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Impact of Unhydrated Lime on the Geotechnical Properties of Clayey Soil

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Abstract

This study investigates the impact of quicklime (CaO) on improving the geotechnical properties of clayey soil. Quicklime was mixed with soil in varying proportions (2%, 5%, and 8% by dry weight) to assess its effects. The results showed that increasing lime content reduced specific gravity, while the optimum moisture content (OMC) and plasticity index increased. Additionally, the liquid limit, plastic limit, and plasticity index decreased, and there were improvements in compressive strength, friction angle, and unconfined compressive strength. Compression parameters such as the compression index (C_c), rebound index (C_r), volume change coefficient (m_v), and compression modulus (a_v) decreased with increasing lime content. The most significant improvement was observed at 2% lime, with further increases to 5% and 8% resulting in less improvement. X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses were conducted to explore the mineralogical and structural changes in the soil, demonstrating the chemical and physical interactions between lime and soil. This research provides valuable insights into the role of quicklime in modifying clayey soil properties, with implications for improving geotechnical performance in civil engineering applications, particularly in road and infrastructure projects.

Keywords: Clay; Quick Lime (LQ); Compressive Strength; Scanning Electron Microscopy (SEM); X-Ray Diffraction (XRD).

1. Introduction

The use of local soils in construction has become increasingly important due to the rising costs of traditional materials. However, local soils often exhibit unfavorable engineering properties, such as low strength and inadequate stability, which limit their applicability in construction. To address these challenges, various additives, including lime, cement, fly ash, and industrial waste products, are commonly used to enhance the engineering properties of soils [1-3].

Soil stabilization techniques, such as compaction, bonding, injection, and mixing with additives, aim to improve soil shear strength, stability, and resistance to deformation. Research has shown that chemical stabilization using materials like lime, cement, and fly ash can significantly modify the physical and chemical properties of soil, enhancing its engineering characteristics [4]. Although extensive studies have been conducted on lime as a stabilizing agent [5, 6], further research is still needed to investigate its long-term effects and improve stabilization methods [7-9].

In addition to lime, combining it with other additives such as cement has been explored to enhance clay soil properties. These studies have demonstrated substantial improvements in geotechnical properties, including increased cohesion and improved structural integrity [10-12]. Furthermore, the use of lime with materials like fly ash or sugarcane bagasse ash has been shown to improve the strength and stability of expansive soils, which undergo significant volume changes with moisture fluctuations, making them suitable for road construction and other infrastructure applications [13,

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14]. Additionally, the combination of lime with pumice and aluminium hydroxide has been found to enhance the bearing capacity of soft soils, offering a more sustainable alternative for road construction [15].

Moreover, stabilization techniques using lime have proven effective in improving soil resistance to freeze-thaw and wet-dry cycles, demonstrating their potential for use in geotechnical applications under challenging environmental conditions [17, 18].

This study aims to investigate the feasibility of stabilizing clay soil using varying proportions of lime and assess its impact on the soil's engineering properties, with a focus on improving its geotechnical characteristics for practical construction applications.

2. Materials and Methods

2.1. Materials Used

2.1.1. Soil Used

For the purposes of this study, the soil samples were collected from a depth of 1.5 meters below the surface of a local site. The initial natural moisture content of the soil was directly measured. Subsequently, the samples were placed in the laboratory and allowed to air dry at room temperature for two weeks to enable the evaporation of natural moisture. Following the air-drying process, the samples were further dried in an oven at 110°C to eliminate any residual moisture, ensuring that the results were not influenced by excess water content. Based on the Unified Soil Classification System (USCS), the soil was classified as low plasticity clay (CL). The particle size distribution and other engineering properties of the soil are provided in Figure 1 and Table 1, respectively.

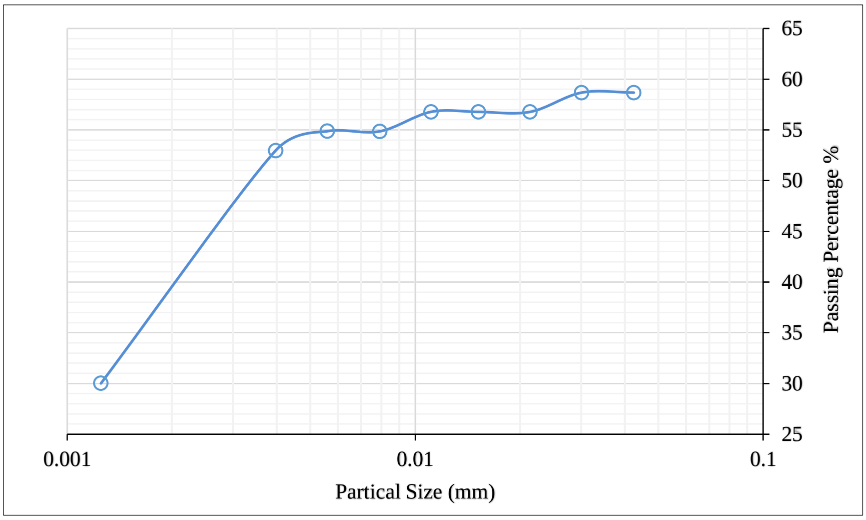


Figure 1. Particle Size Distribution of the Soil Samples Utilized

Table 1. Soil Properties

Index Property	Standard Specification	Index Valve of Soil
Depth – (m)	---	1.5
Liquid limit – (%)	ASTM D 4318 [19]	47.5
Plastic limit – (%)	ASTM D 4318 [19]	27.32
Plasticity index – (%)	ASTM D 4318 [19]	20.18
Specific Gravity (Gs)	ASTM D 854 [20]	2.715
Gravel (larger than 4.75 mm) – G (%)	ASTM D 422 [21]	0
Sand (0.075 to 4.75 mm) – S (%)	ASTM D 422 [21]	4
Silt (0.005 to 0.075 mm) – (M) (%)	ASTM D 422 [21]	41
Clay (less than 0.005mm) – (C) (%)	ASTM D 422 [21]	55
C_u – (kPa)	ASTM D 2166 [22]	206
C – (kPa)	ASTM D3080 [23]	223
Φ – (º)	ASTM D3080 [23]	19.80
C_c	ASTM D 2435 [24]	0.1339
C_r	ASTM D 2435 [24]	0.0213

2.1.2. Quick Lime

Anhydrous lime (quicklime) (CaO) was sourced from the Karbala Lime Factory and incorporated into the soil at three different proportions: 2%, 5%, and 8% by weight of dry soil. Lime was chosen due to its chemical properties, specifically its ability to react with the minerals present in clay, resulting in the formation of cementitious compounds. This reaction enhances soil cohesion, reduces plasticity, and improves resistance to deformation. The physical and chemical properties of quicklime are detailed in Table 2 and Figure 2.

