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Research Article

Mechanical Strength and Microstructure of Soft Soil Stabilized with Cement, Lime, and Metakaolin-Based Geopolymer Stabilizers

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Soft soils require particular consideration when designing civil engineering structures due to their high compressibility, low shear strength, and permeability. Using chemical additives and geopolymers to stabilize soft soils is a practical approach to improve their engineering properties. The objective of the study was to explore the use of conventional stabilizers alongside metakaolin-based geopolymers. This study also aimed to investigate the compaction characteristics, mechanical strength, shear behavior, and microstructure of stabilized soft soil. The compaction test was carried out using various amounts of cement (6%, 8%, and 10%) and metakaolin (3%, 5%, and 7%) based on the dry weight of the soil. Cement, lime, and geopolymer were added to the soft soil at 15% of the dry weight of the soil for triaxial shear tests. The compaction test results indicated that the stabilized soil exhibited the highest maximum dry density at 8% cement content. Adding metakaolin (MK) to the cement-modified soil decreased the maximum dry density, smoothed the compaction curve, and increased the optimum moisture content. The unconfined compressive strength (UCS) test revealed that cement-stabilized soil had the highest yield stress, while adding MK to the cement-modified soil reduced the yield stress after 7 days of curing. Compared to untreated soft soil, there was a significant increase in shear strength parameters for cement-, metakaolin-, and lime-stabilized soil. This study demonstrates that adding chemical additives and geopolymers can improve the soft soil's compaction characteristics, mechanical strength, and shear strength parameters.

1. Introduction

Chemical stabilization is a method used to improve the strength and durability of soft soil. It offers significant economic and engineering benefits [1]. Various chemical agents, such as lime, cement, and pozzolana, as well as industrial waste, such as fly ash (FA) and metakaolin (MK), are utilized for stabilization [2–5]. Marble dust, pumice powder, iron, and chrome slags are also used to stabilize soft clayey soils [6, 7]. Lime and cement are the most widely used binders in chemical soil stabilization [8].

Portland cement (PC) has been widely used in construction and ground improvement due to its superior strength [9–12]. Cement stabilization is a process that involves adding cement to soil or other materials to enhance their durability and strength. The process involves mixing the cement with soil or other materials to create a firm and stable mixture that can withstand heavy loads and resist erosion. The resulting mixture can be a foundation for buildings, roads, bridges, and other structures. Cement stabilization is a widely used technique in the construction industry to improve the stability and durability of various structures. The soil–cement method has been used for almost a century to enhance soil engineering and mechanical properties. Zhang and Tao [13] studied the durability of low-plasticity soil stabilized with cement. The durability of the stabilized soil was tested using wet drying, tube suction, and 7-day unconfined compressive strength (UCS) tests. It was found that the water–cement ratio had a significant impact on the 7-day UCS and the durability of cement-stabilized soil samples. Yin et al. [14] quickly assessed the durability of cement-stabilized clay soil in the field. It was discovered that increasing the clay–water–cement ratio reduces the average degree of hardness. However, unconfined compression tests indicate that the

measured UCS increases for cement-stabilized soil. Wang et al. [15] investigated the impact of soil texture and cement content. The tests conducted were on the hydraulic, strength, and microstructural characteristics of cement-stabilized composite soils. It was found that clay soil requires a higher water-to-cement ratio for the desired compactness, whereas fine sand requires a lower percentage.

Furthermore, increasing cement content resulted in a linear increase in UCS for cement-stabilized soils. Yu et al. [16] studied the impact of the water-to-cement ratio on the properties of cement-stabilized Singapore soft marine clay for wet deep mixing applications. The investigation results showed that the physical characteristics of stabilized clay change almost proportionally with an increase in the water/cement (w/c) ratio. A low w/c ratio ranging from 0.6 to 0.8 was recommended to achieve the optimal stabilization of soft clay through wet deep mixing. Tang et al. [17] analyzed the mechanical behavior of clay soil reinforced with short polypropylene fiber and cement. Fiber reinforcement in uncemented and cemented soil increased UCS, shear strength, and axial deformation at failure.

Lime stabilization is a fundamental process that is used to improve soil properties. It involves adding lime to the soil to increase its pH value, promoting the formation of stable and durable soil aggregates. Lime reacts with soil particles, causing them to bind together, resulting in improved soil structure, reduced plasticity, and increased strength. Harichane et al. [18] studied the use of natural pozzolana and lime to stabilize cohesive soils. The plasticity index was found to decrease as the lime content increased. However, the maximum dry density of lime-stabilized soil decreases, in contrast to natural pozzolana-stabilized soils. Sivapullaiah et al. [19] conducted an experimental study on the role of the amount and type of clay in the stabilization of lime. It was shown that the liquid limit of black cotton soil decreased after lime was added due to a depressed double layer. However, over time, the liquid limit increases. Adding lime causes all black cotton soils to experience an increase in the shrinkage limit. Bourokba Mrabent et al. [20] investigated the effect of lime on some physical parameters of a natural expansive clay from Algeria. It was found that the proportion of lime added impacts the compaction characteristics. Adding lime to clay soil decreases the maximum dry unit weight and increases the optimum water content. Zukri [21] investigated the use of hydrated lime to stabilize Pekan soft clay. Experimental tests such as the Eades-Grim pH test, standard Proctor tests, unconfined compressive strength, Atterberg limit, and standard Proctor tests were conducted. It was found that a minimum of 4% lime was needed to stabilize the clay soil, and adding more lime increased the strength of the samples. Dhar and Hussain [22] studied the strength and microstructural behavior of lime-stabilized subgrade soil for road construction. It has been verified that adding lime reduces linear shrinkage strains and increases soil UCS, split-tensile strength (STS), and California-bearing ratio (CBR) values. Ghobadi et al. [23] examined the use of lime to stabilize clay soils and how pH variations affect shear strength parameters. The results show that adding approximately 7% of lime can effectively stabilize soils. The highest values of cohesion and friction angle were achieved at pH 9.

