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Effect of Alkaline Activated Cashew Nut Shell Ash in the Stabilization of Weak Clayey Soil—An Experimental Study

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Abstract: Weak clayey soils in construction are considered problematic due to their high compressibility and low bearing capacity. This study proposes an environmentally friendly replacement for conventional soil stabilizers through the use of geopolymer (GP) containing Cashew Nut Shell Ash (CNSA) to improve soil characteristics. In this study, the CNSAGP was compared with lime-stabilized soil for unconfined compressive strength (UCS), durability, and improved microstructure. The experimental outcomes showed that 9 M + CNSAGP with 4% CNSA provided a UCS of 1900 kPa, which was higher than the lime-stabilized soil (6% lime with 4% CNSA) at 1400 kPa. Durability test results revealed that the CNSAGP-treated sample had better protection against water damage with a strength loss of about 18%, while the lime-treated sample had a strength loss of about 25%. Thermal stability analysis showed that CNSAGP had lower LOI values compared to lime-stabilized samples (0.17% at 900 °C), which indicates CNSAGP’s heat resistance. Microstructure analysis revealed that CNSAGP-stabilized soil was less porous, the microstructure being denser because of reactions of aluminosilicate and pozzolanic activity. Moreover, it affected the soil’s alkalinity, making it better, and improved Atterberg limits, which affected the plasticity and workability. These findings show that CNSAGP is a long-lasting and eco-friendly means of soil stabilization with higher strength, thermal stability, and durability than traditional methods and can be used in engineering.

Keywords: soil stabilization; cashew nut shell ash; geopolymer; molarity; Atterberg limit; microstructure

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1. Introduction

Clay soils are generally considered problematic in construction activities, potentially causing significant damage and uneven settlement of structures such as pavements and runways owing to their high plasticity and sudden swelling and shrinkage behavior in both wet and dry conditions [1]. Highly plastic clayey soils naturally exhibit poor bearing strength, rendering them unsuitable for constructing high-rise and heavily loaded structures without treatment [2]. Clay soils are characterized by low permeability, resulting in prolonged water retention and an increased risk of waterlogging and structural-related issues during construction [3]. During the construction of underground structures, such as retaining walls and basements, these soils pose potential damage owing to the pressure of the retained water [4]. Clay soils typically contain a high proportion of fine particles that are susceptible to erosion in running water, potentially leading to foundation failure and unstable slopes, thereby increasing the risk of landslides.

Prior to construction, the soil should be stabilized to enhance the performance of clayey soil, particularly its mechanical and physical characteristics, making it suitable for building purposes [5]. During the mechanical stabilization process, the strength of the clayey soil improves considerably, enabling it to support heavy structural and vehicular loads. This technique addresses issues related to changes in soil volume by regulating soil plasticity [6]. Stabilized clay soil demonstrates increased resistance to erosion over time and simplifies the construction process because it directly extends the lifespan of the structure. Numerous studies have demonstrated the importance of soil stabilization in improving soil properties [7]. This method involves combining soil with conventional stabilizing agents such as cement, lime, or fly ash to enhance its strength, durability, and load-bearing capacity [8]. In conventional cement stabilization, the Portland cement was mixed with soil for stabilization, creating a compact soil-cement matrix that decreases plasticity and provides moisture resistance. In comparison, lime-stabilized soil has been shown to improve stability and reduce plasticity [9]. The addition of lime to soil alters its physical behavior and diminishes its swelling potential, resulting in an increased load-bearing capacity.

Additionally, sulfate reactions in soils stabilized with cement and lime can result in swelling and road surface failures, complicating the selection of appropriate soil treatment methods and stabilizing agents. The use of fly ash, either alone or in combination with lime, has demonstrated advantages comparable to those of conventional techniques while offering environmental benefits [10]. Nevertheless, recent research indicates that despite the impressive results of using cement and lime for soil stabilization, these methods have considerable environmental drawbacks, primarily owing to their carbon dioxide emissions during manufacturing [11]. The ongoing extraction of raw materials for lime production has led to resource depletion and habitat disruption. Furthermore, the production and application of these traditional stabilizers can generate dust and aerosols, potentially causing respiratory issues and skin irritation [12]. The expense and transportation of raw materials also increase the overall project costs, as most of these materials are not locally available. Moreover, conventional stabilizers are not suitable for soils with high levels of organic matter and sulfates.

Finding alternative stabilization materials is crucial for mitigating environmental impacts, addressing the negative effects of traditional stabilizers, and achieving sustainability, safety, cost efficiency, and improved performance. Environmental scientist Raymond Pierrehumbert emphasizes that the fundamental goal consists of the complete decarbonization of human activities that produce CO_2, such as the burning of fossil fuels, the creation of cement, and deforestation. What he states is that the time needed to get to zero can be measured by the degree of global warming. Pierrehumbert disappointedly describes the slow pace of decarbonization, and as a result, it has opened up enthusiasm for technological solutions, including geoengineering. But he discouraged any country from relying on such weak narratives and urged everyone to take definite and ongoing actions on emission reductions via the shift to renewable energy and the enforcement of policies [13]. This can be accomplished by recycling and utilizing eco-friendly waste materials as additives or by implementing novel methods such as geopolymers with or without industrial-based admixtures [14].

