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Article

Effect of Macro, Micro, and Nano Lime Particles on the Stabilisation of Expansive Soils

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Abstract. This paper explores the potential of lime to mitigate the shrinkage and expansion properties of expansive soils through plasticity index (PI) testing. Expansive soils are prone to significant volume changes due to moisture fluctuations, which can substantially damage building structures. A series of experiments were conducted to evaluate the effectiveness of lime in these soils, focusing on three distinct particle sizes: macro, micro, and nano. The research examined the impact of varying lime concentrations—1%, 2%, and 3% by weight of soil—on these different soil types. The findings suggest that finer lime particle sizes are more effective in reducing the initial void ratio of the soil, thereby enhancing its bearing capacity. The interaction between smaller lime particles and the soil matrix promotes improved bonding within the treated soil mass, reducing the likelihood of cracking. Overall, this study highlights the significant role of lime particle size in enhancing soil stability and strength.

Keywords: Cracks, expansive soil, lime, soil stabilisation.

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1. Introduction

The physical and mechanical properties of soil are heavily affected by its characteristics. During an earthquake, saturated and loose soils can undergo considerable shaking, leading to reduced soil stability [1, 2]. The challenges in road construction are influenced by geological factors, natural calamities, and climate conditions [3]. Indonesia is a tropical nation with significant rainfall, heightening the likelihood of landslides on slopes containing expansive soils. Compared to other natural disasters like floods, earthquakes, and typhoons, landslides are the most damaging and can lead to more substantial material losses [4]. Soil conditions, especially those involving fractured soil, can contribute to landslides by facilitating the easier infiltration of rainwater and raising water pressure within soil fissures, making slope stability essential [5].

One example is expansive clay soils with high shrinkage expansion [6], and expansive soils are susceptible to water because they contain the mineral montmorillonite, which causes the soil to expand when in contact with water [7, 8]. When construction is carried out on expansive soils, one prevalent type of damage may arise is cracking. Numerous countries, including the United States, Israel, Canada, Australia, and South Africa, encounter challenges associated with expansive soils. The consequences of soil expansion can lead to various issues, such as developing cracks in roadway surfaces, increased lateral stress on retaining walls, heaving and buckling of floor slabs and retaining structures, and diminished bearing capacity.

To overcome this problem, various soil stabilisation approaches have been developed, one of which is the use of binders such as cement and fly ash (FA), which have proven effective in improving the mechanical properties of the soil. Research on stabilising soft clays with ordinary Portland cement (OPC) and FA has improved strength and stiffness and reduced material shrinkage. Some studies, such as those conducted on Bangkok clays, found that adding FA can reduce the shrinkage rate while increasing the OPC content, which increases the strength and stiffness of the mix. These results lead to optimising FA and OPC mixtures to meet the requirements for soft soil improvement applications [9, 10]. In addition, studies on the utilisation of dredged lake bed sediments for road construction materials, such as those conducted at Phayao Lake and Huai Mae Phong Reservoir in Thailand, showed that the sediments could be reused by chemical stabilisation using OPC and FA. Adding FA to OPC-stabilised sediments increases strength, stiffness, and resistance to swelling and shrinkage, making it a more suitable material for road pavements. Optimal mixtures with the right content of OPC and FA can produce mechanical properties that meet the standards required for road construction [11, 12, 13, 14]. Other studies involving FA and rice husk ash (RHA) as Portland cement substitutes for laterite soil stabilisation have also shown promising results. Both waste materials can improve lateritic soils' strength and cyclic resistance, with RHA proving more efficient than FA at certain cement content. These findings reinforce the potential of FA and RHA as effective alternatives in soil improvement for road construction applications [15].

Another viable solution to mitigate the damage caused by expansive soils is incorporating lime as a soil stabilisation material [16].

The application of lime for soil stabilisation has been recognised and utilised since ancient times. The Romans incorporated lime in constructing the Shenshi pyramid, while the ancient Chinese used it to reinforce clay pebbles as foundations for large bridges. In India, lime enhances soil conditions on unpaved roads and rock dams. In the United States, the use of lime for soil stabilisation became widespread starting in the 1960s, with research demonstrating that lime effectively enhances strength and mitigates swelling in expansive clay soils [17].

Studies show that incorporating lime into the soil dramatically diminishes various characteristics: it reduces swelling potential, liquid limit, plasticity index, and maximum dry density. On the other hand, it enhances the optimum moisture content, shrinkage limit, and soil strength. Generally, the ideal proportion of lime for efficient soil modification lies between 1% and 3% by weight. Nonetheless, lime concentrations ranging from 2% to 8% have also been recognised as beneficial for soil stabilisation [18].

Using lime stabilisers to stabilise expansive soils is more useful when there is an extended period before work begins after mixing, as lime better suits longer curing times [19]. In recent years, the application of nanomaterials has been shown to enhance the effectiveness of stabilisers. The differences in particle size between the soil and the embedded nanomaterials can reduce the percentage of voids in the soil, resulting in notable improvements in its physical and chemical properties [20]. The application of nanomaterials (nano MgO and nano Al_2O_3 at a concentration of 0.5% to 2% on expansive soil showed that a 2% addition could reduce the plasticity index value by 6.44% with nano MgO and 9.14% with nano Al_2O_3 [21]. Using nano-lime (1-2%) for stabilising expansive soils can significantly enhance soil properties and mitigate environmental effects [22]. When comparing lime and nano-lime (0.2-1.0%) in addressing problematic soils, research has shown that nano-lime is more effective than ordinary lime in stabilising clay soils.

Nano-lime can significantly reduce plasticity and enhance compaction results. Even a tiny amount of nano-lime (0.5%) notably improves the geotechnical properties of soil compared to standard lime. The chemical reactions between calcium oxide and dissolved silica form calcium silicate hydrate (CSH), strengthening the soil. The stabilisation mechanism involves the flocculation and aggregation of soil particles facilitated by Ca^{2+} ions. Remarkably, even at low doses, nano-lime has a significant impact on the engineering properties of soil [23].