Metakaolin (MK) has been widely used as a highly effective mineral additive in formulating high-performance concrete and cement paste [24, 25]. MK reduces greenhouse gas emissions related to the production of Portland cement. It replaces 5%–20% of Portland cement in a mixture. MK is also an aluminosilicate substance with various percentages of alumina (40%–45%) and silica (50%–55%) [26]. Samuel et al. [27] used a geopolymer-based stabilizer to examine expansion clay strength enhancement and volume change. The MK was used in ratios of 4%, 10%, and 15% according to the dry weight of the soil sample. The results showed that geopolymer-treated soils significantly increased UCS and decreased swelling and shrinkage after only 7 days of curing. Luo et al. [28] studied silty clay's microstructure and mechanical properties stabilized by MK-based geopolymers. The study involved UCS tests, scanning electron microscopy (SEM) analysis, and X-ray energy dispersive spectroscopy (EDS) studies. The results indicated that MK could be an effective agent to solidify silty soil. Abdulkareem and Abbas [29] stabilized soft soil using MK-based geopolymer. The geopolymer is comprised of 8%, 10%, and 14% of the dry weight of the soil. The results showed that the MK-based geopolymers effectively stabilized the soft soil. The geomechanical characteristics and triaxial shear behavior of very soft soils stabilized with geopolymer and traditional stabilizers have not been sufficiently investigated.

This study aimed to stabilize soft soil (SS) with a high moisture content using cement, lime, and MK-based stabilizers. Initially, the study examined the impact of adding MK on the compaction characteristics of cement-modified soil. The strength, shear behavior, and microstructure of the stabilized soil were then analyzed by conducting various tests such as UCS, triaxial shear, and SEM.

2. Materials and Methods

2.1. Experimental Materials

2.1.1. Soil Sample. The soil samples were collected from the construction site in Samsun, Turkey. The soil was then subjected to various experimental tests to determine its properties, including Atterberg limits, specific gravity, gradation, compaction, scanning electron microscopy (SEM), and energy-dispersive spectroscopy (EDS). The summary of the physical properties of the soil is shown in Table 1.

(1). Grain Size Analysis. The soil sample was analyzed for grain size using wet sieve and hydrometer methods following ASTM standards. Figure 1 shows that around 86% of the soil sample passes through sieve no. 200, indicating that the sample mainly comprises silt and clay soils.

(2). Compaction Test. The soil sample was subjected to a compaction test following the ASTM D-698 standard. Figure 2 shows the maximum dry density and the optimum moisture content.

Table 1: Physical properties of soil [25].

Property	Values
Plastic limit, PL (%)	34
Liquid limit, LL (%)	61
Plasticity index, PI (%)	27
Sand fraction ($\geq 75\,\mu$m) (%)	13.92
Silt fraction ($75\,\mu\text{m} \leq 2\,\mu$m) (%)	61.69
Clay fraction $<2\,\mu$m (%)	24.39
Passing sieve $75\,\mu$m (%)	86.08
Specific gravity (Gs)	2.73
Soil pH value	7.88
Optimum moisture content (OMC) (%)	26
Maximum dry density (MDD) (g/cm^3)	1.52
Soil classification (USCS)	MH

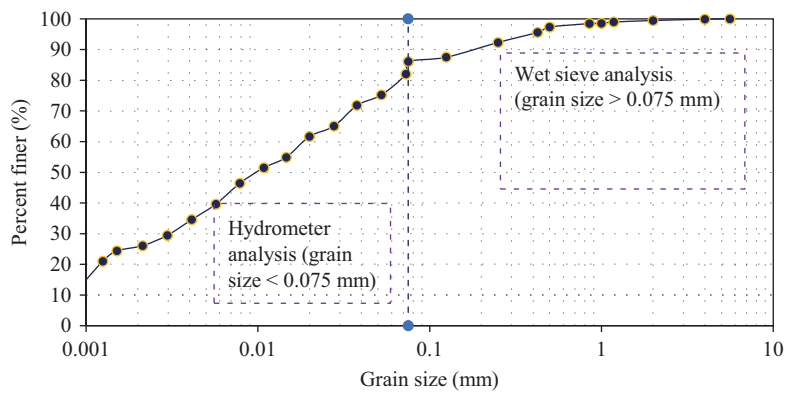


Figure 1: Grain size analysis of soil sample.

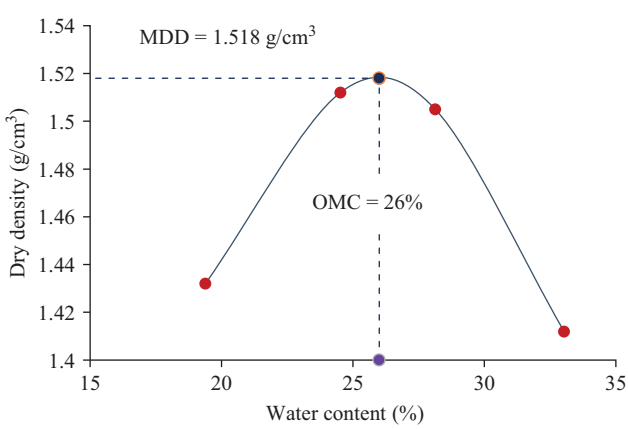


Figure 2: Dry density–moisture content relationship of the soil sample.