Geopolymers are synthetic materials created through the reaction of alkaline-activated silicates or hydroxides with binding agents [15]. These materials have found widespread industrial use because of their interconnected networks and chains of mineral compounds, which are held together by covalent bonds formed during alkali activation reactions. These reactions involve the exchange of oxygen and negatively charged particles between Al^{3+} ions [16]. The main components of geopolymers are aluminum silicate compounds along with calcium-rich substances that aid the formation of tobermorite, a specific compound [17]. The strength of geopolymer materials is determined by their polymerization levels [18].

Geopolymerization typically involves the use of alkali-silica cations combined with alkaline activators and is generally classified into four categories [19]. Many researchers are investigating geopolymer materials because of their environmentally friendly raw materials and alkali-activation reactions, which help reduce their environmental impact [20].

In this study, a geopolymer matrix was developed using CNSA, which was introduced between soil particles. An alkaline activator solution was created using sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to activate the CNSA for stabilization. This research aims to enhance the strength and durability of structures by improving the mechanical properties, durability, and microstructure of clayey soil treated with cashew shell ash-based geopolymer (CNSAGP). The goal is to reduce or control soil shrinkage and swelling behavior and increase the soil's resistance to environmental factors during wet-dry cycles. This study evaluated the performance of CNSA-based geopolymer-stabilized clayey soil in comparison with lime-treated soil. Initially, the research identified problematic soil with high plasticity and examined its parameters to determine the composition of the CNSA geopolymer matrix and the optimal percentage of lime required for effective stabilization. After stabilization, the stabilized soil samples' characteristics were evaluated under different CNSA ratios, curing temperatures, and conditions, and they were compared with soils that had been treated with lime. The engineering behavior of the soil was evaluated using strength and durability parameters, whereas the microstructure was examined using scanning electron microscopy (SEM) analysis. Finally, the results of lime- and CNSAGP-stabilized specimens were compared to address the identified research gap, evaluate the performance of the novel CNAGP stabilizers, and offer a sustainable and innovative solution for the construction industry.

2. Materials and Methods

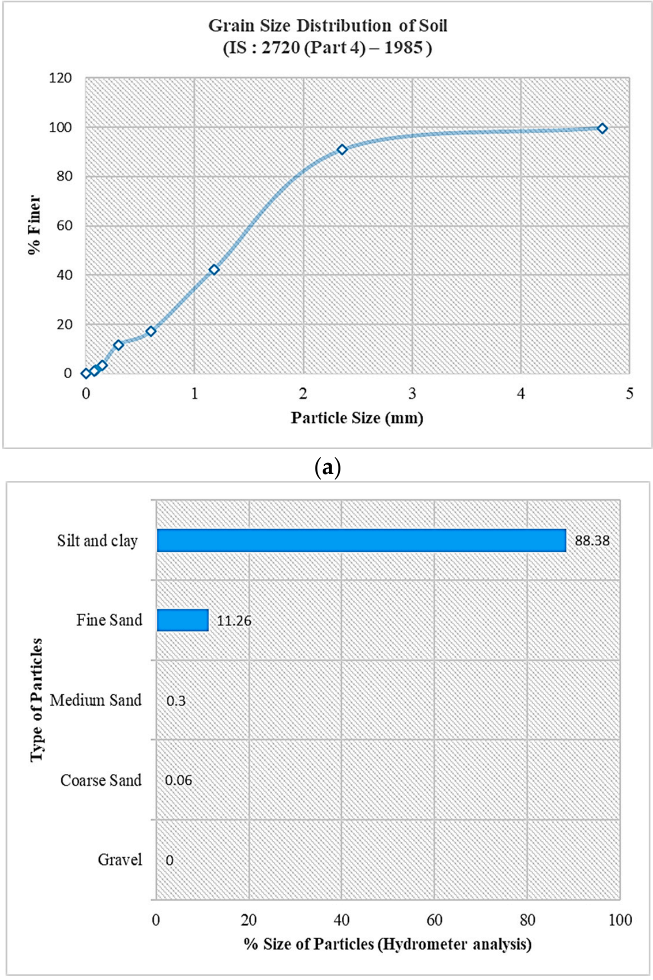
2.1. Clayey Soil

This study conducted an investigation by extracting clayey soil from an abandoned dry lake near Paiynoor Village, Chennai, India. The soil was obtained at a depth of one meter beneath the surface and exhibited dark brown coloration. Sufficient samples were collected for laboratory examination and carefully stored in sealed plastic containers to preserve moisture content. The collected materials, including weeds, were extracted using a trowel. A notable characteristic observed at the site was the soil's porous nature and its susceptibility to compression, setting it apart from inorganic soils, such as clay and sand, which are primarily composed of solid silicate particles. The soil underwent a drying process, first in sunlight and then in an oven at a controlled temperature of 110 °C for 24 h. Subsequently, the physical properties of the pre-stabilized soil were analyzed, and the results are presented in Table 1.

Table 1. Pre-stabilization property of soil.