This research considers the effect of different lime particle sizes—macro, micro, and nanomaterials—on improving expansive soils' physical and mechanical properties. The novelty of this research lies in its exploration of how varying lime particle sizes—macro, micro, and nano—affect the stabilisation of expansive soils. While previous studies have looked at lime as a stabilising agent for these types of soils, this research is unique in focusing specifically on the particle size of lime and how that influences the soil's physical and mechanical properties. The study aims to identify the most effective lime particle size for enhancing soil stability and strength, which could lead to more efficient and optimised soil treatment methods. By testing a range of lime sizes (from macro to nano), the study goes beyond the traditional approaches, considering the potential for finer particles (especially nano-sized lime) to have enhanced reactivity with the soil, thus improving stabilisation more effectively than larger particles. This approach could lead to new insights in soil engineering, providing a deeper understanding of how particle size affects the performance of stabilising agents like lime in expansive soils.

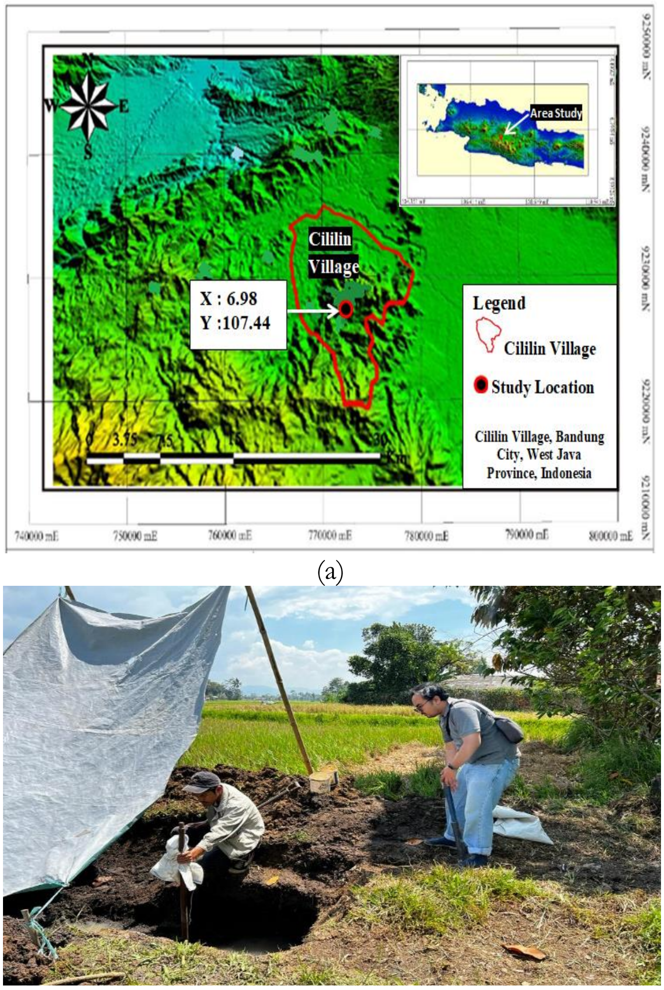
2. Research Methods

2.1. Soil Sample

The soil sampling site for expansive clay was in Cililin Village, in Bandung City, West Java Province. If travelling over land, Cililin Village is approximately 36 kilometres away from Bandung, the capital city of West Java Province, Republic of Indonesia. The coordinates of the soil sample location, 6.98°S and 107.44°E, can be viewed in Fig. 1, as taken from Google Earth. Figure 1b presents the process of test-pit sampling to collect soil sampling.

The expansive clay was found at around 4 to 5 meters deep. The disturbed soil was meticulously excavated, stored in plastic bags, and transported to the lab for further examination. Visual assessments suggest that the soil in Cilin Village, Bandung City, West Java Province, is expansive, distinguished by its dark brown to black hue and organic material. The characteristics of this soil, such as its density, natural moisture content, optimum moisture content, plasticity, and classification, are specified in Table 1.

Figure 2 depicts the soil classification based on the Unified Soil Classification System (USCS), categorising the material as high-plasticity clay (CH) with an optimum moisture content of 31.9% and a plasticity index of 35.18%. The gradation curve for the soil sample is presented in Fig. 3.



(a)

(b)

Fig. 1. Sampling Site Process (a) site location, (b) test pit sampling.

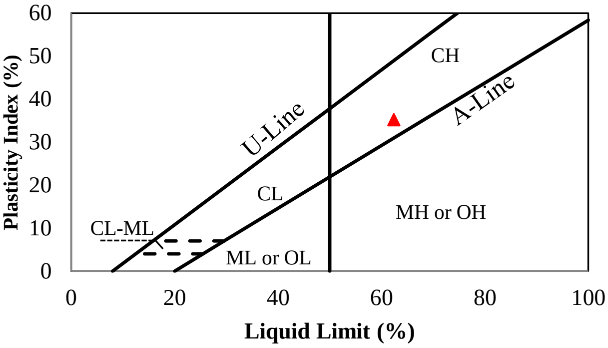


Fig. 2. USCS Classification for original.

Table 1. Properties of selected soil.

Description	Value
Density (kN/m³)	16,74
Water content (%)	48,46
Optimum moisture content (%)	31,9
Liquid Limit (LL) (%)	62,38
Plastic Limit (PL) (%)	27,2
Plasticity index (%)	35,18
Activity level (Ac) (%)	1,3
Unified Soil Classification System	CH

