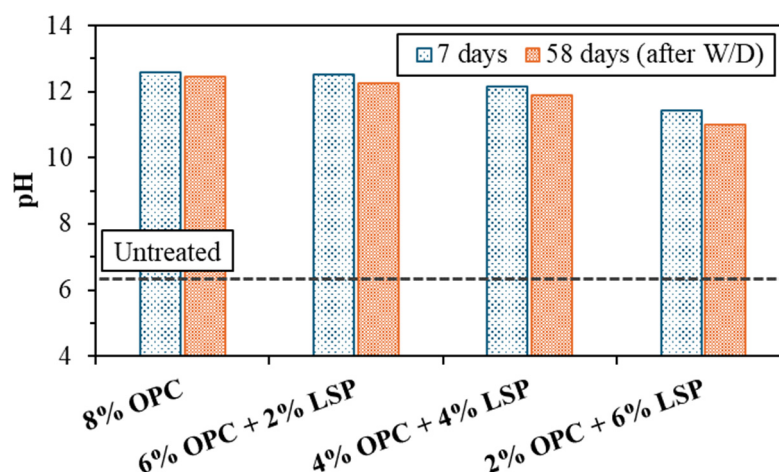


Figure 11. pH of untreated and stabilized soil samples.

According to the cation and anion analysis results summarized in Figure 12, OPC- and LSP-stabilization reduced the sulfate and chloride concentrations in the soil, which is naturally rich in these salts. This reduction was due to the chemical interactions between the stabilizers and the soil minerals, which immobilized the sulfate and chloride ions, preventing them from remaining in the solution. After exposure to the durability experiment with the W/D cycles, there was a slight increase in the sulfate concentration and a significant decrease in the chloride concentration. Moisture intrusion during prolonged capillary suction and moisture fluctuations during W/D cycles can lead to the leaching of chloride ions, reducing their concentration in the soil. On the other hand, sulfate ions might become more concentrated due to the dissolution of sulfate minerals during the wetting

phases and their partial precipitation during the drying phases. This dynamic process may cause an increase in sulfate concentration while reducing chloride levels [42,43].

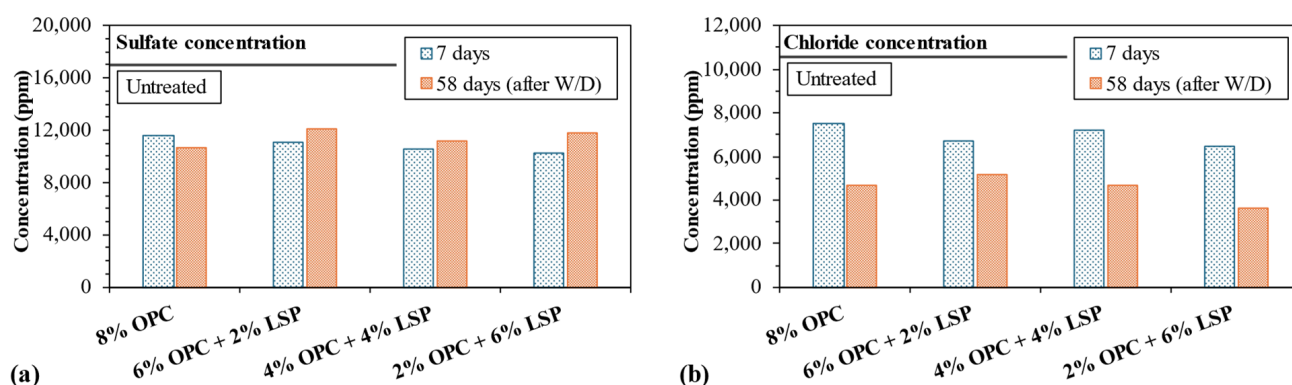


Figure 12. (a) Sulfate and (b) chloride concentrations in untreated and stabilized soil samples.