(3). SEM and EDS Tests. The mineral composition of the soil was analyzed using SEM and EDS tests. Figure 3 reveals that the main components are silicate oxide (SiO_2) and aluminum oxide (Al_2O_3).

(4). Soil Classification. The soil in the study area was classified using the Unified Soil Classification System (USCS) based on the results of the plasticity index and liquid limit tests. The soil is classified as high-plasticity silt (MH), as shown in Figure 4.

2.1.2. Metakaolin. The metakaolin was obtained from a local supplier in Turkey. The company provided the mineralogical composition of the metakaolin, and the results are presented in Table 2. Metakaolin consists mainly of Al_2O_3 and SiO_2, which facilitates the geopolymerization process.

2.1.3. Cement and Lime. Cement and lime are commonly used to stabilize the soil in civil engineering projects. The stabilizers were obtained from local suppliers in Turkey. A pH test estimated the minimum amount of lime used for stabilization. The soil–lime pH test determines the amount of lime and soil needed to maintain a pH level that will support the necessary chemical processes for soil stabilization. This test method determines the lowest percentage of lime that gives a soil–lime pH of 12.4, as shown in Figure 5.

2.1.4. Alkali Activators. The geopolymerization of metakaolin was carried out using a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Several researchers recommended these activators for their superior results.

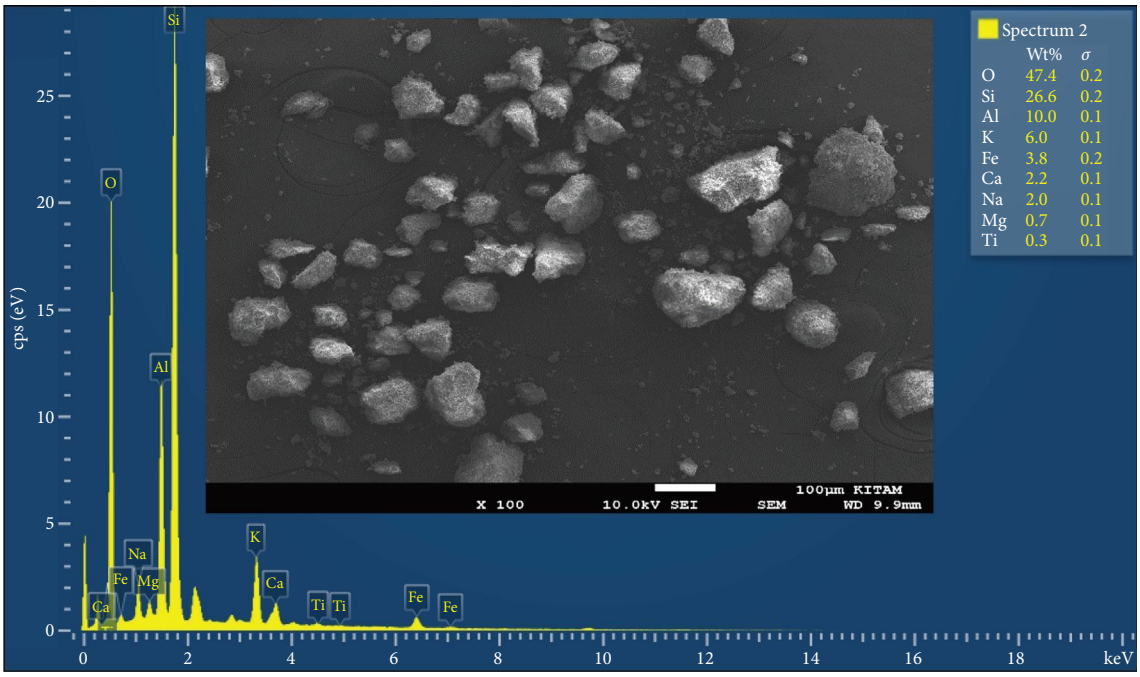


Figure 3: EDS results of the soil sample.

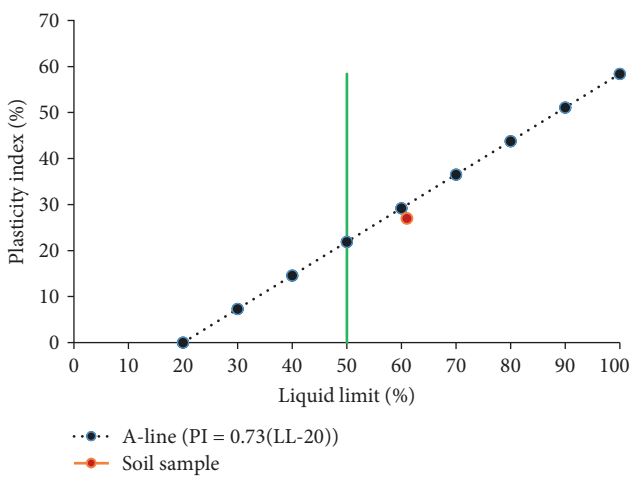


Figure 4: Classification of the soil sample in the plasticity chart.

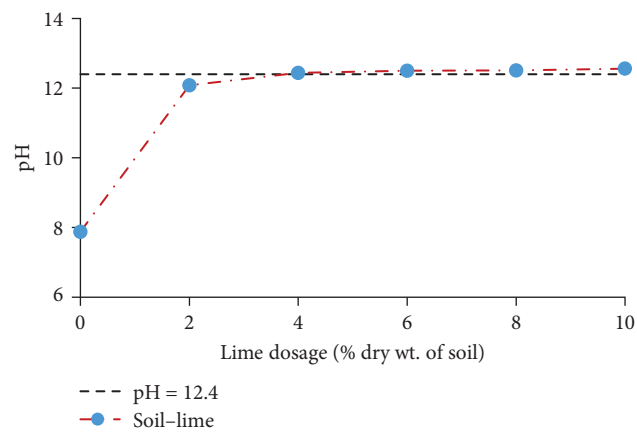


Figure 5: pH variation after lime treatment.