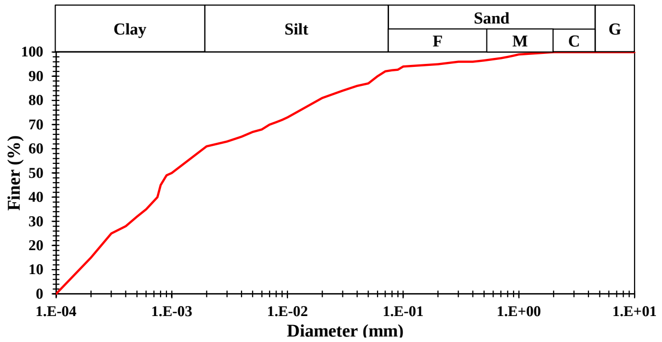
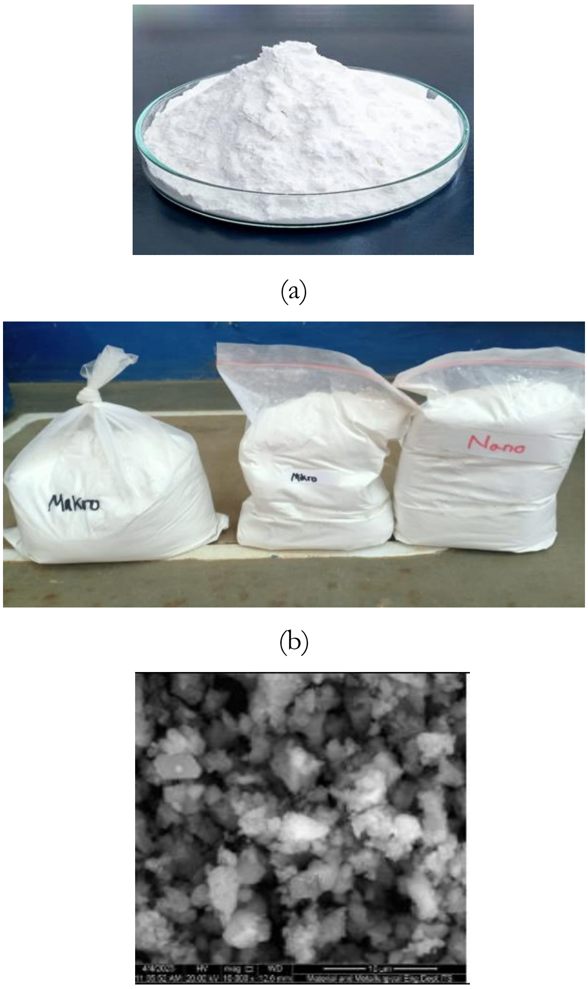


Fig. 3. Grain size distribution of soil sample.

2.2. Quicklime

Quicklime was used in this study due to its established efficacy as a stabiliser for soil, as illustrated in Fig. 4. The primary chemical composition of quicklime consists of calcium ions (Ca^{2+}) and oxide ions (O^{2-}), which react to form calcium oxide (CaO) [24]. Quicklime, generally known as calcium oxide, is produced through the thermal decomposition of limestone (calcium carbonate, $CaCO_3$) at approximately 90°F, leading to a substance that mainly consists of calcium carbonate [25].



(a)

(b)

(b)

Fig. 4. Quicklime as an additive in this research. (a) Physical quicklime, (b) Macro, micro and nano quicklime and (c) SEM test image.

Quicklime is a white solid that reacts quickly and is prone to oxidation. When calcium oxide (CaO) is combined with water, it produces calcium hydroxide ($Ca(OH)_2$). This substance is known as quicklime when it is solidified in water. The morphological image of quicklime obtained from the SEM test outlined in earlier research is displayed in Fig. 2 [24, 26]. The appearance of the limestone surface displays clusters of white particles, believed to be calcite with a rhombohedral arrangement, observed at a magnification of 10μm; comparatively small spaces are present.

This research examines three sizes of Quicklime, a lime variant utilised for soil treatment. The largest particles, called macro-material lime, usually exceed 1 mm and consist of coarse grains or flakes. These more considerable fragments can be incorporated into the soil quite effortlessly. Adding this lime type to expansive soils prone to swelling and shrinking enhances the soil's structure. It also aids in minimising soil expansion and contraction. Furthermore, macro lime can decrease the acidity of acidic soils and improve the soil's overall stability by binding the soil particles together.

Micromaterial lime consists of lime particles smaller than macro-material lime, yet they are still large enough to affect the physical properties of the soil significantly. A Particle Size Analyzer (PSA) test is utilised to determine the size of these micromaterials. [27]. PSA testing on quicklime is conducted to examine both the micromaterial and nanomaterial particle sizes. The results from PSA testing on lime micromaterial particles indicate a particle size of 552.7 nm, which falls within the micromaterial range and can influence soil stabilisation processes through improved reaction efficiency and particle binding.

Lime nanomaterials are characterised by their tiny particle size, which is significantly smaller than that of lime micromaterials and even finer than individual grains of soil or particles found in expansive soil. Particle Size Analysis (PSA) testing is utilised to determine the particle size of these micromaterials accurately. The results of the PSA testing indicate that the particle size of lime nanomaterials measures an exceptionally fine 174.7 nanometers (nm). This highlights their considerably more significant surface area than larger particles, enhancing their potential effectiveness in soil stabilisation applications.

2.3. Sample Preparation

The initial preparation of the samples involved passing the soil through No. 4 and No. 40 sieves. The soil samples designated for treatment were mixed with an optimal moisture content of approximately 31.9%, as these characteristics influence soil strength to yield effective results [28]. Quicklime was incorporated at necessary percentages (1%, 2%, 3%) for each macro, micro, and nano quicklime particle size, based on the dry weight of the soil. The variable notations are available in Table 2.

A Grain Size Analysis was performed to determine the grain distribution in the soil classification according to SNI 3423-2008. The soil was immersed in water for 7 days for the UCS and consolidation samples. Six compacted samples were created for the CBR test; half were soaked, while the other half remained dry. The samples were submerged for 7 days.

Table 2. Variable in this study.

Description	Variables
Initial Soil	P0
Soil + 1% Macro Lime	P1
Soil + 2% Macro Lime	P2
Soil + 3% Macro Lime	P3
Soil + 1% Micro Lime	P4
Soil + 2% Micro Lime	P5
Soil + 3% Micro Lime	P6
Soil + 1% Nano Lime	P7
Soil + 2% Nano Lime	P8
Soil + 3% Nano Lime	P9

2.4. Method of the Research

Table 3 presents a comprehensive summary of the tests conducted in this study, emphasising the standardised procedures employed during testing. It features a list of tests performed under two distinct conditions: with Quicklime and without Quicklime. Each test was meticulously executed by the guidelines established by the American Society for Testing and Materials (ASTM), ensuring that the methodology adhered to recognised standards of accuracy and reliability. A variety of tests were administered throughout this study. Atterberg Limits to inspect the liquid limit and plastic limit test procedures were tested by ASTM D4318 [29] to determine the swelling and shrinkage of the soil.

The unconfined compressive strength (UCS) test followed the ASTM D-2166-89 guidelines. The soil sample had a height of 74 mm and a diameter of 37 mm. The test was performed with a load capacity of 10 kN and a strain rate of roughly 1%. The outcomes from the UCS test were utilised to create a graph showing the correlation between the uniaxial compressive strength (q_u) values and the different proportions of quicklime.