4.4. Mineralogical Compositions

The XRD patterns of the stabilized soils subjected to the durability experiment (Figure 13) reveal that the stabilization reaction products formed in the soil matrix were primarily C-S-H and ettringite. Gypsum peaks diminished upon introducing LSP, which can be attributed to the LSP reacting with the sulfate ions to form ettringite, thus consuming the available gypsum. The calcite peaks became stronger and sharper with the addition of LSP, indicating an increased presence of calcium carbonate. LSP was initially abundant in calcite, contributing to the observed higher calcite content. The halite peaks diminished due to the purely OPC treatment, likely because the OPC bound the chloride ions, reducing halite precipitation. However, when the OPC was partially replaced with LSP, halite peaks reappeared, suggesting that the binding capacity for the chloride ions was reduced.

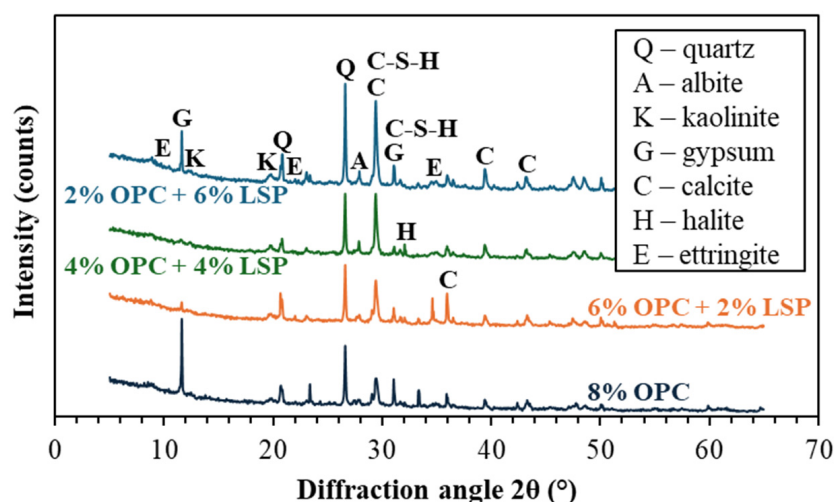


Figure 13. XRD pattern of stabilized soil samples post-durability testing.

Quantitative phase analysis (Figure 14) showed the contents of the major stabilization products, C-S-H and ettringite. The most significant amount of C-S-H was formed in the sample treated with purely 8% OPC. This was because the OPC provided a high amount of calcium, which reacted with the silicates and aluminates in the soil to form C-S-H. As the OPC was partially replaced with LSP, the formed C-S-H amount decreased, likely due to the reduced availability of the reactive calcium that participates in the hydration process. Simultaneously, the amount of precipitated ettringite increased with the addition of LSP, as the presence of sulfate and aluminates from the soil and stabilizers promoted ettringite formation.

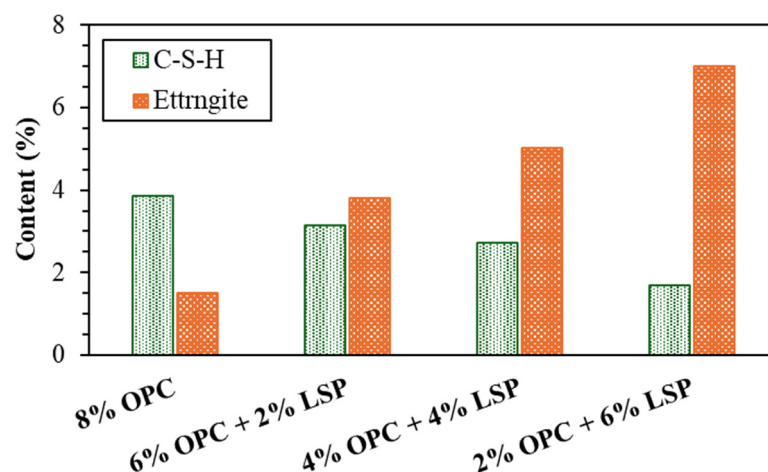


Figure 14. Contents of C-S-H and ettringite in stabilized soil samples post-durability testing.