Table 2: Mineralogical composition of metakaolin.

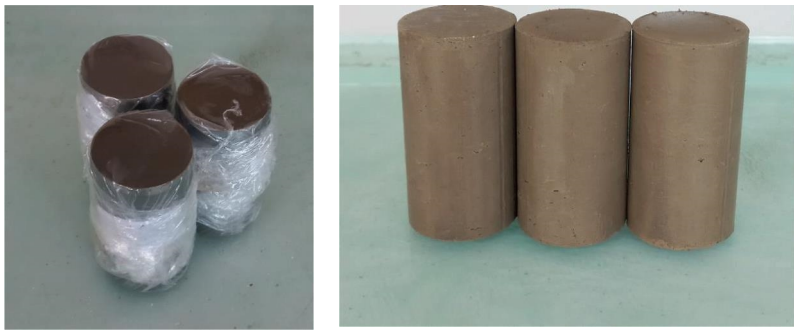
Compounds	Wt. (%)
SiO_2	$50.00 \pm 1{,}0$
Al_2O_3	$45.00 \pm 1{,}0$
Fe_2O_3	0.50 Max
TiO_2	1.00 Max
CaO	0.50 Max
MgO	0.40 Max
$K_2O + Na_2O$	0.55 Max

2.2. Laboratory Tests and Sample Preparation. Experimental tests were conducted on soft soil stabilized with metakaolin, cement, and lime. The tests included compaction, unconfined compression, and triaxial shear.

2.2.1. Compaction Test. The compaction test was performed according to the ASTM D-698 standard using an automatic soil compactor. The study aimed to determine the maximum dry density (MDD) and the optimum moisture content (OMC) of soil stabilized with cement and metakaolin. The cement was added to the soil in proportions of 6%, 8%, and 10% of the dry weight of the soil, whereas metakaolin was added in proportions of 3%, 5%, and 7% of the dry weight of the soil. Cement and metakaolin were mixed before being added to the soil. The samples were carefully blended to ensure a uniform mix before compaction, as depicted in Figure 6.

2.2.2. Unconfined Compression Strength (UCS) Test. The soil sample was dried in an oven at 105°C, pulverized with a Los Angeles abrasive apparatus, and shifted through a 2 mm sieve. The soft soil was initially prepared with a moisture

Figure 6: Sample preparation for the compaction test.



(a) (b)

Figure 7: UCS specimen preparation. (a) Wrapped specimens and (b) demolded specimens.

content of 0.75 liquid limit (LL) value. Cement and metakaolin slurry was added to the soft soil to prepare the UCS specimens. Cement was added in an amount of 8% of the dry weight of the soil, while the water-to-binder ratio was maintained at 0.8. Metakaolin was added in quantities of 3%, 5%, and 7% of the dry weight of the soil. The cement–metakaolin mixture and the soft soil were thoroughly mixed using an automatic mixer for 5–10 min. The resulting mixture was then transferred to a metallic mold with a diameter of 38 mm and a length of 76 mm. Figure 7 illustrates the preparation of samples for UCS tests. Two identical specimens were prepared, and the weight of each specimen was controlled to ensure uniformity and reliability. The soil samples were placed in a curing chamber for 24 hr after being wrapped in plastic films. The next day, the samples were removed from the mold, rewrapped in plastic film, and placed in the curing chamber. The UCS test was performed following the ASTM D2166 standard procedure.

2.2.3. Unconsolidated Undrained Triaxial Shear Test (UU). The triaxial shear test determines the stress–strain relationships and the strength of a cylindrical specimen of remolded and stabilized soil samples. During the test, the sample was subjected to a confining fluid pressure in a triaxial chamber, and no drainage was allowed. The compression of the specimen was performed at a constant rate of axial deformation, which is strain controlled. The samples were prepared from soft soil samples stabilized with cement, lime, and metakaolin-based geopolymers. The soil was prepared with an initial moisture content of 0.75 LL and left to saturate for 24 hr. The cement, lime, and metakaolin binders were added to the soft soil in a ratio of 15% of the soil's dry weight. The ratio of water to cement and alkali activator to metakaolin binder was 0.8. The details of the laboratory-testing program are shown in Table 3. The cement, lime, and geopolymer slurry were added to the soft soil and thoroughly mixed with an automatic mixer. The resulting mixture was then added to a mold with a diameter of 38 mm and a length of 76 mm. Samples were statically compacted, and their weight was carefully controlled. Subsequently, the prepared specimens were covered with plastic film and cured at room temperature for 14 days before testing.

2.2.4. Scanning Electron Microscopy (SEM) Test. SEM allows three-dimensional imaging of solid materials and surface details at the nanoscale. A SEM test was performed to understand better the microstructure of the cement-, metakaolin-, lime-, and geopolymer-stabilized soil samples. The test was conducted on modified soil samples after UCS and triaxial shear tests. A piece of specimen was taken from samples that had been oven dried below 50°C to prepare for the SEM examination. The SEM tests were conducted at the Black Sea Advanced Technology Research and Application Center of Ondokuz Mayis University (OMU).

Table 3: Laboratory testing program.