Figure 2. Quicklime used

Table 2. The Physical and Chemical Properties of The Quicklime

Index Properties	Index Value
Physical Properties	
Specific gravity, G_s	3.2
Retained on Sieve # 30, % by weight	0
Retained on Sieve # 200, % by weight	10
Chemical Properties	
CaO, %	94.2
Free Water, %	0.09
SO_3, %	0.06
L.O.I, %	3.2

2.1.3. Sample Preparation

To evaluate the effect of lime on the geotechnical properties of the soil, soil-lime mixtures were prepared with varying proportions of lime. The clay soil was first dried and ground before being incorporated into the mixtures. The appropriate amounts of clay soil and lime were then blended under dry conditions to ensure a homogeneous mixture. Three lime proportions of 2%, 5%, and 8% by weight of dry soil were used. For each lime proportion, the samples were compacted to achieve the maximum dry density and optimum moisture content, which were determined using standard Proctor tests. All experimental procedures were conducted in the Soil Mechanics Laboratory at the Civil Engineering Department, University of Technology.

3. Experimental Tests

This study involved conducting laboratory experiments to assess the impact of lime on the physical properties, unconfined compressive strength, direct shear strength, and cohesion parameters of both untreated (unstabilized) and treated (stabilized) clay soil samples. The experimental procedures included the evaluation of essential geotechnical properties such as specific gravity, compaction characteristics, optimum moisture content, Atterberg limits, unconfined compressive strength, direct shear strength, and cohesion. Various geotechnical properties were investigated, including consistency limits (Atterberg limits: Liquid Limit (L.L.), Plastic Limit (P.L.), and Plasticity Index (P.I.)), maximum dry unit weight (Ydry max), optimum moisture content (OMC), specific gravity (G_s), unconfined shear strength (C_u), compressive strength (C), internal friction angle (Φ), and consolidation parameters like the compression index (C_c) and rebound index (C_r) for soft clay soil. The tests were conducted at the maximum dry density and optimum moisture content for both untreated and treated soil samples with varying lime proportions. Static compaction was performed using a standard Proctor mold to investigate the effects of lime on the clay, with a specific focus on unconfined compressive strength, direct shear strength, and cohesion characteristics. Refer to the flowchart in Figure 3 to understand the workflow.

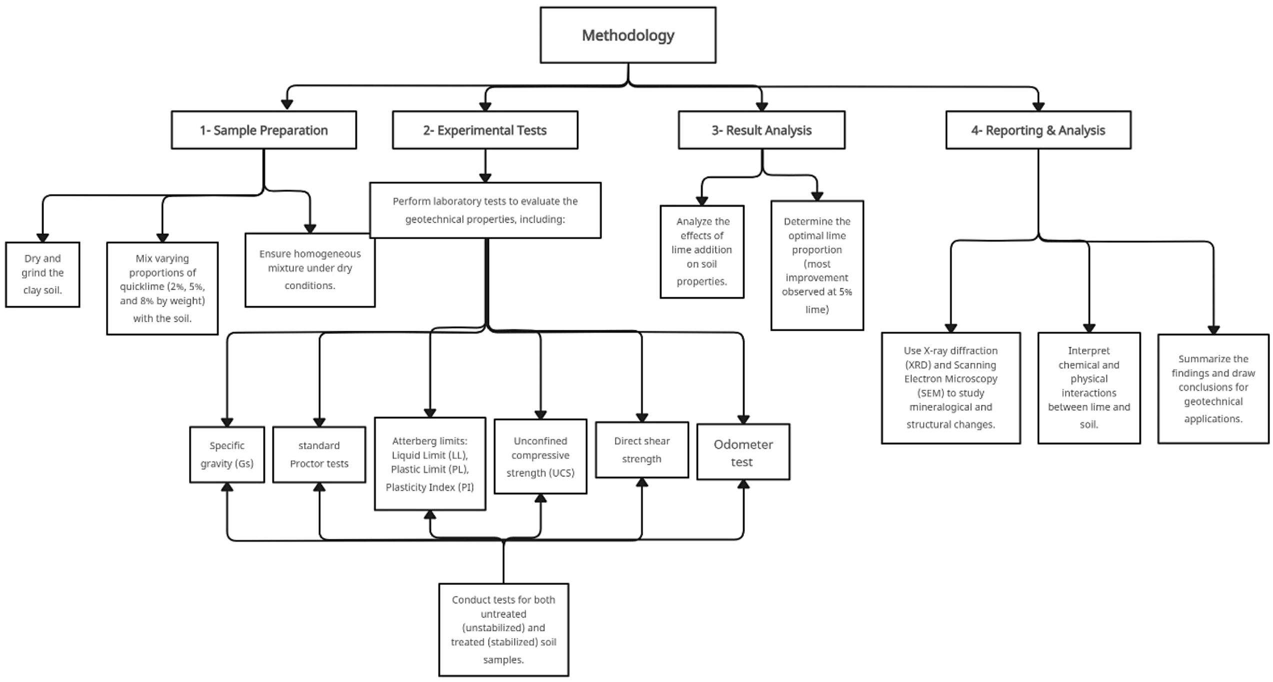


Figure 3. Flowchart for methodology

3.1. Effect of Lime (LQ) on the Properties of Natural and Stabilized Soils

The same testing procedures were conducted on both natural and stabilized soil samples, which were modified with lime at proportions of 2%, 5%, and 8%. The tests were designed to evaluate the effect of different lime proportions on the soil's physical and geotechnical properties. The results were carefully analyzed to determine how lime influenced the soil's behavior during compaction, strength, and cohesion.

3.1.1 Specific Gravity

The specific gravity of the soil was determined following the standard procedure for measuring the specific gravity of soil solids using a water displacement pycnometer. Figure 4 illustrates the variation in specific gravity with different lime contents. The specific gravity increased from 2.715 to 2.764 at a 5% lime content. This increase can be attributed to the rearrangement of soil particles as lime, which has a higher density than clay, fills the voids between the particles, leading to a denser structure. The presence of lime also enhances the cohesion between soil particles, further contributing to the increase in specific gravity. However, a slight decrease in specific gravity was observed, from 2.764 to 2.761, in samples containing 8% lime. This decrease is attributed to the lower specific gravity of lime, approximately 3.2, which is lower than the density of soil particles. As the lime content increases beyond a certain threshold, the added lime may not fully compensate for the increase in mass caused by the rearrangement of particles, leading to a slight reduction in the overall specific gravity of the soil-lime mixture. This phenomenon has been observed in earlier studies [8], which also noted similar trends at higher lime contents.