Soil Behaviour	Values
Liquid Limit (LL)	59.25%
Plastic Limit (PL)	24.25%
Plasticity Index (PI)	40%
Specific Gravity @ 27 °C (G)	2.48
pH value of Soil	6.3
Maximum Dry Density (MDD)	1570 kg/m^3
Optimum Moisture content (OMC)	25.40%
UCS Strength (kPa) (28 days curing)	256.19

The graphs below illustrate the particle size distribution composition of the soil material using sieve and hydrometer analyses. Figure 1a shows the cumulative percentage of finer particles against particle size and reveals that most particles are smaller than 2 mm, with 90.9% of the sample passing through this size and nearly all particles passing through a 4.75 mm gradation. This shows a gradual buildup of smaller particles. Figure 1b, showing particle size distribution, indicates that the material is dominated by silt and clay at 88.38%, and fine sand was 11.26% with small portions of medium sand, coarse sand, and gravel. In this analysis, the high level of the material's fineness was emphasized, the presence of which is observed from the dominance of silt and clay fractions.



(**a**)

(**b**)

Figure 1. (**a**). Particle size distribution of Collected Soil. (**b**). % Particle size of Collected Soil.

2.2. *Cashew Nut Shell Ash*

Cashew nut shell ash (CNSA) was utilized in this study to synthesize the industrial-based geopolymer collected from the cashew refinery and oil extract industry, Panruti, Tamil Nadu, India. CNSA was produced by incinerating the shells at 750 °C, and the burnt ash was utilized as a supplementary cementitious material in combination with a geopolymer in this study, as shown in Figure 2.

Literature study reveals that CNSA contains high concentrations of silica and minerals, which contribute to its enhanced compressive strength and longevity. As usual, the chemically processed cashew nut shells exhibit high adsorption behavior toward harmful substances and heavy metals, thereby offering an economical and eco-friendly solution [21]. Shells treated with H_2SO_4 showed the highest adsorption capacity through monolayer physisorption, as evidenced by the pseudo-first-order and Langmuir model results [22]. For an extended period, cashew nut shell ash has been employed as a sustainable cementitious material owing to its potential pozzolanic properties [23].

Cashew nut shell ash (CNSA) is an industrial by-product created from the remnants of cashew nut processing. The process involves separating the nut from its shell, extracting oil, and burning the leftover material. CNSA serves as an alternative to traditional cement stabilizers [24]. The chemical composition of CNSA, particularly its CaO and SiO_2 contents, plays a crucial role in determining its rheological and mechanical properties, which in turn affect its compatibility and flow characteristics [25]. Research has shown that CNSA can enhance the early strength of stabilized soil composites within a week of curing, which is comparable to that of other agricultural waste-derived additives. Furthermore, when used in combination with lime, CNSA significantly increased the unconfined compressive strength of the soil. In concrete applications, the incorporation of cashew nut shell ash (CNSA) improves thermal insulation, enhances overall performance, and reduces environmental impact [26]. Additionally, it increases the compressive strength in a sustainable way, with precise regression models capable of predicting the thermophysical properties of the resulting concrete.

Figure 2. Cashew Nut Shell ash.

Researchers have investigated the use of cashew nut shell ash (CNSA) as an eco-friendly and economical substitute for conventional cement in the cement industry [18]. Various literature studies state that incorporating cashew nut shell ash (CNSA) in soil stabilization results in beneficial pozzolanic and chemical compositions within the soil matrix, rendering it an excellent material for stabilizing clay-rich soils. In addition to their economic and environmental benefits, CNSA materials have emerged as promising substitutes for traditional stabilizers. It is recommended that ongoing research be conducted to further investigate CNSA's potential, and more extensive applications in the construction sector are necessary. Figure 3 illustrates the energy-dispersive X-ray spectroscopy (EDS) analysis used to identify the percentage of individual elements present in CNSA. The analysis revealed that the presence of the following elements in the cashew nut shell ash, as shown in Table 2, was used in this study.

Table 2. CNSA Compounds (EDS) and physical parameters.

Properties/Compounds	Proportion
N (Nitrogen)	0.01%
O (Oxygen)	20.88%
Na (Sodium)	0.09%
Mg (Magnesium)	0.17%
Al (Aluminum)	0.57%
Si (Silicon)	0.19%
Cl (Chlorine)	0.12%
K (Potassium)	1.97%
Ca (Calcium)	0.56%
Ti (Titanium)	0.10%
Fe (Iron)	0.47%
Cu (Copper)	0.26%
C (Carbon)	78%