Parameters	Geopolymer stabilization	Cement and lime stabilization
Materials	Soft soil (SS), MK	SS, lime, cement
Alkali activator (L)	70% Na_2SiO_3 + 30% NaOH	—
MK content	15%	—
Cement and lime content	—	15%
L/MK	0.8	—
Soil and water content (LL)	0.75	0.75
Water/binder ratio (w/b)	0.8	0.8
Curing time (days)	14	14
Test	Triaxial (UU)	Triaxial (UU)

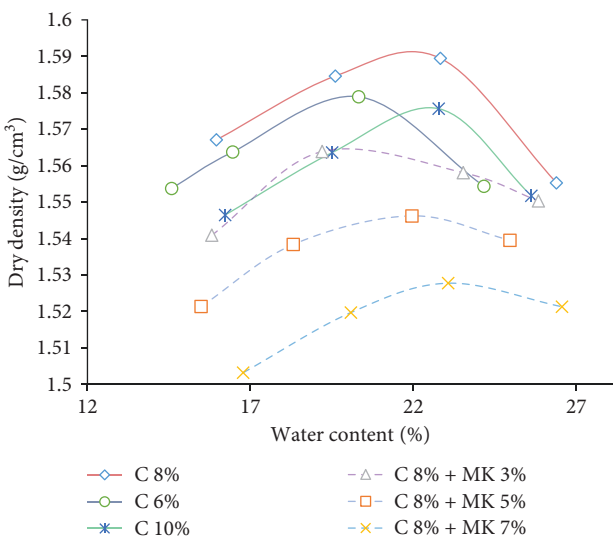


Figure 8: Compaction curves for cement–metakaolin-stabilized soil.

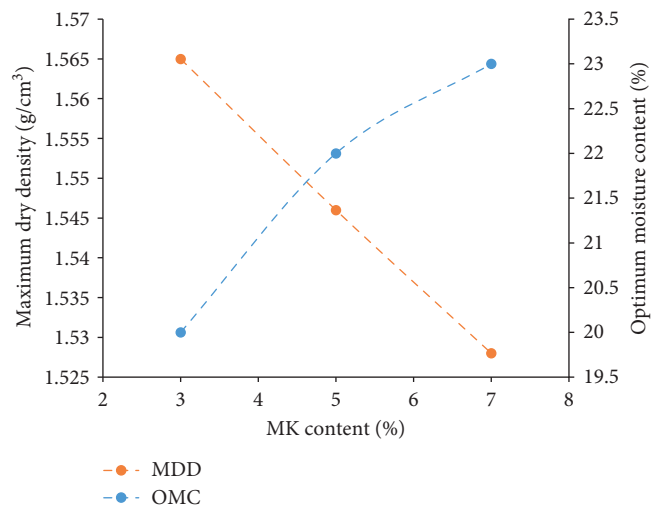


Figure 9: Relationship between MDD, OMC, and MK content.

3. Results and Discussion

3.1. Compaction Characteristics. The cement- and metakaolin-stabilized soil compaction characteristics were carried out using an automatic soil compactor. Figure 8 illustrates the variations in OMC and MDD. The OMC values for the 6%, 8%, and 10% cement contents were 20, 22, and 22.5, respectively. According to previous research findings, increasing the amount of cement also increases the optimum moisture content [24, 30, 31]. The amount of water required for cement hydration increases with increasing cement content, causing an increase in OMC. Furthermore, water is held in the flocculent structure between the cement and soil [24, 32]. The soil's maximum dry density (MDD) was measured at 6%, 8%, and 10% cement contents. The MDD values obtained were 1.579, 1.591, and 1.576 g/cm^3, respectively. In Figure 8, the maximum dry density of the soil was achieved at 8% cement content, and further increasing the cement content reduced the maximum dry density. The researchers explored the reduction of MDD with higher cement contents in fine-grained soils such as silt and clay [33]. The decrease in MDD is caused by cation exchange, which causes particles to flocculate, aggregate, and become slightly coarser [34, 35].

Figure 9 shows that MDD decreases as the MK content increases. In addition, the OMC decreases at low MK contents and then increases at higher MK contents. The decrease in MDD with increasing MK is due to the lower specific gravity of MK and the immediate formation of cemented products [36]. Soft soils stabilized with lime, fly ash, volcanic ash, and rice husk ash demonstrate similar behavior [30, 36–39]. Adding 3%, 5%, and 7% MK to 8% cement reduced the maximum dry density of the soil to 1.565, 1.546, and 1.528 g/cm^3, respectively. Compared to cement, MK treatment flattens the compaction curve, allowing for the prescribed density over a broader range of moisture contents. A study by Bell [40] found similar results when lime was used to stabilize clay minerals and soils.

3.2. Unconfined Compressive Strength (UCS). Unconfined compressive strength (UCS) tests were conducted after 7 days of curing to examine the strength development of the sample. Figure 10 illustrates the stress–strain relationship of cement and soft soil modified with metakaolin. The unconfined compressive strength (UCS) of the untreated soft soil was 23.38 kPa. While for the cement-treated soft soil, it was 1,382.13 kPa. The treated and untreated soft soil had a significant difference in mechanical strength. Figure 11

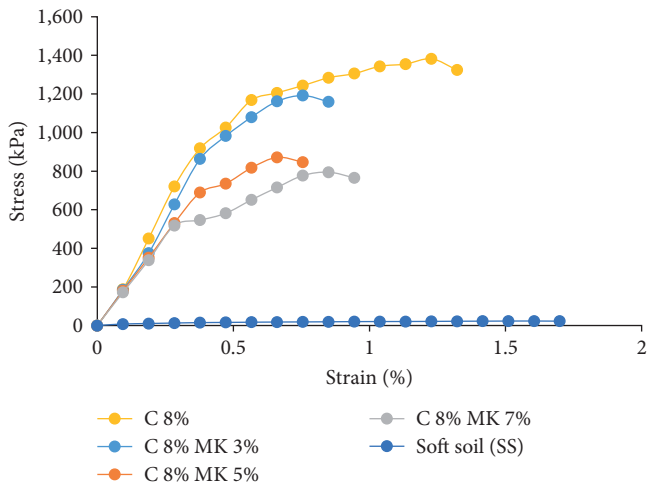


Figure 10: Stress–strain behavior of soil treated with MK and cement (C) at 7-day curing.