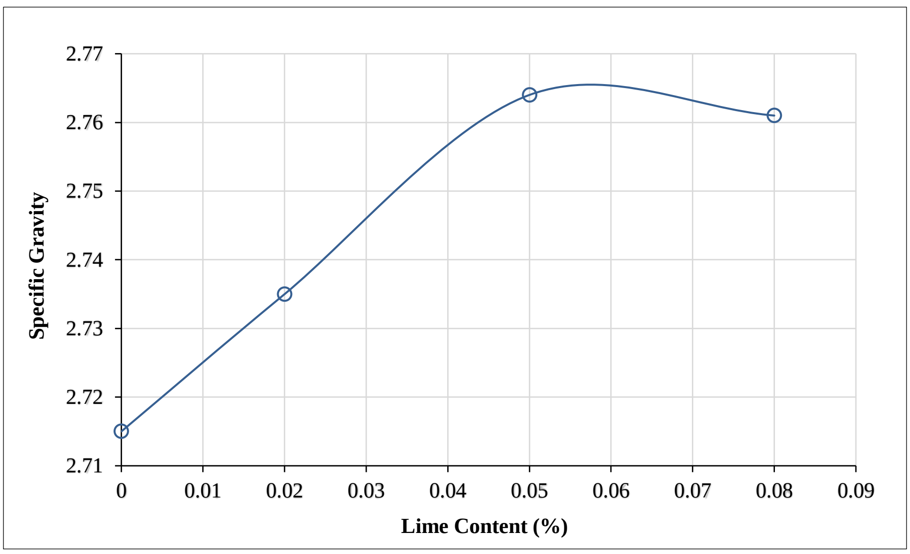


Figure 4. Relationship between specific gravity and percentage of Lime

3.1.2. Compaction

The compaction test was performed to determine the relationship between dry unit weight and moisture content in the soil. Figure 5 illustrates this relationship with varying lime content, while Figure 6 shows the effect of lime on optimum moisture content (OMC). At 8% lime, the moisture content increased from 21.46% to 24.89%. This increase, despite a reduction in surface area due to flocculation, is attributed to the fine particles and free lime present in the soil. These finer particles, along with the free lime, require additional water for pozzolanic reactions, which contribute to the rise in moisture content. The increase in OMC can also be attributed to the water-absorbing nature of lime, which forms hydration products that draw moisture from the surrounding soil. Moreover, the maximum dry density decreased from 1.60 to 1.498 g/cm³ (Table 3). This reduction is primarily due to lime's lower specific gravity (approximately 3.2) compared to the soil particles. Additionally, lime acts as a coating on the soil particles, which can increase the size of the voids within the soil structure, thereby reducing the overall soil density. These effects have been observed in previous studies, where lime was found to influence the soil's compaction characteristics by altering the soil structure and increasing the porosity, which reduces the dry density [25]. Similar findings have been reported in earlier research [7, 8, 26], which indicated that the addition of lime leads to an increase in moisture content and a decrease in maximum dry density due to similar mechanisms of pozzolanic reactions and changes in soil particle arrangements.

Table 3. Results of compaction tests

Soil sample	Lime content (%)	Maximum dry density (gm/cm³)	Optimum moisture content (%)
Unstabilized soil	-	1.601	21.46
Stabilized soil	2	1.539	22.33
	5	1.510	23.47
	8	1.498	24.89

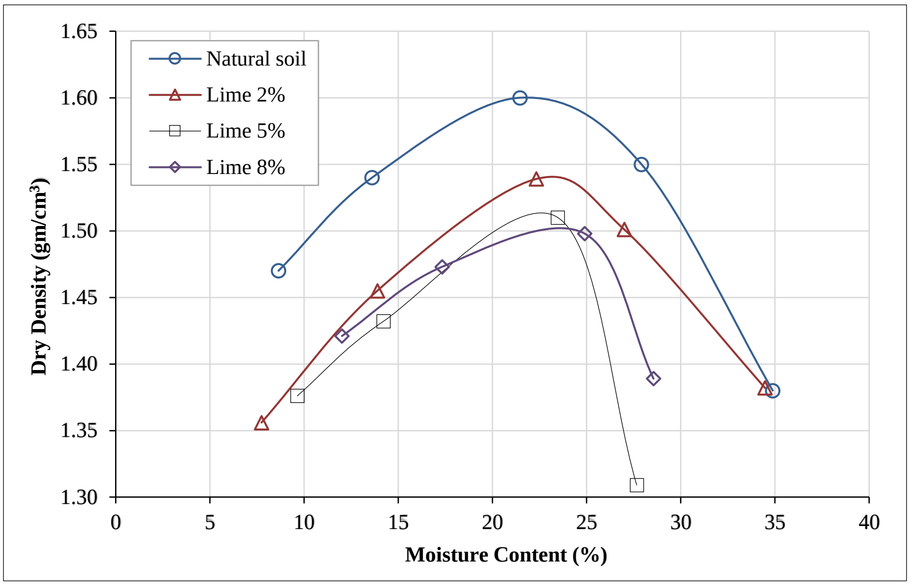
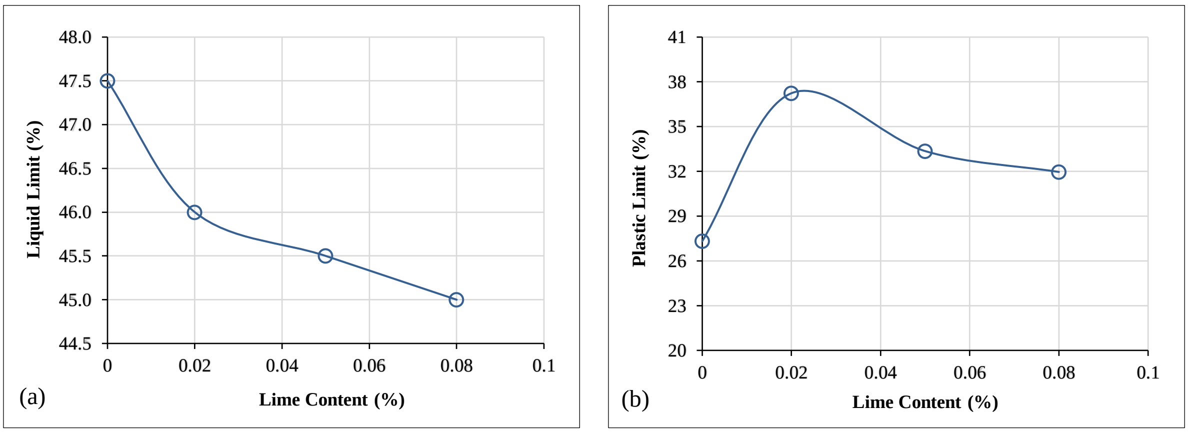