It is important to note that the durability experiment also influenced the contents of the significant stabilization products. Moisture intrusion through prolonged capillary suction and moisture fluctuations due to W/D cycles can affect the stability and distribution of these products. Prolonged capillary suction can lead to the leaching of some reaction products, particularly those that are soluble, while W/D cycles can cause the repeated dissolution and precipitation of minerals, potentially redistributing and concentrating certain phases like ettringite and calcite.

4.5. Mechanical Properties

As shown in Figure 15, the stabilized mixes exhibit significantly higher UCS than the untreated soil symbolized with the dotted line, demonstrating the effectiveness of the designed stabilizing mixes. The highest increase in UCS, approximately 71%, was observed in the purely 8% OPC-treated soil sample (28 days cured). This substantial improvement can be attributed to OPC's high calcium content and reactivity, which promotes the formation of solid binding phases like C-S-H. As the LSP partially replaced the OPC, the UCS decreases, with the least effective mix being 2% OPC + 6% LSP. This trend reflected the lower reactive calcium availability and reduced reactivity when LSP, which has a higher content of fine particles and less reactive components, is used in higher proportions.

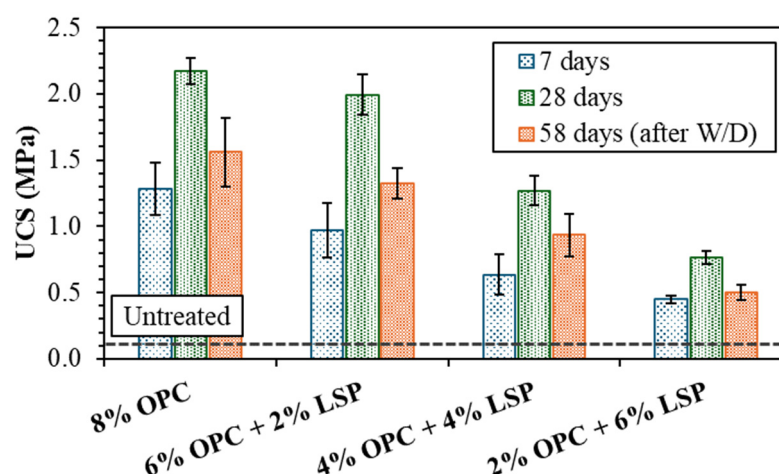


Figure 15. UCS of untreated and stabilized soil samples.

The residual strength of the stabilized soil samples was evaluated after the durability experiment, providing a realistic assessment of the long-term performance. The UCS of the stabilized soil samples exposed to moisture fluctuations (W/D cycles) was compared to

the UCS of the 7-day cured samples. It was found that the residual strength values of all the designed mixtures exceeded the threshold value of 80%, which is the commonly recommended minimum for maintaining adequate structural integrity in stabilized soils [44]. Remarkably, the strength of the samples increased after undergoing capillary suction and W/D cycles. This increase can be attributed to continued pozzolanic reactions and further stabilization processes that occur during the moisture fluctuations, leading to a denser and more durable soil matrix.

The direct shear test results, summarized in Figure 16, indicated a significant increase in the shear strength due to OPC and LSP treatment. The best-performing mix was, again, the purely 8% OPC-treated soil. A 25% replacement of OPC with LSP (6% OPC + 2% LSP) also proved efficient in enhancing the shear properties of the tested soil. This improvement can be attributed to the increased cohesion and binding between the soil particles, facilitated by forming C-S-H and other stabilization products. The sample treated with 2% OPC + 6% LSP was the least effective, showing a less significant increase in the shear strength. This is likely due to the insufficient reactive calcium content and reactivity when a higher proportion of LSP is used, leading to weaker bonding and cohesion between the particles.