The compressibility test was conducted using a one-dimensional consolidated compression method, as specified in ASTM D-2435-89. A soil sample measuring 2 cm in height and 50 cm in diameter underwent gradual increases in pressure of 25, 50, 100, 200, 400, and 800 kPa. Manometer readings were taken at various intervals over 0 to 1440 minutes, while axial deformation was measured using a dial gauge with a precision of 0.01 mm. The coefficient of compressibility was then calculated based on these observations.

$$C_c = \frac{e_1 - e_2}{p_2 - p_1} \qquad (1)$$

where Cc is the coefficient of compressibility, $e1$ and $e2$ are void ratios, p2 and p1 are pressures.

Table 3. Summary of Experimental Tests.

Experimental Test	Reference Standard	Test Variation	
		With Lime	Without Lime
Atterberg Limits	ASTM D4318	√	√
Unconfined Compressive Strength Test	ASTM D-2166-89	√	√
Compressibility Test	ASTM D-2435-89	√	√
CBR Laboratory	ASTM D-1883	√	√
Permeability Test	ASTM D2434	√	√

The strength of the samples was evaluated using the California Bearing Ratio (CBR) test. The CBR machine used had a capacity of 50 kN and was equipped with a dial gauge that provided an accuracy of 0.01 mm. Testing was conducted by SNI 1744-1989 and ASTM D-1883 standards, utilising 10, 30, and 65 impacts for each sample. The CBR samples were prepared under optimum moisture content (OMC) conditions, which were determined from the results of the Standard Proctor Test [30].

The procedure of mixing and testing for tested soils is presented in Fig. 5. This study performs two main processes, especially for mixing and testing materials. The first is soil preparation, and the second is quicklime preparation. The mixing process is performed until lime material and soil are evenly distributed. Furthermore, physical and engineering tests are performed to check soil properties. CBR testing is also performed to inspect the improvement of soil bearing.

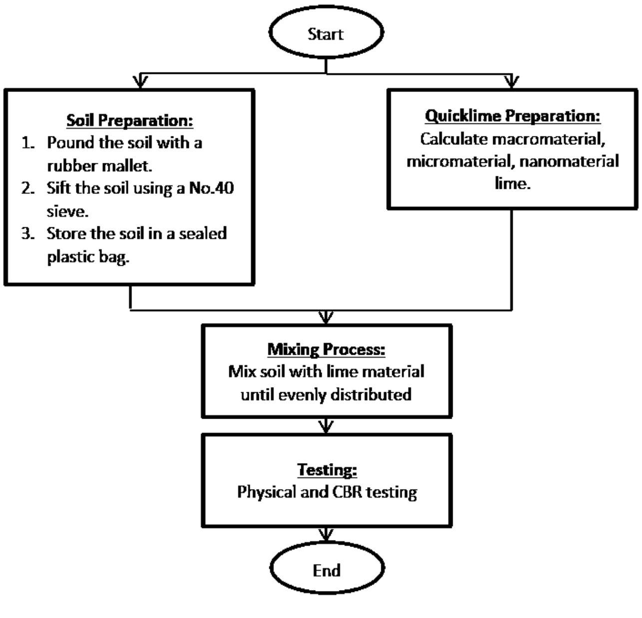


Fig. 5. Flowchart of the mixing and testing processes.

3. Result and Discussion

3.1. FTIR (Fourier Transform Inrafred) Test

Fourier Transform Infrared (FTIR) analysis of soils fulfils various roles in geochemical and agronomic evaluations. A significant benefit of employing FTIR in soil examinations is its capacity to characterise soil organic matter. This method effectively detects and measures the soil organic carbon (SOC) content, a vital factor in soil health and fertility. Moreover, FTIR is often combined with machine learning techniques to improve the accuracy of SOC-level predictions in soils [31]. Using FTIR for mineralogical analysis successfully identifies minerals present in soils and sediments. This method enables the detection and examination of mineralogical alterations caused by interactions with plants or different environmental factors [32, 33] and the identification of chemical components [34].

The FTIR test results from the study were analysed following the procedures described in earlier research [35]. The soil sample analysis revealed several essential minerals through their specific wave numbers. A wave number of 794.67 cm^{-1} signifies the existence of quartz (SiO_2), while a wave number of 3448.72 cm^{-1} is linked to kaolinite ($2H_2O\ Al_2O_3\ 2SiO_2$).

Additionally, montmorillonite is associated with the wave number range of 3624.25 cm^{-1} to 3695.61 cm^{-1}. Table 4 presents the FTIR test, highlighting montmorillonite as the primary mineral in the soil sample. FTIR spectrum can be seen in Fig. 6. These significant results validate that the soil examined in this study is categorised as expansive soil, as referenced in the applicable literature [36].

Table 4. FTIR Test.

No	Number of waves (vm-1)	Mineral types
1	794.67	quartz
2	3448.72	kaolinite
3	3624.25	Montmorillonite
4	3695.61	Montmorillonite

Sulphur improves the binding capability of lime with soil; however, in excessive amounts, it can lead to adverse effects, as it may interact with water to form sulfuric acid, which could harm the soil structure. Calcium, the main component of quicklime (CaO), is the most critical stabilising agent. It binds with soil particles to decrease plasticity and expansiveness, which is essential for effective soil stabilisation. While other elements also play a role in this process, calcium is the primary element that improves soil properties.

Based on the X-ray fluorescence (XRF) testing findings, quicklime contains 897.700 ppm of SO_3, acting as a hydrolyAsis binding agent capable of reacting with water. The CaO percentage is 96.331%, reducing soil moisture by releasing heat during the lime and water reaction. Furthermore, SiO_2 is present at 1.465%, functioning as an adsorbent that pulls water molecules into its pores, thereby facilitating the drying and hardening of clay soil. Magnesium oxide (MgO) is also included at 0.815%, helping to lower soil moisture through reactions with water that generate heat and expand the magnesium, thus further decreasing soil moisture content. [38].