Figure 5. Compaction curves of natural soil and Lime (2%, 5% and 8%)



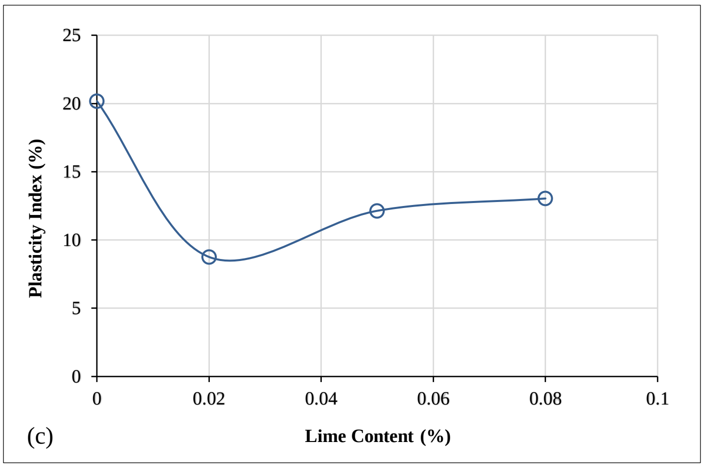


Figure 6. Relationship between (a) Liquid Limit (b) Plastic Limit (c) Plasticity Index and content of Lime

3.1.3. Atterberg Limits

Consistency limits, including the liquid limit (L.L.) and plastic limit (P.L.), are essential soil engineering properties. Figure 6 shows the variation in the liquid limit and plastic limit with different lime contents. The decrease in the liquid limit is due to exchanges between free calcium in lime and cations adsorbed by clay, which reduces the volume of the diffuse double layer surrounding the clay particles, facilitating particle flocculation. Adding lime to clay soil increases its water absorption and plastic limit as the lime content increases. Initially, soil properties improve with the addition of lime, but this effect diminishes once a certain lime threshold is surpassed, leading to aggregation and reduced water retention, as shown in previous studies [7, 8, 26]. Regarding the plasticity index, its fluctuation in both increase and decrease can be attributed to the complex interactions between lime and soil particles. Lime may reduce plasticity by promoting flocculation, while higher lime contents can cause a slight increase in plasticity due to the formation of new chemical bonds or changes in the soil composition. These variations reflect the intricate balance between the physical and chemical changes induced by lime treatment.

3.1.4. Unconfined Compressive Strength

The unconfined compressive strength (UCS, qu) test was performed on cohesive soils at maximum dry density and optimum moisture content. The undrained compressive strength (C_u), defined as half of the UCS, was also calculated. Figure 7 presents the stress-strain relationship derived from UCS tests for both untreated and lime-treated soils, along with the UCS values for each lime content percentage. Figure 8 includes images illustrating the experimental procedure and the results of the UCS tests conducted on soil samples before and after the addition of lime at 2%, 5%, and 8%. Adding lime to clay soil in the range of 2% to 5% increases the compression strength (C_u) to 373 kPa. This increase can be attributed to a chemical reaction between the lime and clay particles, which enhances the cohesion between particles and strengthens the bonds between soil grains. This process, known as the pozzolanic reaction, helps in the formation of cementitious compounds that improve the soil's overall strength.

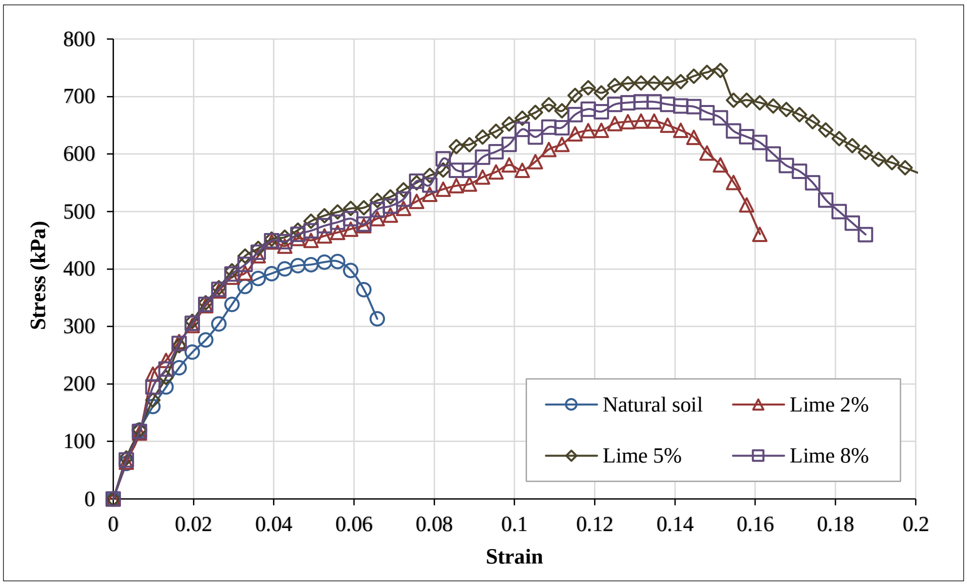


Figure 7. Stress-Strain relationship for natural soil at optimum side with Lime with percentage (2%, 5% and 8%)

Figure 8. Soil Samples for UCS Test Before and After Lime Addition

However, when lime content exceeds 8%, the chemical reactions may create unstable structures, resulting in reduced soil cohesion and a lower compression index. This reduction occurs because excessive lime can disrupt the soil's structure, causing the formation of weak or expansive compounds that do not significantly contribute to strength improvement. As found in previous studies [5, 7], this trend demonstrates that there is an optimal range for lime addition, beyond which the benefits diminish, and the strength of the soil decreases.

3.1.4.1. Time Effect

The unconfined compressive strength (UCS) test was conducted on soil samples with Quicklime (QL) at intervals of 0.5 hours, 7 days, and 14 days, with no tests performed beyond 28 days, as this period is sufficient for construction applications. Figure 9 demonstrates the increase in strength over time for lime-stabilized soil. The strength gain is attributed to two key factors: (1) the formation of chemical and physicochemical bonds between quicklime and soil particles, enhancing strength, and (2) the crystallization of new minerals from initially disordered reaction products [27]. These new minerals further contribute to the stability and durability of the soil structure, enhancing its overall strength. Additionally, the increase in strength is linked to the characteristics of saturated cohesive soils, such as clay sensitivity and thixotropy. Clays may lose strength due to structural breakdown, but they gradually regain strength over time through the reorganization of the soil particles and further mineral formation. This behavior is crucial for understanding the long-term performance of lime-treated soils [28].