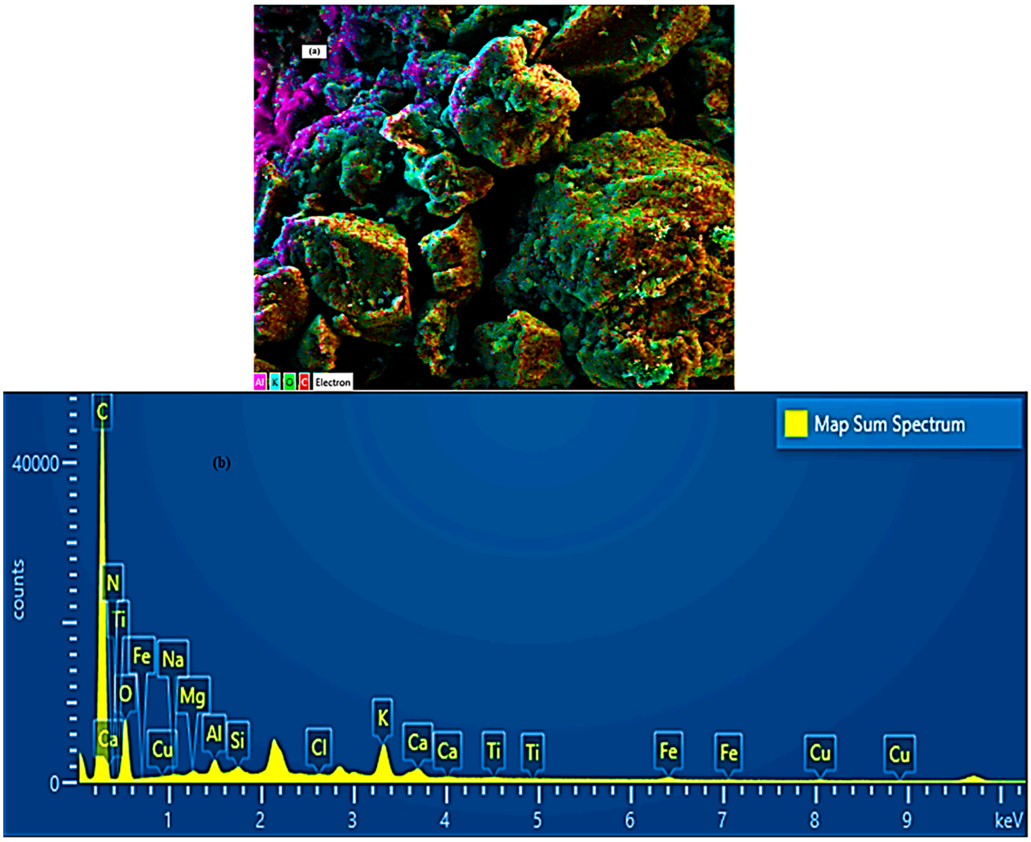


Figure 3. EDS of Cashew Nut Shell ash.

2.3. Geopolymer Syntheziation

Alkali activators such as highly concentrated sodium hydroxide reacted with solid aluminosilicate to form a "geopolymer", which is an inorganic binding material [27]. The geopolymer was considered beneficial to the environment because of its manufacturing process, which involves the use of byproducts of industries including fly ash, ground granulated blast furnace slag (GGBS), metakaolin, and metal slag [28]. Geopolymers have been discussed to present several advantages over traditional construction binding materials in the construction industry; primarily, they display great durability and strength, less shrinkage, and are resistant to fire and corrosion [29]. The synthesis of a geopolymer entails a chemical reaction between the alkaline solution and aluminosilicate called "alkaline activation", which forms a three-dimensional polymer chain of geopolymer similar to that of natural zeolite [30]. Usually, alumino silicate materials contain high content of alumina (Al_2O_3) and silica (SiO_2), which are obtained from fly ash, GGBS, and metakaolin [31]. An alkaline activator can be made up of potassium (KOH), sodium hydroxide (NaOH), potassium (K_2SiO_3), and sodium silicate (Na_2SiO_3) [32]. The preparation of geopolymers for different uses commonly involves the dissolution, condensation, gelation, and polycondensation of materials [33]. To assess the strength, UCS specimens were prepared by combining a calculated amount of sodium-based hydroxide solid for a 1 L solution, with the quantity determined based on the concentration in terms of molarity. Sodium-based silicates, also known as water glass, were obtained in powder form from a local chemist in Chennai, India. It had a SiO_2/Na_2O molar ratio of 3 and contained 11% Na_2O and 31% SiO_2 by weight.

As illustrated in Figure 4, sodium hydroxide solutions with molarities of 3 M, 6 M, and 9 M were prepared and mixed with a sodium silicate under a solution binder ratio of 1:2 (V:V) with distilled water. The combination of sodium hydroxide and sodium silicate produces an exothermic reaction, necessitating the preparation of an alkaline activator solution one day prior to use.

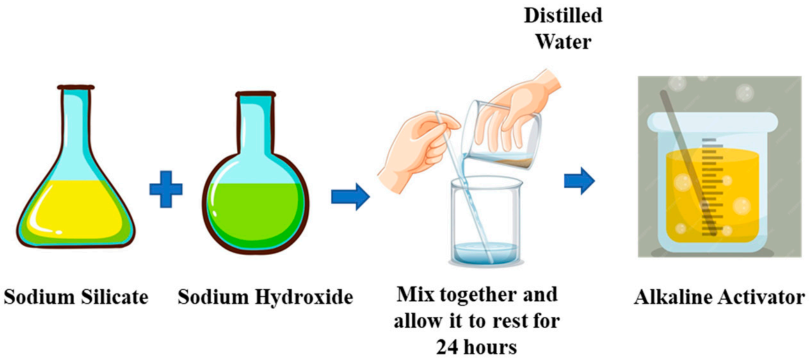


Figure 4. Preparation of Alkaline activator.

In the geopolymerization process, the aluminosilicate precursors like fly ash/clay transform into a long-lived 3D geopolymer gel through the medium of an alkaline activator [20]. This sequence starts by dissolving silica (Si) and alumina (Al) from precursors in highly concentrated sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) [34]. Based on the alkaline activator, this dissolution leads to the release of $(SiO_4)^{4-}$ and $(AlO_4)^{5-}$ tetrahedra, which undergo condensation reactions to form oligomers as shown in the below equation.

$$Si(OH)_4 + Al(OH)_4{}^- \rightarrow (Si - O - Al) + 4H_2O$$

These oligomers polymerize into a three-dimensional gel network containing Si–O–Si and Si–O–Al bonds with the support of alkali ions such as Na^+ or K^+ ions. Water also has an important function of improving ion conductivity and increasing the density of the structure during the curing process [35]. Curing at temperatures varying between 40 and 100 °C is preferred, as it increases the rate of the reaction and the strength of the cement [36]. The synthesized geopolymer has features of high compressive strength, enhanced durability, and resistance to chemicals and heat and can be utilized for construction, environmental remediation, and fire resistance [37]. This eco-friendly process also lowers CO_2 emissions by using industrial waste and serves as a better option than regular cement.