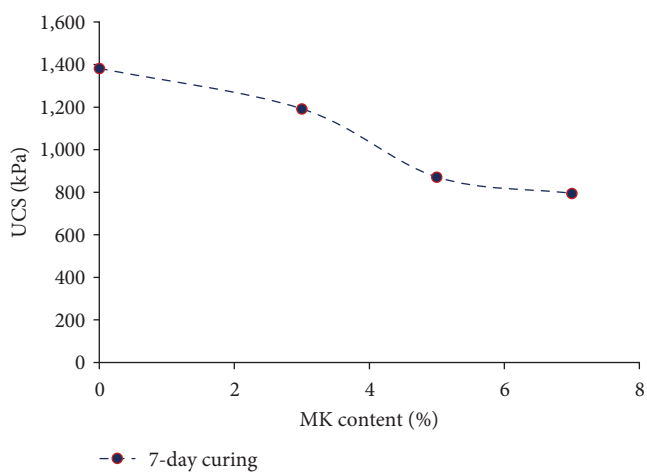


Figure 11: UCS values for different MK contents.

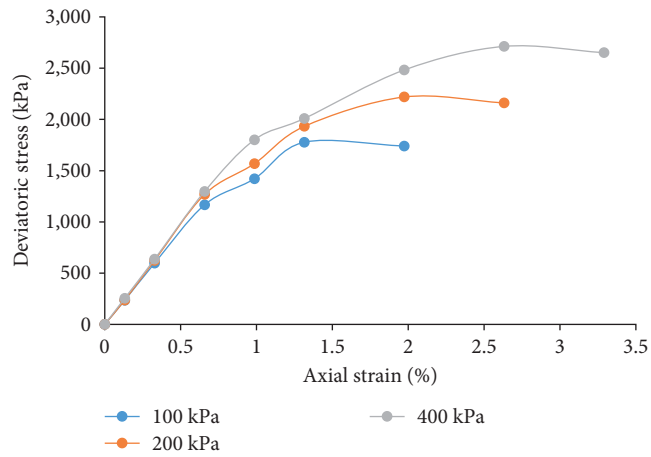


Figure 12: Stress–strain behavior for cement-stabilized SS.

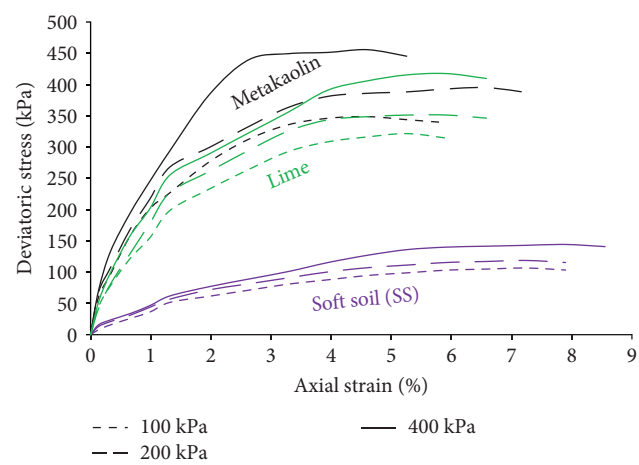


Figure 13: Deviatoric stress–strain behavior of treated and untreated SS.

shows that the UCS values for the MK-treated cement-modified soil at 3%, 5%, and 7% were 1191.83, 871.38, and 794.66 kPa, respectively. The cement-stabilized soil resulted in the highest UCS value while adding MK to the cement-modified soil reduced the UCS values. A study conducted by Wu et al. [24] shows that adding MK to the cement-modified soil resulted in a decrease in UCS values at 7 days of cure.

3.3. Unconsolidated Undrained Triaxial Shear Test (UU)

3.3.1. Stress–Strain Relationship. The unconsolidated undrained triaxial shear test (UU) was conducted on cement-, lime-, and geopolymer-stabilized SS to determine undrained cohesion and angle of internal friction. Figure 12 illustrates the stress–strain behavior of cement-stabilized SS. The highest deviator stresses were observed when the SS was stabilized with cement. The deviator stresses were 1,777.65, 2,218.77, and 2,712.27 kPa for confining cell pressures of 100, 200, and 400 kPa, respectively.

Figure 13 illustrates the deviator stress–strain behavior of geopolymer-treated SS, lime-treated SS, and untreated SS, which showed a stress–strain relationship similar to UCS test results. The SS was markedly improved by using MK and lime. Stabilization with geopolymer and lime resulted in significantly higher deviator stresses than untreated SS at all confining pressures.

3.3.2. Shear Strength Parameters. Figure 14 shows the Mohr circles with failure envelope for cement stabilization. The undrained cohesion (C_u) and the undrained angle of internal friction ϕ_u were found to be 385 kPa and 36°, respectively. These values were the highest compared to MK and lime-stabilized SS.

The Mohr circles for geopolymer-, lime-stabilized, and untreated SS are shown in Figure 15. The angle of internal friction for untreated SS was 3.4°. On the contrary, the geopolymer- and lime-stabilized SS were 8.4° and 8.1°, respectively. The undrained cohesion of untreated SS, lime-stabilized SS, and geopolymer-stabilized SS was 44.03, 124.02, and 137.03 kPa, respectively. The friction of the internal angle of the SS was doubled with geopolymers and lime stabilizers, whereas the undrained cohesion increased almost three times.