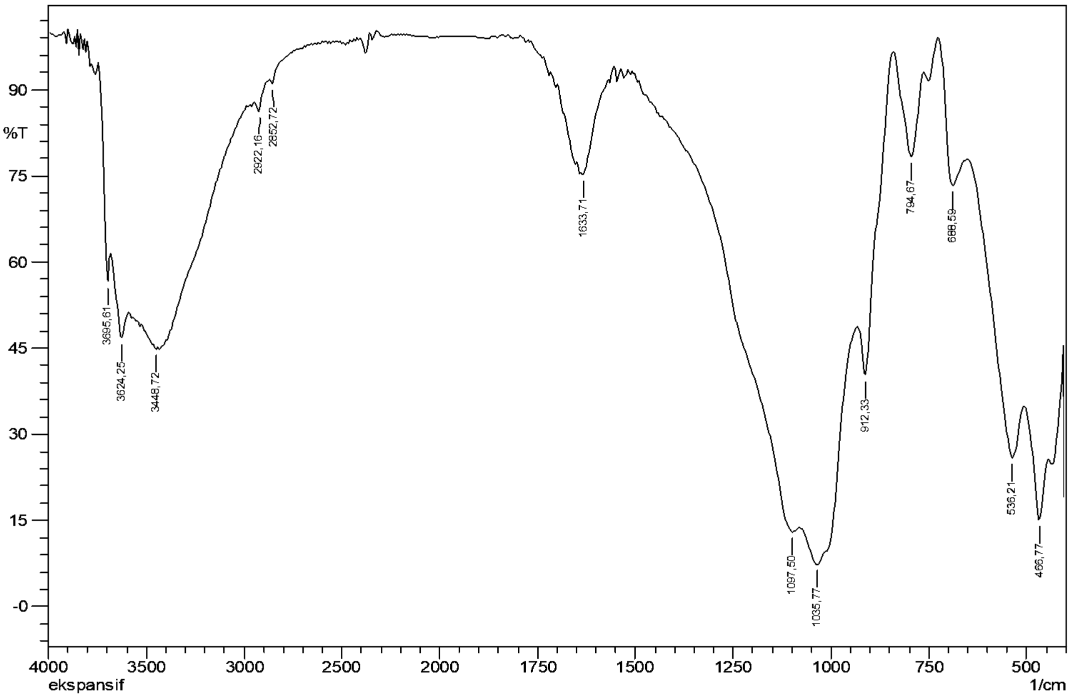


Fig. 6. FTIR Spectrum.

Table 5. XRF Test of Quicklime.

Element	NF = 1.003	Oxides	NF = 0.891
Compound	Content	Compound	Content
Mg	0.573%	Mg	0.573%
AI	0.351%	AI	0.351%
Si	0.811%	Si	0.811%
S	4 40.600 ppm	S	4 40.600 ppm
Cl	32.700 ppm	Cl	32.700 ppm
Ca	97.341%	Ca	97.341%
Ti	184.600 ppm	Ti	184.600 ppm
v	48.800 ppm	v	48.800 ppm
Mn	70.600 ppm	Mn	70.600 ppm
Fe	0.376%	Fe	0.376%
Cu	2.200 ppm	Cu	2.200 ppm
Zn	285.300 ppm	Zn	285.300 ppm
As	2.800 ppm	As	2.800 ppm
Sr	0.288%	Sr	0.288%
Zr	24.700 ppm	Zr	24.700 ppm
Ag	0.126%	Ag	0.126%
Sn	113.500 ppm	Sn	113.500 ppm
Sb	39.200 ppm	Sb	39.200 ppm
Te	105.800 ppm	Te	105.800 ppm

3.2. Atterberg Limits

The soil's Plasticity Index (PI) and Activity Level (Ac) were analysed before and after treatment. The PI was calculated by finding the difference between the liquid limit (LL) and the plastic limit (PL). In contrast, the Activity Level (Ac) was determined by taking the PI's ratio to the clay fraction's percentage. Table 6 provides a summary of the PI and Ac results. In previous studies, the initial soil exhibited a higher PI than the treated soil, decreasing the PI from 18.76% to 12.32% [39, 40]. The reduction in plasticity index (PI) and acidity (Ac) in the soil treated with quicklime is due to the bonding strength of the soil particles. This occurs due to the substances produced in the soil during the hydration reaction between quicklime and water [41].

The reaction between quicklime (CaO) and expansive soil can be represented by the following chemical equation: $CaO + H_2O \rightarrow Ca(OH)_2$. Expansive soils are primarily composed of minerals such as silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3). When quicklime is added to expansive soil, it reacts with water to produce calcium hydroxide ($Ca(OH)_2$). This calcium hydroxide subsequently interacts with the silica and alumina in the soil to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These newly created compounds are critical in modifying the soil's microstructure. Specifically, they reduce the amount of free water surrounding the soil particles, significantly diminishing the potential for soil expansion and enhancing the overall stability and performance of the soil [42]. The enhancement in soil strength can be linked to developing new bonds among soil particles via a pozzolanic reaction. When quicklime comes into contact with the silica and alumina found in the soil, it generates calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels that effectively occupy the gaps between particles. These products of the reaction improve the mechanical characteristics of the soil by increasing its load-bearing capacity and the frictional interactions among particles. Consequently, this process diminishes the chances of deformation and cracking that may arise from changes in moisture levels. Thus, stabilising expansive soil with quicklime significantly improves its stability and strength.

The effects of quicklime on the soil that has been treated, considering the P0, P1, P4, and P7 lime variables, are illustrated in Fig. 7. The findings indicate that as the particle size of quicklime decreases, both the Plasticity Index (PI) and Activity (Ac) also decline. Notably, the PI and Ac values for 1% macro quicklime exceed those of both macro and nano-sized quicklime samples. Specifically, the PI reduces from 35.181% to 30.364%, 26.351%, and 23.579% with the introduction of 1% macro, 1% micro, and 1% nano quicklime, respectively. Likewise, the Ac diminishes from 1.303% to 1.12%, 0.97%, and 0.87% following the same treatments. In summary, it can be inferred that using quicklime for soil stabilisation significantly lowers both the Plasticity Index (PI) and Activity (Ac).

Table 6. Atterberg limits.