The increase in compressive strength (C_u) over time is primarily due to chemical reactions between lime and clay, which form rigid compounds, strengthening soil particle bonds and improving cohesion and density, as shown in Figure 8. These compounds continue to harden over 7 and 14 days, increasing the soil's structural stability and resistance to compression. Table 4 presents the effect of time on C_u values. As documented in previous works [9], the strength of lime-stabilized soils continues to improve with time, making it suitable for construction applications.

Table 4. Effect of time on values of C_u

LQ percentage	C_u (kPa) After 0.5hr	C_u (kPa) After 7days	C_u (kPa) After 14days
2%	329	356	377
5%	373	389	432
8%	345	350	365

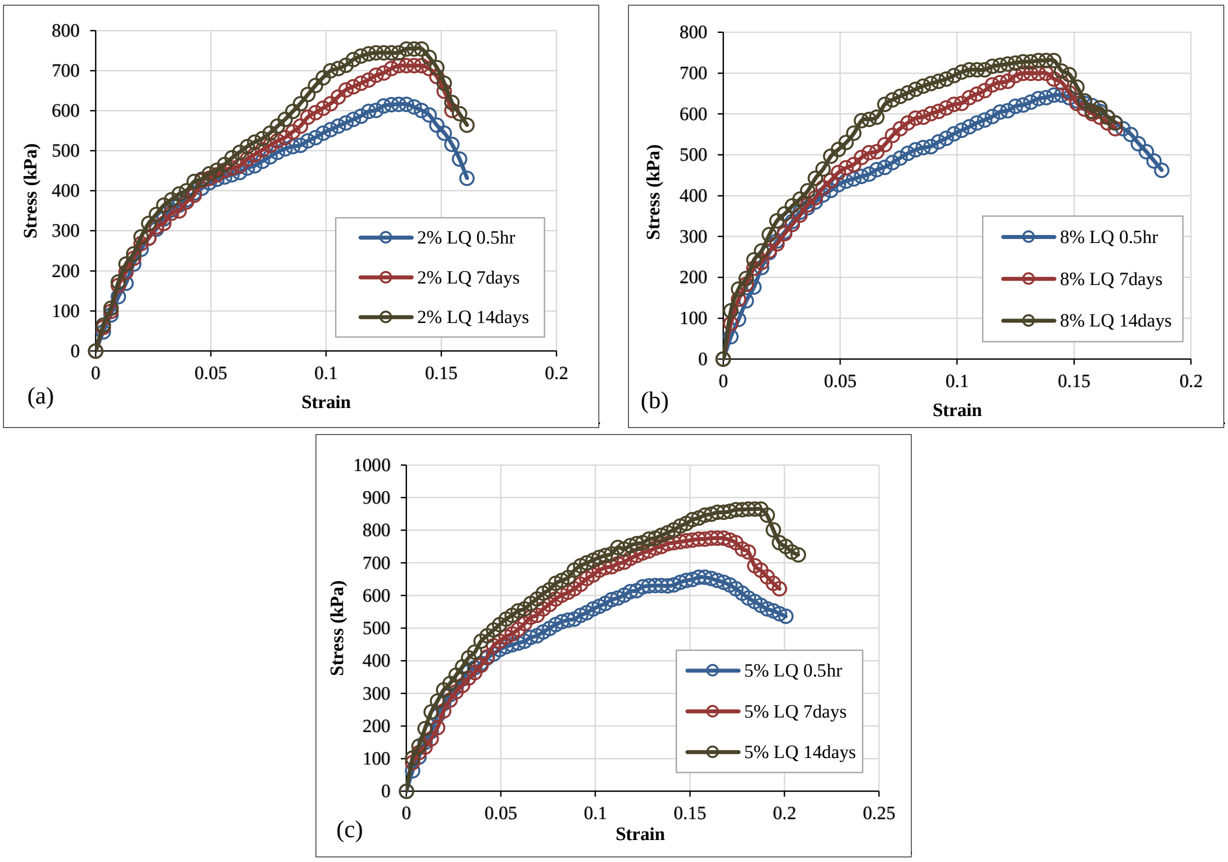


Figure 9. Relationship between the strain-stress curve of natural soil and stabilized soil with (LQ) at different curing time 0.5 hr, 7 days and 14 days (a) 2% LQ (b) 5% LQ (c) 8% LQ

3.1.5. Direct Shear Strength

A direct shear test was conducted to assess the shear strength and internal friction angle of untreated and lime-reinforced soils. Figure 10 shows the relationship between normal and shear stress. Adding 5% lime improved the chemical bond between clay particles, resulting in an increase in compressive strength (C) from 223 kPa to 333 kPa and an increase in the internal friction angle (φ) from 19.80° to 35.73°. This improvement is attributed to the formation of stable structures through chemical bonding, which enhances the soil's resistance to shear stress. However, at 8% lime, the chemical reactions cause the formation of unstable structures, which reduce cohesion and, as a result, decrease both the compressive strength and the internal friction angle, as shown in Table 5. The weakening of these properties occurs because excessive lime disrupts the soil's structure, leading to the formation of weak or expansive compounds that do not significantly contribute to soil strength. This observation aligns with previous research [8], which also reported a decrease in shear strength and internal friction angle at higher lime contents due to the destabilization of the soil structure.

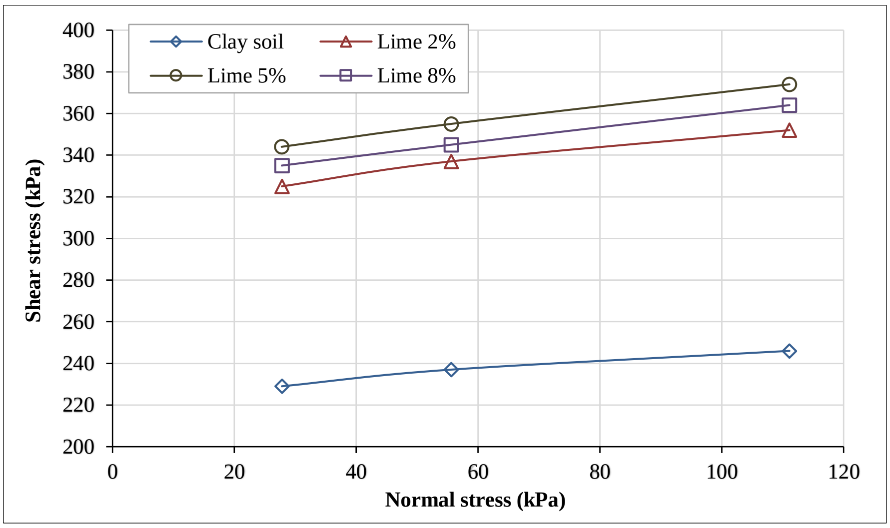


Figure 10. Results of direct shear test of the soil with and without Lime with percentage (2%, 5% and 8%) at optimum sides