2.4. Preparation of Soil Specimen

In this study, the specimens were prepared by using manual hand mixing to maintain homogeneity. Also, a pre-process was carried out before the introduction of the alkaline solution into the reaction mixture. Before the hydroponic experiment, the soil was first sieved in order to remove debris and to have a uniform grain size of 425 microns. The sieved soil was then dried in an oven at 110 °C to remove any moisture left on the soil because moisture could alter the stability of the mixture and also interfere with the chemical reactions that take place during stabilization. These pretreatment procedures were important to enhance the reactivity of the soil with the alkaline solution and to obtain results with a high degree of repeatability. Unconfined compression (UCS) cylindrical specimens were cast using a prepared clayey soil with traditional stabilizer laboratory-grade lime and novel geopolymer as a stabilizer with or without CNSA. To maintain sample integrity, the soil was examined for contaminants before specimen formation. Cylindrical samples 38 mm in diameter and 76 mm in length were fabricated using various ratios of lime and CNSA-based geopolymers, as outlined in Table 3. The water content was maintained constant at the optimum moisture content (OMC) value of the soil throughout the sample preparation process.

Table 3. Mix proportion of Materials.

Mix ID	Weight of Soil (g)	Weight of Lime (g)	Weight of CNSA (g)	Geopolymer (GP) Molarity	Volume of Water (mL)	Volume of GP Solution (mL)
PS	153	-	-	-	24	-
PS + 2L	149.94	3.06	-	-	24	-
PS + 4L	146.88	6.12	-	-	24	-
PS + 6L	143.82	9.18	-	-	24	-
PS + 2 L + 2 CNS	146.88	3.06	3.06	-	24	-
PS + 2 L + 4 CNS	143.82	3.06	6.12	-	24	-
PS + 2 L + 6 CNS	140.76	3.06	9.18	-	24	-
PS + 4 L + 2 CNS	143.82	6.12	3.06	-	24	-
PS + 4 L + 4 CNS	140.76	6.12	6.12	-	24	-
PS + 4 L + 6 CNS	137.7	6.12	9.18	-	24	-
PS + 6 L + 2 CNS	140.76	9.18	3.06	-	24	-
PS + 6 L + 4 CNS	137.7	9.18	6.12	-	24	-
PS + 6 L + 6 CNS	134.64	9.18	9.18	-	24	-
PS + 2 CNS +2 M GP	149.94	-	3.06	2 M	-	24
PS + 4 CNS + 2 M GP	146.88	-	6.12	2 M	-	24
PS + 6 CNS + 2 M GP	143.82	-	9.18	2 M	-	24
PS + 2 CNS + 4 M GP	149.94	-	3.06	4 M	-	24
PS + 4 CNS + 4 M GP	146.88	-	6.12	4 M	-	24
PS + 6 CNS + 4 M GP	143.82	-	9.18	4 M	-	24
PS + 2 CNS + 6 M GP	149.94	-	3.06	6 M	-	24
PS + 4 CNS + 6 M GP	146.88	-	6.12	6 M	-	24
PS + 6 CNS + 6 M GP	143.82	-	9.18	6 M	-	24

Soil samples, sieved through a 4.75 mm sieve, were cast and molded the unconfined compression (UCC) using a 30 kN hydraulic jack compressor, as shown in Figure 5. Cast samples were stored in sealed Ziplock bags for 7, 14, and 28 days. For traditional stabilization, soil samples were mixed with lime at 2%, 4%, and 6% of the total soil weight and cured at room temperature for 28 days. Conversely, CNSA geopolymer specimens used an alkaline activator with NaOH molarity levels of 2 M, 4 M, and 6 M, maintaining an alkaline binder-to-CNSA ratio of 1:2, with CNSA at 2%, 4%, and 6% of the total soil weight. These samples were cured under different conditions, including ambient room temperature and in an oven at 50 °C, 75 °C, 100 °C, and 125 °C for a period of 48 h.

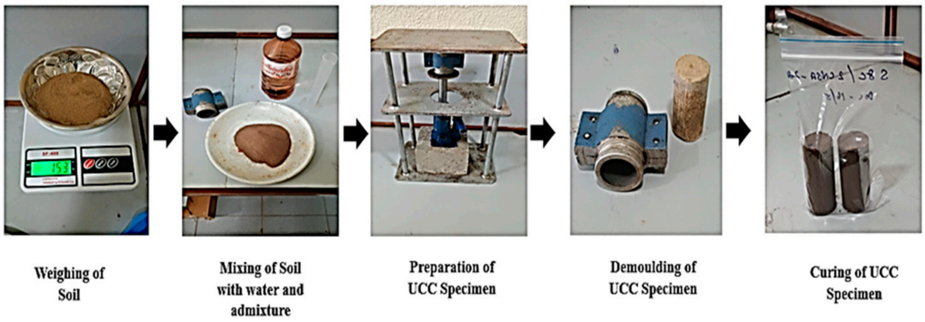


Figure 5. Preparation of Soil Specimen.