Variable	Plasticity Index (PI) %	Activity Level (Ac) %
P0	35.181	1.30
P1	30.364	1.12
P2	29.053	1.08
P3	28.319	1.05
P4	26.351	0.98
P5	11.505	0.43
P6	10.921	0.40
P7	23.579	0.87
P8	7.621	0.28
P9	7.544	0.28

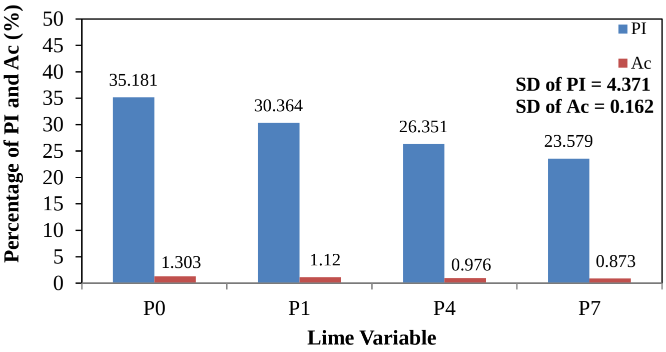


Fig. 7. Comparison of PI and Activity for 1% macro, 1% micro, and 1 %nano lime adding in P0, P1, P4, and P7 limes variable.

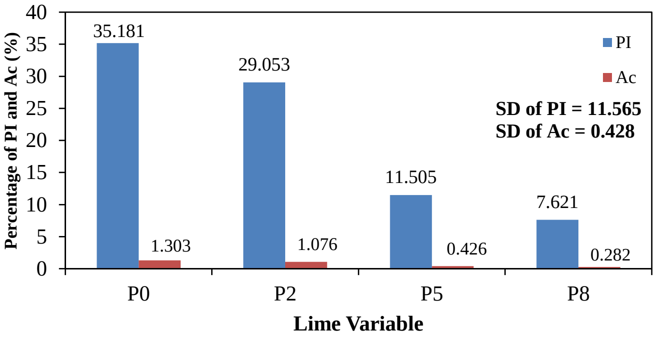


Fig. 8 Comparison of PI and Activity for 2% macro, 2% micro, and 2% nano lime adding in P0, P2, P5 and P8 with.

The effect of quicklime on soil that has been treated for the P0, P2, P5, and P8 lime variables is shown in Fig. 8. The analysis reveals that both the Plasticity Index (PI) and Activity Level (Ac) decrease as the particle size of quicklime diminishes. Interestingly, 2% micro quicklime shows greater efficiency than macro and nano-sized quicklime samples. Specifically, the PI decreases from 35.181% to 29.053%, 11.505%, and 7.621%, while the Ac drops from 1.303% to 1.076%, 0.426%, and 0.28% when 2% macro, 2% micro, and 2% nano quicklime are used to treat the soil, respectively. In summary, it can be concluded that using quicklime for soil stabilisation significantly reduces both the Plasticity Index (PI) and Activity Level (Ac).

Further analysis of the influence of quicklime on treated soil is illustrated in Fig. 9. The data indicates that as the particle size of quicklime is reduced, both PI and Ac continue to decline. The PI and Ac values for 2% macro lime were more significant than those for the macro and nano lime samples. The Plasticity Index (PI) fell from 35.181% to 28.319%, 10.921%, and 7.544%, while the Ac decreased from 1.303% to 1.049%, 0.404%, and 0.279% when the soil was partially treated with 3% macro lime, 3% micro lime, and 3% nano lime. Supporting the previous results for 2% and 1% treatments, it can be concluded that lime stabilisation effectively lowers the Plasticity Index (PI) and Activity Level (Ac).

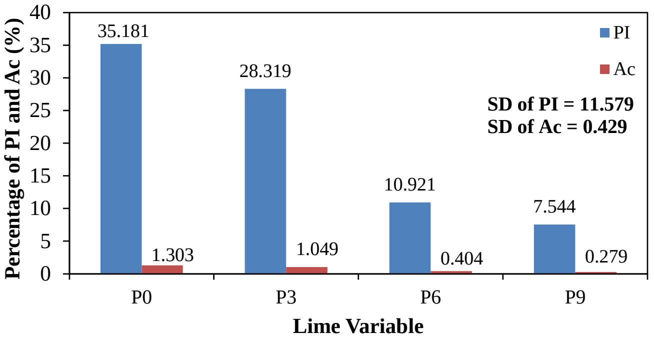


Fig. 9. Comparison of PI and Activity for macro, micro, and nano lime in P0, P3, P6 and P9.

The decrease in Plasticity Index (PI) and Activity Level (Ac) upon lime addition can be explained by the process of lime sorption on soil particles; lime chains replace water molecules on the outer surface of soil particles. [43]. The outcomes of testing the Atterberg limits on both native soil and lime-stabilised soil with various lime particle sizes—macro, micro, and nano—indicate that as the particle size of lime decreases, the Liquid Limit value decreases, the Plastic Limit value increases, and the plasticity index value decreases. In particular, the particle size of the macro-material is more significant than that of the micromaterial, while the micromaterial particle size is greater than that of the nanomaterial.

In the study of Ansary et al. [44], it was observed that the Plastic Limit increases with higher amounts of stabilising materials. The increase in the Plastic Limit can be attributed to the flocculation of clay particles. Typically, a rise in the Plastic Limit with the addition of lime is considered significant, as the Plastic Limit is a key indicator of the lime content required to achieve the desired soil modification [45, 46]. On the other hand, a reduction in the Liquid Limit has been observed in soils that contain montmorillonite. [47]. The reduction is mainly caused by cation exchange processes initiated by divalent calcium ions [43, 48]. As the amount of lime applied increases, the soil's activity level rises, aligning with Bell's research findings. [49]. A higher lime content improves the soil's ability to change, indicating better stabilisation and modification.

3.3. Effect of Stabilizers on the Clay Classification

Figure 10 illustrates the original and stabilised soil classification, categorised by particle sizes of macro-material quicklime, micromaterial quicklime, and nanomaterial quicklime. The results from the consistency limit test were represented on the Casagrande plasticity graph to establish the soil classification by the Unified Soil Classification System (USCS) [50]. As demonstrated in Fig. 10, the original soil, categorised as CH (high plasticity clay), shows data points above the A-line. Nevertheless, with an increasing percentage of lime stabiliser, these points slowly move below the A-line. This movement indicates a significant change in the plasticity properties of the soil due to the addition of lime, which subsequently affects its classification and behaviour according to USCS standards.