Table 5. Direct shear test results

Soil sample	Lime content (%)	C (kPa)	φ (º)
Unstabilized soil	0	223	19.80
	2	317	31.63
stabilized soil	5	333	35.73
	8	325	34.71

3.1.6. Consolidation Test

The consolidation test was conducted on untreated and lime-treated soil samples with varying lime contents to evaluate their effects on the compression index (C_c), swelling index (C_r), coefficient of compressibility (a_v), and coefficient of volume change (m_v). The results, shown in Figure 11 and summarized in Table 6, reveal that the average consolidation parameters decrease with increasing lime content up to 5%, then increases at 8%. This behavior is attributed to the pozzolanic reactions that alter the soil matrix. The free calcium in lime exchanges with cations absorbed by clay minerals, reducing the size of the diffused water layer and allowing closer contact between clay particles in accordance with previous studies [26]. Figure 12 shows the Oedometer device and cell used in the consolidation test.

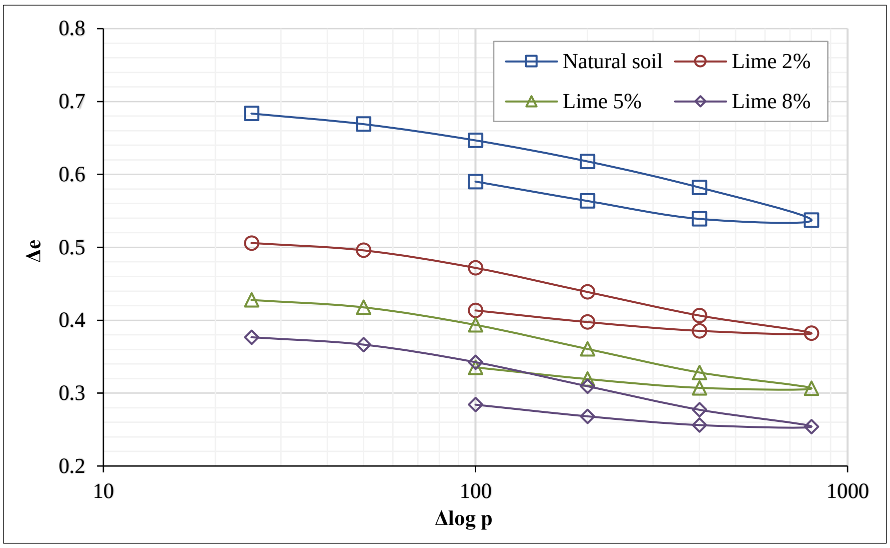


Figure 11. Variation of void ratio with vertical stress for soil and Lime with percentage (2%, 5% and 8%) prepared at optimum side in odometer test

Table 6. Results of consolidation tests

Soil sample	Lime content (%)	e_o	C_c	C_r	$a_v \times 10^{-3}$	$m_v \times 10^{-3}$
Unstabilized soil	.....	0.6968	0.1339	0.0213	0.1926	0.1135
	2	0.5131	0.0942	0.0162	0.1655	0.1094
Stabilized soil	5	0.4309	0.0897	0.0141	0.1606	0.1122
	8	0.3818	0.0919	0.0152	0.1630	0.1178

Figure 12. Oedometer device and cell used

3.1.7. Scanning Electron Microscopy (SEM)

Materials science and surface science, utilizing Scanning Electron Microscopy (SEM), are extensively used to magnify and examine surface structures and analyze surface variations [29]. SEM provides the advantage of investigating a material by directing an electron beam in a vacuum environment, which is focused using electromagnetic lenses to generate high-resolution images. These images are created by detecting secondary electrons or reflections resulting from the interaction of the electron beam with the material.

Microscale analysis is frequently applied in geotechnical engineering, especially for stabilizing clayey soils [30, 31]. During the stabilization process, a specific amount of lime is introduced to the clay soil, triggering ion exchange and flocculation–agglomeration within a short time frame. Any cation may replace other ions in this process. The soil texture changes due to the flocculation–agglomeration process, causing clay particles to cluster into larger aggregates. As a result, a reduction in the liquid limit, an increase in the plastic limit, a decrease in the plasticity index, a rise in the shrinkage limit, improved workability, and enhanced strength and deformation properties of the soil are expected. The pozzolanic reaction may continue over an extended period, making its effect more prominent in the long term. The interaction between clay minerals and lime leads to the formation of calcium silicate gel, which fills the pores and serves as a binding agent between soil particles, thereby improving soil strength [30].

Figure 13 presents the Scanning Electron Microscope (SEM) analysis of untreated clay soil. The image reveals irregularly shaped soil particles with visible voids and spaces between them, indicating a high porosity and a loosely structured arrangement. This structural characteristic suggests that the untreated clay has low mechanical strength and poor stability, as a result of the disorganized particle arrangement. The high void ratio between the particles contributes to the soil's vulnerability to changes in moisture content, leading to fluctuations in its strength and other geotechnical properties. These observations highlight the need for the addition of stabilizing agents, such as lime, to improve the physical and mechanical properties of the soil.