3. Results and Discussion

3.1. Engineering Behavior of Stabilized Soil

This study investigated the engineering properties of stabilized soils by evaluating their strength characteristics through unconfined compression strength (UCS) testing and durability via capillary soaking. Strength tests were performed using the UCS apparatus after 7, 14, and 28 days of curing. Simultaneously, soil specimen durability was evaluated by measuring the percentage decrease in the strength of the UCS. This was achieved by immersing a 28-day cured stabilized UCS specimen in a basin containing distilled water at a standard depth of 1.5 cm for 24 h. The soaked specimens were then tested using a UCS apparatus, and the results were compared to those of the unsoaked UCS specimens. This section analyzes the strength and durability characteristics of soil stabilized with lime and CNSA geopolymer.

3.1.1. Strength Assessment of Stabilized Soil Using Lime with CNSA

Figure 6 below shows the changes in the 28-day unconfined compressive strength (UCS) of stabilized soil with different percentages of lime alone and lime mixed with CNSA, as shown in Figure 6. This is presented using a two-tailed, unpaired Student's *t*-test from the experimental replicates.

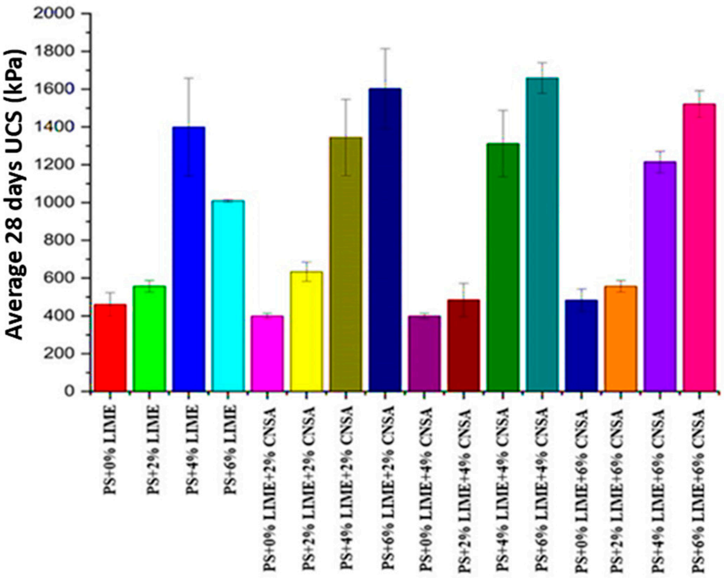


Figure 6. Lime composition vs. 28 days average UCC Strength (kPa) of Stabilized Soil with and without CNSA.

It was also observed that the unconfined compression (UCC strength gradually increased from 400 kPa at 2% lime to 1600 kPa at 6% lime, which revealed that lime improves the strength of the soil through pozzolanic reactions and soil aggregation. When CNSA is added, the value of UCS further increases, whereby the combination of 6% lime and 4% CNSA gave the highest UCS value of nearly 1750 kPa. This signifies a synergistic relationship whereby CNSA contributes extra silica and alumina, which is used to react with lime to produce more durable cementitious materials. However, when only CNSA is used, it can enhance the UCC strength, but to a lesser extent, with a maximum of around 1200 kPa at 6% CNSA, relative to the outcome attained with lime. Furthermore, these outcomes corroborate that incorporating CNSA with lime enhances the dependency and adjustment of reactive compounds within the soil, hence adding strength as per the study. This means that the observed strength variation is a result of increased binding due to pozzolanic reactions and the right proportions of lime/CNSA.

3.1.2. Unconfined Compression Strength of GP Treated Soil Under Varied Molarity with and Without CNSA

Figure 7 shows the fluctuation in unconfined compressive strength (UCS) of CNSAGP with different molarities of solution 3M, 6M, and 9M and curing conditions and without Cashew Nut Shell Ash (CNSA and without CNSA) presented using a two-tailed, unpaired Student's *t*-test from the experimental replicates. It illustrates the impact of curing temperature (ambient, 50 °C, 75 °C, 100 °C, and 125 °C) on the UCC strength. For soil stabilized at 3 M molarity, the UCC strength improves from about 400 kPa under normal curing conditions to possess a value of 800 kPa at 125 °C, although 4% CNSA develops a higher strength than 2% CNSA. UCC strength increases significantly at 6 M molarity, reaching up to 1400 kPa with 4% CNSA at 125 °C, suggesting that further improvements to molarity and heat curing could lead to increased stabilization. The 9 M molarity treatments demonstrate the highest strength improvements of up to 1800 kPa at 125 °C with 4% CNSA. It could be deduced that the incorporation of higher molarity and higher curing temperatures promotes the formation of the pozzolanic reactions and geopolymerization, leading to better binding. Curing at ambient temperature always results in the lowest values of compressive strength regardless of the curing condition, while curing at 100 °C and 125 °C have higher values of compressive strength. This synergistic effect between CNSA, higher molarity, and elevated curing temperatures enhances soil stabilization as a result of better geopolymer binder formation.