3.4. Compaction Analysis of Unconfined Compressive Strength Test Results

The Unconfined Compressive Strength (UCS) of the samples was evaluated, and the results are presented in Fig. 11. It was observed that the UCS tends to increase as the moisture content in the samples decreases. As illustrated in Fig. 11, the mechanical properties of the soil are relatively poor at point P0 due to high moisture content, which results in soil saturation. The highest UCS recorded was 5.116 kg/cm², achieved with soil samples treated with 3% nanomaterial lime. The treated soil samples demonstrated higher UCS values than their untreated counterparts.

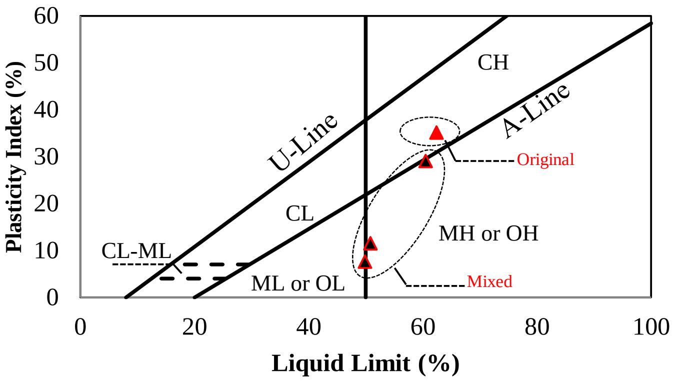


Fig. 10. USCS Classification for original and mixed soil to present the effect of adding lime in changing soil type.

Furthermore, the UCS decreased with the increasing wetting and drying cycles, even when the moisture content remained constant. A significant reduction in strength was particularly noted during the initial drying phase, especially after the moisture content dropped below 50%. The decline in strength became more pronounced as the moisture content continued to decrease. Figure 9 indicates that the variation in strength reduction from P1 to P8 is quite significant throughout the drying period.

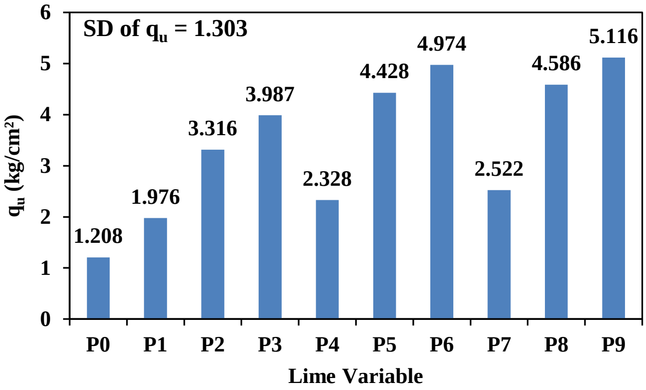


Fig. 11. Effect of lime mixing on UCS test.

In general, it can be concluded that soil stabilisation with lime effectively enhances the UCS (Unconfined Compressive Strength) [51]. Soil stabilised with lime is typically well-suited to support engineering constructions such as roads, buildings, or hydraulic structures. [52] [53] [54]. Although the initial laboratory results are promising, more research is necessary to effectively apply these findings to practical field-scale measurements of soil-bearing capacity. This study used Unconfined Compressive Strength (UCS) testing machines in a controlled environment, highlighting the need for further field studies to validate these results and adapt them for real-world engineering projects.

3.5. Density Characteristics

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of both the initial soil and the expansive clay soil mixed with lime are illustrated in Fig. 12. The test results reveal that the Optimum Moisture Content (OMC) increases. At the same time, the Maximum Dry Density (MDD) decreases with the addition of lime. This behaviour has been consistently observed in previous studies on clay soils stabilised with lime. [55]. The occurrence can be linked to the incorporation of lime, which improves the clumping of soil particles. This action causes these particles to adhere to one another, increasing volume. As a result, this clumping alters the effective gradation of the soil, raising the void ratio and reducing the soil's ability to compact, ultimately resulting in a lower dry density. [56].

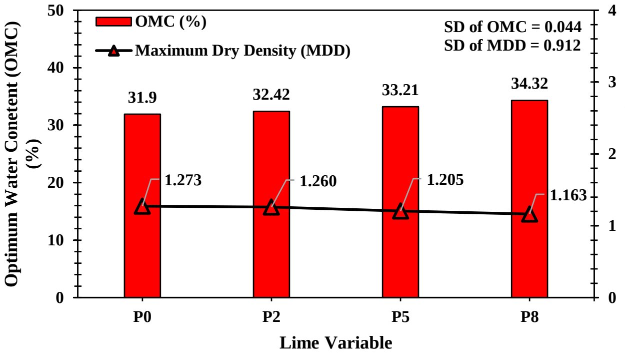


Fig. 12. Compaction characteristics.

3.6. CBR Soaked and Unsoaked

CBR testing based on ASTM D-1883 [57], maximum dry density (MDD) and optimum moisture content (OMC) of the initial soil and expansive clay soil mixed with lime can be seen in Fig. 13. The CBR test results for both treated and untreated soils are illustrated in Fig. 13. The CBR value of the soil shows an increase with the addition of 2% of lime particles. As depicted in Fig. 13, the CBR value rises with higher concentrations of quicklime and smaller particle sizes of the quicklime.

The test results suggest smaller lime particles improve the soaked and unsoaked CBR values. The soaked CBR demonstrates a more pronounced enhancement with 2% micro lime compared to macro and nano lime samples, especially regarding cost-effectiveness. More specifically, the soaked CBR increased from 1.94% to 2.83%, 7.07%, and 8.16%. Conversely, the unsoaked CBR improved from 7.1% to 8%, 9.01%, and 9.22%. This beneficial effect stems from the interactions between the lime and expansive soil particles, which facilitate the reconfiguration of soil grains into larger aggregates. This mechanism promotes a denser arrangement of particles and stronger inter-particle connections, ultimately improving the soil's bearing capacity. In summary, lime on high-plasticity clay significantly enhances the CBR value. Therefore, it can be concluded that the combination of lime and expansive clay significantly elevates the CBR of the soil, ensuring safety and requiring minimal maintenance for road pavements. [58]. This increase in California Bearing Ratio (CBR) value can be attributed to changes in soil structure that cause flocculation and fill the voids in soil due to adding lime, which enhances the adhesion between the soil particles and lime. [59]. Sodha et al. [60] explain that the increase in the California Bearing Ratio (CBR) is directly related to the relatively high shear strength of the soil. This suggests that quicklime, as an additive, is highly effective in enhancing the resilience of subbase materials. The rise in CBR values can be attributed to the greater viscosity of quicklime compared to water; when compacted, this characteristic increases the soil's dry unit weight. As a result, improved compaction leads to higher soil density and overall strength of the subbase. The findings of this study align with previous research that has demonstrated similar enhancements with the use of quicklime. [61].