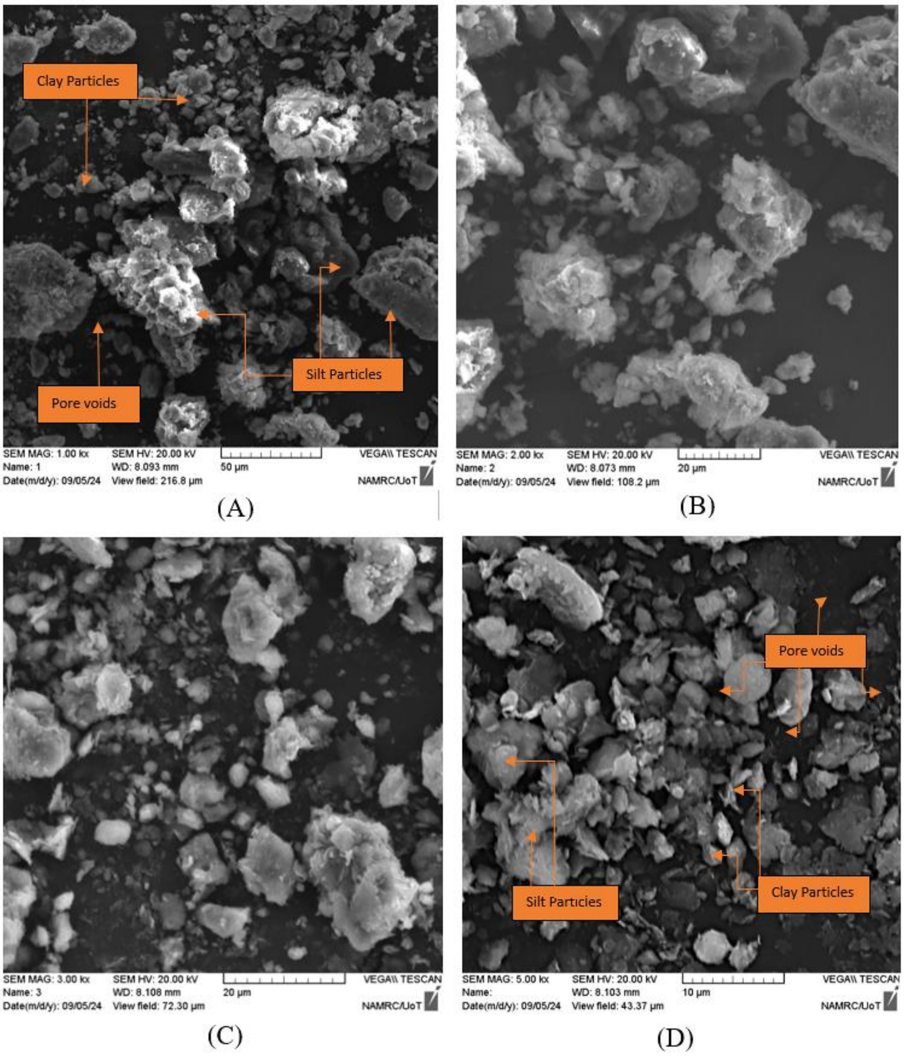


Figure 13. SEM micrograph of natural soil. (A) Image captured at 1000x magnification. (B) Image captured at 2000x magnification. (C) Image captured at 3000x magnification. (D) Image captured at 5000x magnification

Figure 14 illustrates the SEM analysis of clay soil stabilized with 5% lime, which was identified as the optimal lime addition ratio in the conducted tests. The SEM image clearly reveals two types of particles: small, irregular calcium oxide (CaO) particles and larger calcium hydroxide ($Ca(OH)_2$) particles. The formation of these calcium compounds is attributed to the interaction between lime and clay minerals in the soil. Calcium oxide particles are formed during the initial reaction of lime with water, while calcium hydroxide forms as lime further reacts with moisture in the soil.

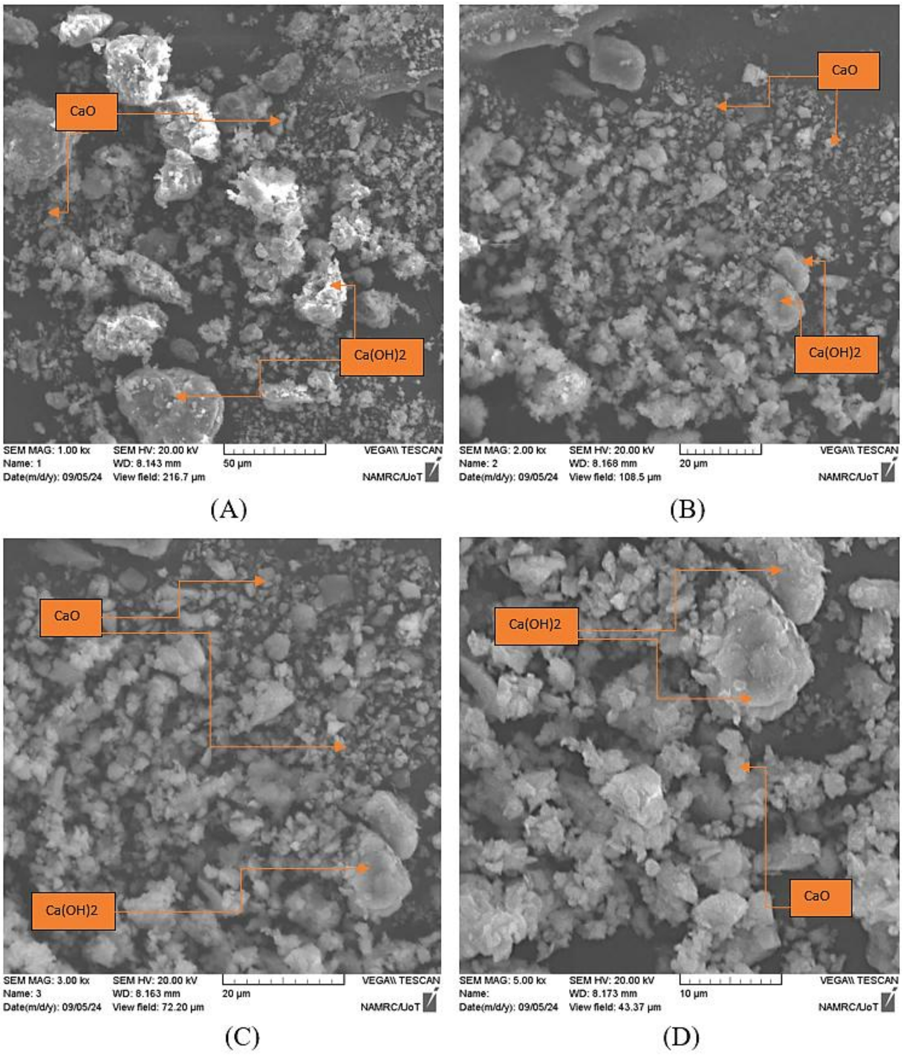


Figure 14. SEM micrograph of soil with 5% quicklime. (A) Image captured at 1000x magnification. (B) Image captured at 2000x magnification. (C) Image captured at 3000x magnification. (D) Image captured at 5000x magnification

In addition to these lime-derived particles, the SEM images also highlight the formation of cementitious compounds, primarily calcium silicate hydrate (C-S-H), resulting from the pozzolanic reaction between lime and clay minerals. This reaction leads to the agglomeration of clay particles into larger aggregates, filling the pores and reducing the soil's porosity. The cementitious materials produced during this process act as a binder between soil particles, enhancing the overall strength and reducing the plasticity of the soil. These structural changes result in improved geotechnical properties, including increased strength, reduced plasticity index, and enhanced workability, thus demonstrating the effectiveness of lime in stabilizing clayey soils.