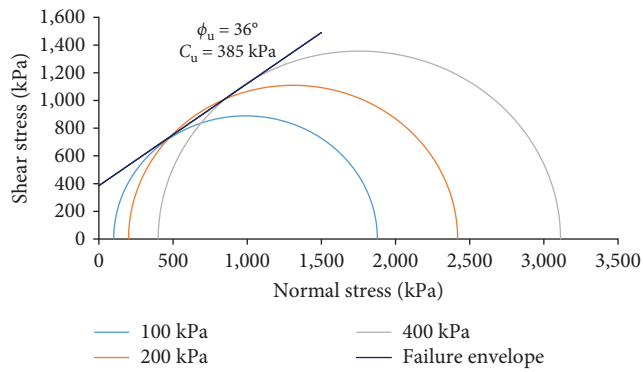


Figure 14: Mohr's circles for cement-stabilized SS.

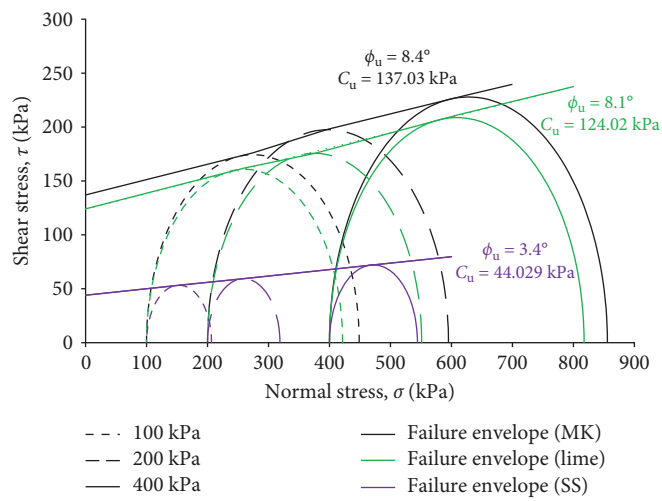
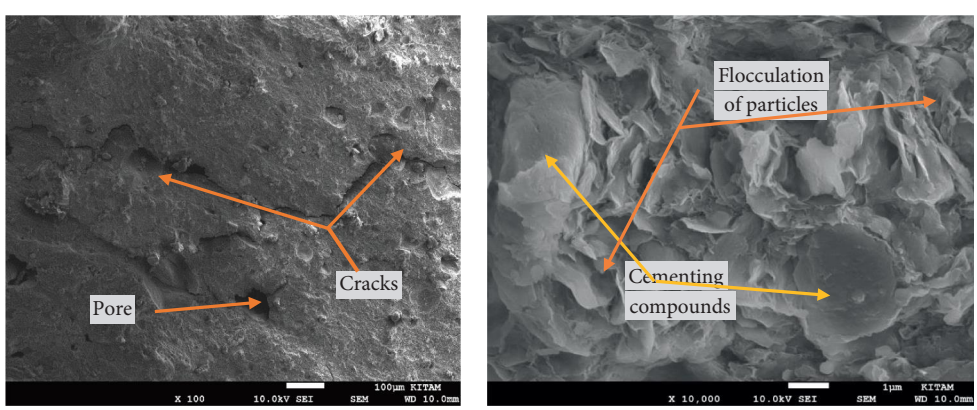


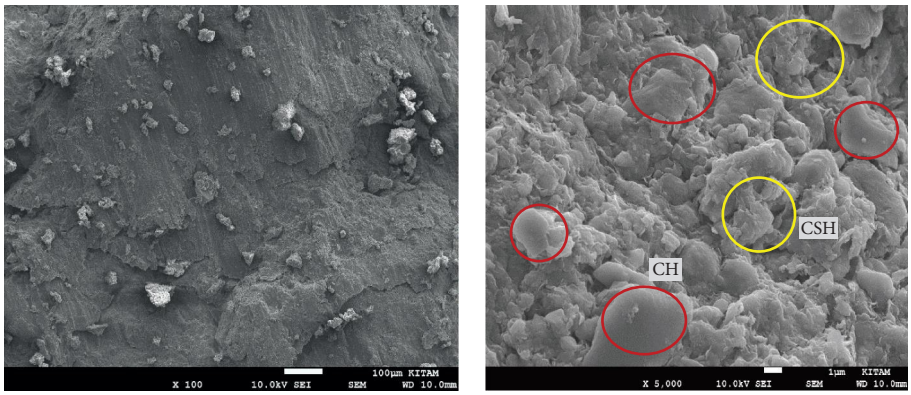
Figure 15: Mohr's circles for MK-based geopolymer-stabilized SS, lime-stabilized SS, and untreated SS.



(a) (b)

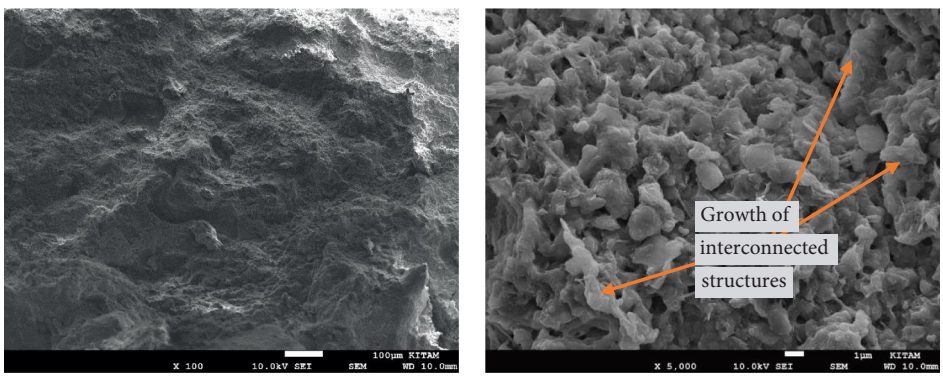
Figure 16: SEM images of cement-treated SS after 14 days of curing. (a) C 8% at 100x and (b) C 8% at 10,000x.