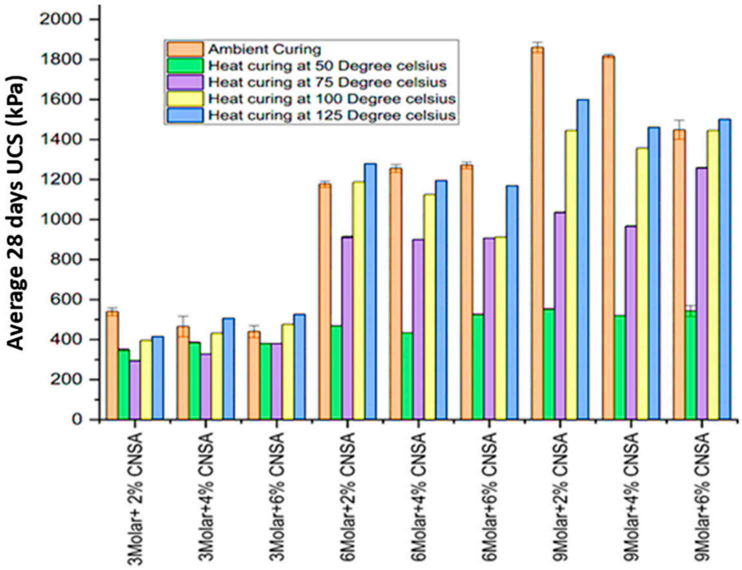


Figure 7. UCS of GP Stabilized soil under different Molarity with and without CNSA.

3.1.3. UCS Behavior of Lime vs. CNSAGP Stabilized Soil

Figure 8 shows the average 28-day UCS of soil stabilized with different proportions of lime and CNSAGP, with and without CNSA. As the molarity and CNSA content rise, UCC strength significantly rises for CNSAGP-stabilized soil at varying molarities. The maximum strength is observed with 9 M + 4% CNSA, which gives about 1900 kPa, showing that the optimum geopolymer reactions are highly favored where the molarity is high and the CNSA content is also high. At lower molarities, for example, at 3 M, the UCC strength is considerably lower and ranges from about 700 to 800 kPa at 4% CNSA, which reflects the poor stabilization attributable to weak geopolymerization reactions.

On the other hand, for the lime-stabilized soil (PS without CNSAGP), the UCC strength rises moderately with lime content. For example, 6% lime at a PS+ level provides a maximum of 800 kPa, which is significantly lower than that of stabilized soils with CNSAGP. Lime and CNSA show the aspect of synergy whereby their combined influence on the strength of the composite surpasses the sum of the individual effects, with the PS+6% lime + 4% CNSA producing strength of about 1400 kPa. These changes can be caused by the increase in pozzolanic and geopolymer reactions in CNSAGP-stabilized soils, as well as the effect of molarity and CNSA content on cementitious bonding strength compared to lime-stabilized soils. The findings suggest that CNSAGP, when combined with CNSA at their optimal blends, provides better stabilization of soil than lime alone.

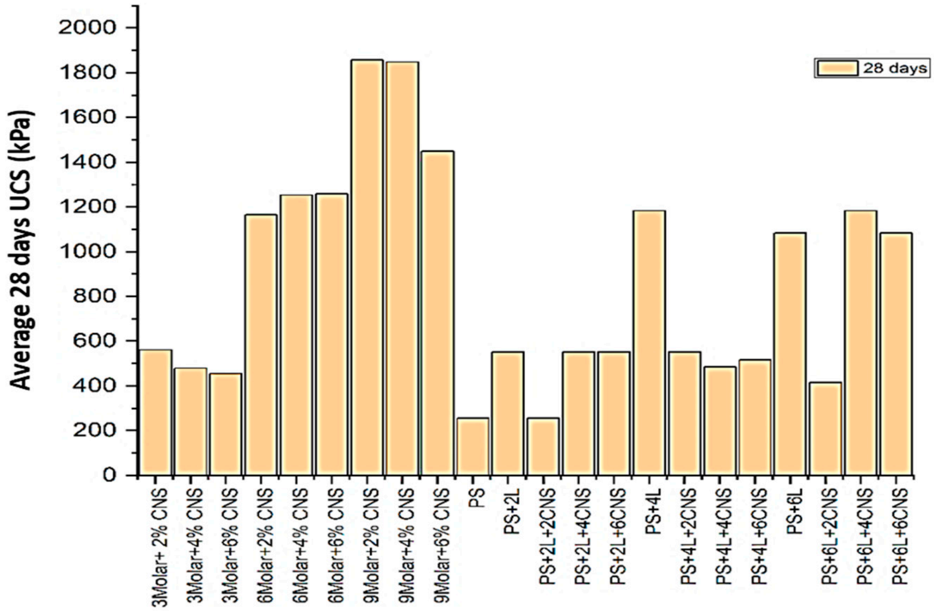


Figure 8. Strength of Lime vs. CNSAGP stabilized soil.

3.1.4. Average Stress–Strain Behavior of Lime and CNSAGP Stabilized Soil

Figure 9 soil stress–strain graph indicates the performance of soil treated with lime and geopolymer with CNAs and without CNAs. The detailed investigation suggests that the samples that incorporated lime and CNSA have higher peak stress than the other samples containing lime only, this leads to the improvement of mechanical characteristics through improved pozzolanic reactivity of CNSA and lime.