3.1.8. X-Ray Diffraction (XRD)

X-ray diffraction (XRD) has steadily emerged as one of the most essential analytical techniques for both qualitative and quantitative analysis of geological samples [32]. Numerous foundational theoretical studies have been published on the application of XRD for qualitative and quantitative work [32]. XRD is often considered the most reliable method for routine quantitative analysis, especially when compared to other techniques like Fourier transform infrared spectroscopy (FTIR), chemical analysis, and electron microscopy [33]. However, the quantitative analysis of certain minerals, particularly clay minerals, remains challenging due to their diverse chemical compositions, preferred orientations, structural disorder, and extensive structural variability [34].

The XRD device was used to analyze the mineral composition of both natural soil and soil stabilized by adding 5% of quicklime. Soil minerals are fundamental in understanding the mechanisms of chemical stability and help identify the types of clay minerals present in the studied soils to assess their potential for expansion. Two soil samples were tested, as indicated by the SEM analysis. These tests were conducted at the Nanotechnology & Advanced Materials Research Center at the University of Technology. X-ray diffraction (XRD) analysis was conducted to evaluate the mineral composition of both untreated natural soil and soil stabilized with 5% quicklime. This technique is essential for identifying and characterizing the clay minerals in the soil samples, as these minerals play a critical role in determining the soil's chemical stability and its potential for expansion.

Figure 15 presents a comparative analysis of the mineral phases in both the natural soil and the lime-treated soil. The XRD pattern of the untreated natural soil reveals the presence of common clay minerals, including kaolinite, montmorillonite, and illite, which are typically found in clayey soils. These minerals are highly sensitive to moisture variations, contributing to the soil's high plasticity and swelling potential. Upon the addition of 5% quicklime, significant changes in the mineral composition of the soil are observed.

The XRD pattern of the stabilized soil indicates the formation of new mineral phases, such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which are the products of the pozzolanic reaction between lime and clay minerals. These cementitious compounds improve the soil's strength and reduce its expansion potential by stabilizing the soil structure.

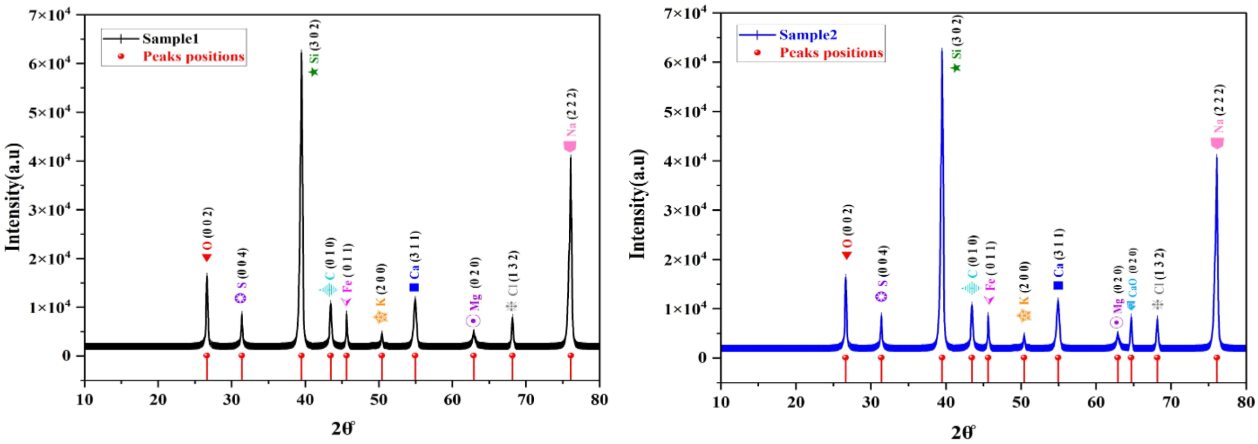


Figure 15. (a) XRD of Natural Soil, (b) XRD of Soil with Lime (CaO) 5%

The identification of these mineral phases through XRD provides valuable insight into the chemical reactions occurring within the soil during stabilization. These reactions contribute to the enhancement of the soil's geotechnical properties, including reduced plasticity, improved strength, and lower expansion potential, which are crucial factors in soil stabilization.

Table 7 presents a detailed breakdown of each mineral and its corresponding elements identified in the XRD analysis for both untreated and stabilized soils. The table provides information about the clay minerals (such as kaolinite, montmorillonite, and illite) and the chemical elements associated with these minerals. The XRD results indicate how each mineral is linked with specific elements, with calcium, silicon, and aluminium being key elements in the cementitious compounds formed during the lime stabilization process.

This data helps correlate changes in the soil's mineral composition with improvements in its geotechnical properties, such as increased strength and reduced expansion and plasticity. By analysing this information, the relationship between the elements and minerals can be better understood, as well as how the lime stabilization process impacts the chemical and structural transformations in the soil. This deeper understanding enhances the ability to analyze the chemical interactions between lime and clay minerals in the soil, improving the knowledge base for future soil stabilization techniques.

Table 7. Element and the corresponding clay minerals

Element	Clay minerals
Si	Kaolinite Illite Quartz Montmorillonite Wollastonite Albite
O	ALL
AL	Kaolinite Illite Montmorillonite Albite
C	Calcite
Ca	Calcite Wollastonite
Na	Albite
K	Halite
Fe	Goethite
Mg	Dolomite
S	Pyrite
Cl	Halite

4. Conclusions

- The specific gravity of the soil increased with the addition of 2% and 5% lime, but began to decrease slightly at 8% lime content. This decrease is attributed to the low specific gravity of lime, which is approximately 2.3.
- A reduction in the liquid limit and plasticity index was observed with the addition of lime, due to the chemical reactions between the lime and soil. However, an increase in the plasticity index was also noted due to the increased water absorption by the soil upon lime addition.
- The optimum moisture content increased from 21.64% to 24.89% with the addition of lime, while the maximum dry density decreased from 1.60 to 1.498 g/cm^3.
- Significant increases in unconfined compressive strength (Cu), compressive strength (C), and internal friction angle were observed due to lime's role in improving particle bonding and enhancing structural cohesion. The greatest increase occurred at 5% lime content, after which a decrease was observed at 8%, where chemical reactions formed unstable structures, reducing cohesion strength.
- Lime improved the compressibility of clay soil by reducing the consolidation coefficients av, mv, Cc, and Cr.
- Based on the lime-soil interactions, the optimum lime content was determined to be 5%.

5. Declarations

5.1. Author Contributions

Conceptualization, Z.H.S., H.H.K., and Z.W.S.; methodology, Z.H.S., H.H.K., and Z.W.S.; formal analysis, Z.H.S. and H.H.K.; data curation, H.H.K. and Z.W.S.; writing—original draft preparation, Z.H.S., H.H.K., and Z.W.S.; writing—review and editing, Z.H.S., H.H.K., and Z.W.S.; visualization, Z.H.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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