3.4. Microstructural Analysis. SEM tests are performed on untreated and treated soil samples to aid in interpreting observed behaviors. It has been found that untreated soils exhibit a blocky arrangement of loosely packed particles, whereas stabilized soils have a compact and dense microstructure without pores or unhydrated crystals. The properties of cement-treated soil improve due to the soil–cement reaction, which generates primary and secondary cementitious materials within the soil–cement matrix [3, 41]. During the cement hydration, two primary products are formed: calcium hydroxide (CH) and calcium silicate hydrate (C—S—H). A secondary hydration reaction occurs as the process continues, forming



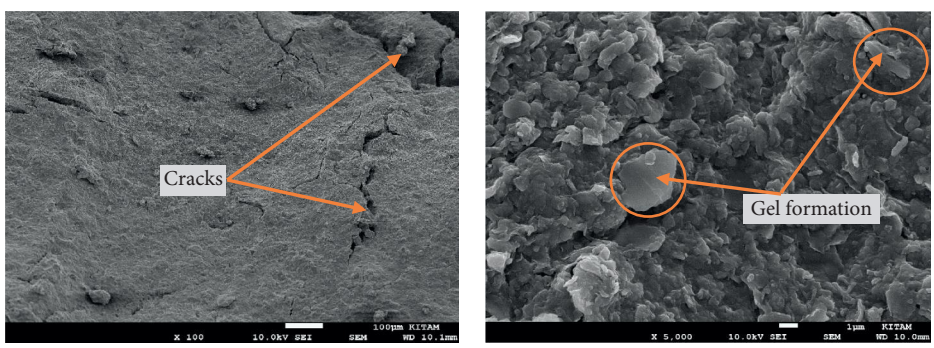
(a) (b)

Figure 17: SEM images of cement–MK-treated SS after 14 days of curing. (a) C 8% + MK 5% at 100x and (b) C 8% + MK 5% at 5,000x.



(a) (b)

Figure 18: SEM images of lime-treated SS after 14 days of curing. (a) Lime at 100x and (b) lime at 5,000x.



(a) (b)

Figure 19: SEM images of MK-based geopolymer-treated SS after 14 days of curing. (a) MK at 100x and (b) MK at 5,000x.

additional cementitious compounds. These compounds include aluminum-containing CSH gel and crystalline products such as calcium aluminate hydrates (C_3AH_6 and C_4AH_{13}) and alumino-silicate hydrates (C_2ASH_8) [42]. Figures 16(a) and 16(b) show the SEM results of cement-treated SS at 100 and 10,000 times magnification, respectively. Pores and cracks are observed at 100 times magnification, whereas higher magnification shows cementing compounds and flocculation particles. SEM images of cement–MK-treated SS after 14 days of curing are presented in Figures 17(a) and 17(b). The cemented soil containing MK displays a denser structure [42], as shown in Figures 17(a) and 17(b). As shown in Figure 18, applying lime treatment to soft soil results in the development of interlinked structures after 14 days of curing. Geopolymer stabilization of SS results in gel formation, as shown in Figure 19. In addition, microcracks were observed at lower magnification.

4. Conclusions

In this paper, experiments were conducted to investigate the effect of various chemical stabilizers on high-plasticity silt (MH) soil. The experimental tests consisted of compaction, unconfined compression strength (UCS), undrained unconsolidated triaxial shear (UU), and scanning electron microscopy (SEM). From the findings, the following conclusions can be drawn:

(1) The compaction test was conducted on soil samples modified with cement and MK. Cement was used in proportions of 6%, 8%, and 10% of the dry weight of the soil, whereas MK was used in proportions of 3%, 5%, and 7% of the dry weight of the soil. The highest maximum dry density (MDD) was achieved when the cement was 8% of the dry weight of the soil. However, the optimum moisture content (OMC) increased with increasing cement content. On the other hand, adding MK to the cement-modified soil decreased MDD, increased OMC, and smoothed the compaction curve.

(2) In the UCS test, the cement content was kept at 8%, whereas MK ratios of 3%, 5%, and 7% of the dry weight of the soil were added to the cement-modified SS. UCS specimens were cured in the curing chamber for 7 days at room temperature and 100% humidity. The UCS value obtained for the 8% cement content was 1,382.13 kPa. The UCS values obtained for the 3%, 5%, and 7% cement-modified soft soil stabilized with MK were 1,191.83, 871.38, and 794.66 kPa, respectively. It can be concluded that the addition of MK to the cement-modified soil results in a reduction in UCS values.

(3) The unconsolidated undrained triaxial shear test (UU) was performed on both treated and untreated SS. The results showed that cement-treated SS had the highest deviator stress compared to MK and lime-treated SS. The shear strength parameters were determined using Mohr–Coulomb failure envelopes. SS treated with cement exhibited the maximum undrained angle of internal friction (ϕ_u) and undrained cohesion (C_u). Geopolymer and lime stabilization significantly enhanced the shear strength parameters compared to untreated SS.

The findings of this study suggest that cement, MK-made geopolymers, and lime can be used to stabilize SS. MK is an eco-friendly alternative that can partially replace traditional stabilizers for SS stabilization. However, the study mainly focused on MH soil. Therefore, further research is recommended to investigate the effectiveness of these stabilizers in other types of soil.

Data Availability

Data sets generated and analyzed during the study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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