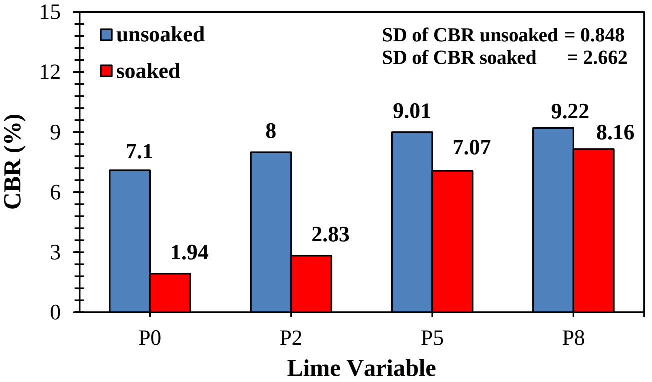


Fig. 13. CBR values for soaked and unsoaked treatments.

3.7. Consolidation

Consolidation is the process by which the volume of water-saturated soil decreases, leading to reduced permeability. This phenomenon occurs as total stress increases and pore water gradually disperses over time. The duration of the consolidation process varies based on the soil's permeability. [62]. Results of the consolidation test, including the Coefficient of Consolidation (Cv), Compression Index (Cc), and Settlement of Consolidation (Sc) values, are displayed in Fig. 14.

Due to the high susceptibility of the expansive soil used in this study to settlement, achieving a constant or precise value at any given stress incrementally is impossible [63]. The reduction in the compressibility index and the settlement of consolidation following the addition of quicklime can be linked to the development of compounds formed during pozzolanic reactions throughout the curing period. These compounds, which consist of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), enhance the adhesion between soil particles. They establish connections via cation exchange and flocculation processes, which improve the soil's ability to withstand compression [64, 65]. The lower the compression index (Cc) value, the more compact the soil is, suggesting that stabilising soil with lime that has finer particle sizes can successfully decrease the Compression Index (Cc) value [66]. In a different observation, the decrease in compressibility caused by incorporating 2% of each particle size of macro quicklime, micro quicklime, and nano quicklime can be linked to the creation of new structures resulting from the interaction between lime and the elements of expansive soil. During this process, lime acts as a strengthening agent that binds the soil particles together, improving solidity and elevating compression resistance. [67].

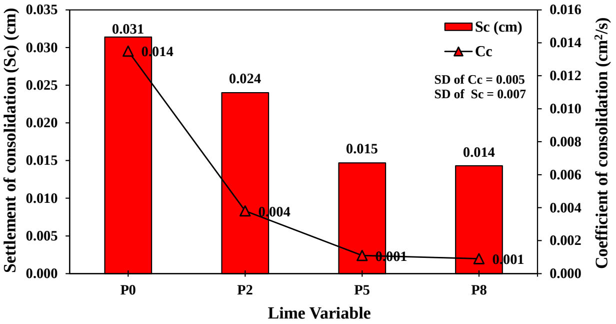


Fig 14. Coefficient consolidation and consolidation settlement of sample.

3.8. Chemical Interaction Between Lime and Soils

Lime, commonly in calcium carbonate ($CaCO_3$), is crucial in enhancing soil fertility. When added to soil, lime can change its acidity. The interaction between lime and soil initiates a series of chemical processes that significantly alter the soil's pH level. Lime reacts with soil acids, primarily hydrogen ions (H^+), in a neutralisation reaction. When lime is applied to acidic soil, it releases calcium ions (Ca^{2+}) and carbonate ions (CO_3^{2-}). These ions react with hydrogen ions (H^+) to produce water (H_2O) and carbon dioxide (CO_2), effectively increasing the soil's pH and making it less acidic.

The calcium ions released by lime improve soil structure. Calcium is essential for forming soil aggregates, which enhance soil structure and promote water infiltration. For example, phosphorus, which can become 'locked' in acidic soils, becomes more accessible when the pH is raised. Similarly, other nutrients such as magnesium, molybdenum, and potassium are more readily available when the soil pH is adjusted. Additionally, the carbonate ions (CO_3^{2-}) from lime can act as a buffer, helping to maintain a stable pH in the soil.

4. Conclusions

This paper discusses an initial investigation into how lime impacts high-plasticity clay soil swelling and shrinkage characteristics. The study involved experiments with three distinct lime particle sizes: macro quicklime, micro quicklime, and nano quicklime, serving as soil stabilisers. A comparative evaluation was performed to determine the most effective method concerning the lime acquisition, swell-shrink behaviour, and variations in moisture content over time, considering the addition of lime stabilisers with different particle sizes.

Test results showed that the untreated soil had a maximum dry density (MDD) of 1.273 g/cm³ and an optimum moisture content (OMC) of 31.9%. When 2% of macro quicklime, micro quicklime, and nano quicklime were introduced, the soil's maximum dry density decreased as the size of the lime particles diminished while the optimum moisture content increased. In the California Bearing Ratio (CBR) evaluations, both soaked and unsoaked tests indicated that CBR values improved with smaller lime particle sizes. Additionally, values for permeability, settlement of consolidation (Sc), and compression index (Cc) all fell as the size of the lime particles decreased. Adding lime reduced the soil's initial void ratio and compressibility, primarily because the lime occupied the pores within the soil, effectively blocking them from water infiltration. The smaller the lime particle size, the more proficiently the pores were filled, resulting in a sturdier soil structure and reduced compressibility under load.

Based on these findings, lime with smaller particle sizes, especially nano-lime, significantly improved the stability of expansive soils. Soil characteristics such as maximum dry density, optimum moisture content, permeability and compressibility were considerably enhanced. Therefore, it is recommended that quicklime with nanoparticle sizes be applied to stabilise expansive soils in construction projects to improve the efficiency and bearing capacity of the soil. However, this study was limited to a specific soil type and a limited variation of lime concentration. Therefore, further research is needed to explore using lime with different particle sizes on various soil types and more varied field conditions.

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