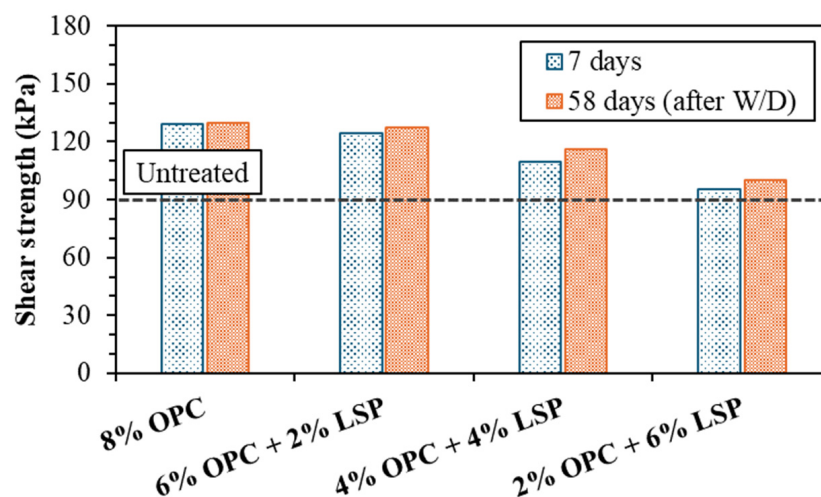


Figure 16. Shear strength of untreated and stabilized soil samples.

The effect of moisture fluctuations on shear strength did not indicate a significant change. This stability can be attributed to the soil's enhanced resistance to moisture-induced degradation, achieved through stabilization. Even under varying moisture conditions, the stabilized soil matrix maintained its integrity and cohesion, preventing substantial loss in the shear strength. This demonstrates the durability and reliability of the stabilization methods used in this study.

5. Conclusions

This study investigated the effectiveness of conventional OPC and its partial replacement with a non-traditional low-carbon alternative like LSP as a stabilizing agent for sulfate-bearing saline soil. This comprehensive experimental program was designed to identify and understand the impact of the designed stabilizing mixes on soil plasticity, swelling characteristics, geochemical properties, mineralogical compositions, and mechanical properties. The key findings of this study are as follows:

- The stabilization of the sulfate-bearing saline soil with OPC and LSP reduced soil plasticity. The maximum reduction of 91% was achieved with purely 8% OPC treatment, while a 25% OPC replacement with LSP (6% OPC + 2% LSP) resulted in a comparable 86% reduction. However, higher levels of LSP substitution were less effective in reducing plasticity;

- The stabilized soil samples exhibited lower volumetric expansion compared to the untreated soil. The best-performing mix was a combination of 6% OPC and 2% LSP. Wetting–drying cycles demonstrated that the stabilized soil samples maintained their volumetric stability better than the untreated samples, with partial OPC replacement with LSP still proving effective;
- Chemical treatment transformed the initially acidic soil into an alkaline material, promoting pozzolanic reactions. The reduction in the pH over the prolonged exposure to capillary suction and wetting–drying cycles highlighted the importance of selecting an optimal stabilizer dosage. The analysis also showed a significant reduction in the sulfate and chloride concentrations, with LSP contributing to a notable increase in calcite content due to its initial abundance;
- Stabilized mixes demonstrated considerably higher UCS and shear strength compared to untreated soil. The partial substitution of OPC with LSP resulted in decreased UCS, but still provided significant strength improvement. The durability experiments confirmed that the residual strength of the stabilized samples exceeded the recommended thresholds, indicating the designed mixes' long-term stability, resilience, and durability.

This study highlights the potential of partially replacing OPC with LSP to achieve sustainable soil stabilization with reduced environmental impact. The findings suggest that appropriate proportions of OPC and LSP can effectively improve the geotechnical properties of sulfate-bearing saline soils. Notably, the mixes stabilized with 6% OPC and 2% LSP showed comparable results to purely 8% OPC-treated soil samples, indicating that the partial replacement of OPC with LSP is particularly efficient at a substitution level of 25%. This offers a viable alternative for sustainable construction practices. However, future research should focus on investigating the sensitivity of the proposed stabilization method across various soil types to enhance its applicability and ensure consistent performance under different conditions.

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