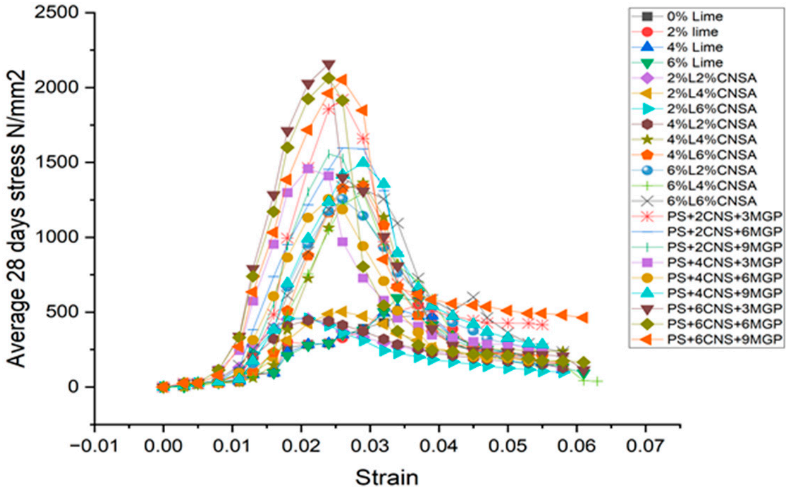


Figure 9. Stress–Strain Behavior of Stabilized soil specimen.

Further performance enhancement is achieved by the integration of geopolymer, where the geopolymer-stabilized samples possess a steeper stress–strain curve and enhanced peak stress that leads to an enhanced elastic modulus and, therefore, higher load-bearing capability. A steep slope, which is actually the stress–strain ratio, is shown by curve fits of the elastic regions using graphs. This suggests that the geopolymer-CNSA combinations exhibit an enhanced modulus of elasticity. The pozzolanic reactions that occur between lime, CNSA, and geopolymer may be the reason for this change. These reactions lead to the formation of a harder matrix, reduced porosity, and strengthened bonds. These properties are two-fold, revealed in the enhanced elastic and plasticity performance, while CNSA serves as the best admixture to enhance stabilization.

3.1.5. Durability Assessment

Figure 10 shows the percentage loss in the UCS of the soil stabilized with lime and geopolymer and with the addition of CNSA and after capillary soaking for a period of 48 h over the saturated sand layer. The results reveal that untreated soils and those treated with CNSA have a relatively higher UCS, and the lime-treated soils without CNSA have lower UCS reductions of more than 25% for 0% and 2% lime treatments. This suggests that the proposed technique offers little resistance to capillary soaking, as lime alone cannot effectively address moisture penetration. On incorporation of CNSA, the percentage reduction in UCS is lesser and ranges between 20 and 23% due to the durability aspect where CNSA reacts with lime to form a denser pozzolanic gel. CNSA has been proven to enhance the geopolymer-stabilized soils, and this is evidenced from the development shown above. All of these combinations result in lower UCS values below 20%, with the PS + 6% CNS + 6 M GP combination having the lowest at approximately 18%. This is compared to the improved water resistance that geopolymer stabilization offers to form a tighter matrix that is less permeable. The variation can be explained on the basis of the higher bonding material and water resistance of the geopolymer as well as the presence of CNSA, which also acts as a pozzolanic material. It eliminates the negative impacts of capillary soaking and therefore enhances the performance of the stabilized soil in the long run.

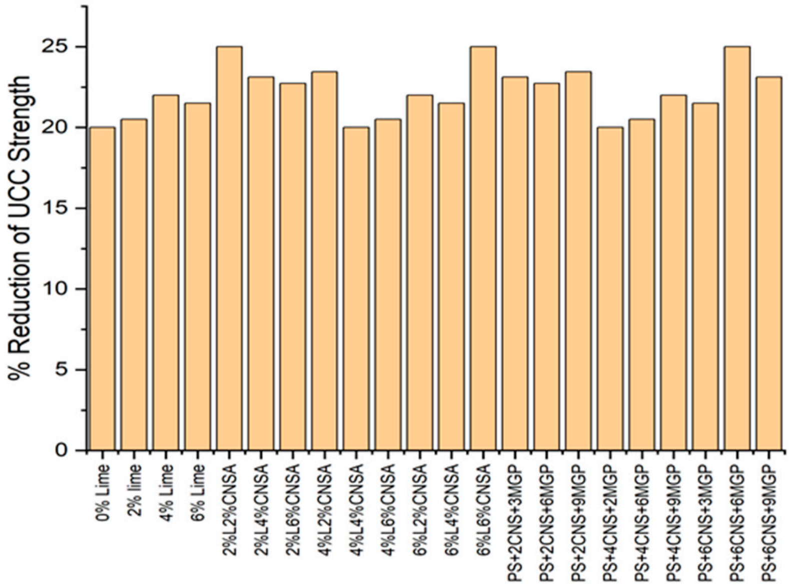


Figure 10. Reduction strength due to capillary soaking.

3.2. Physical Characteristics of Stabilized Soil

3.2.1. pH Value of Stabilized Soil

Figure 11 shows the pH ranges of the stabilized soils based on the additions of lime and geopolymer with/without CNSA, presented with a 5% error bar from the experimental replicates. It is also observed that there is a general trend of increase in the pH values with the increase in stabilizer content and geopolymer molarity. Lime-treated soils demonstrate a slow but steady process of pH increase; the 2% lime-treating program yields soils with a pH of 6.5, while the 6% lime-treating program results in 7.0. Lime-SAA has a pH of approximately 7.2–7.4 and thus implies an increase in alkalinity due to the products of the reaction that include C-S-H gel and other strongly alkaline products.

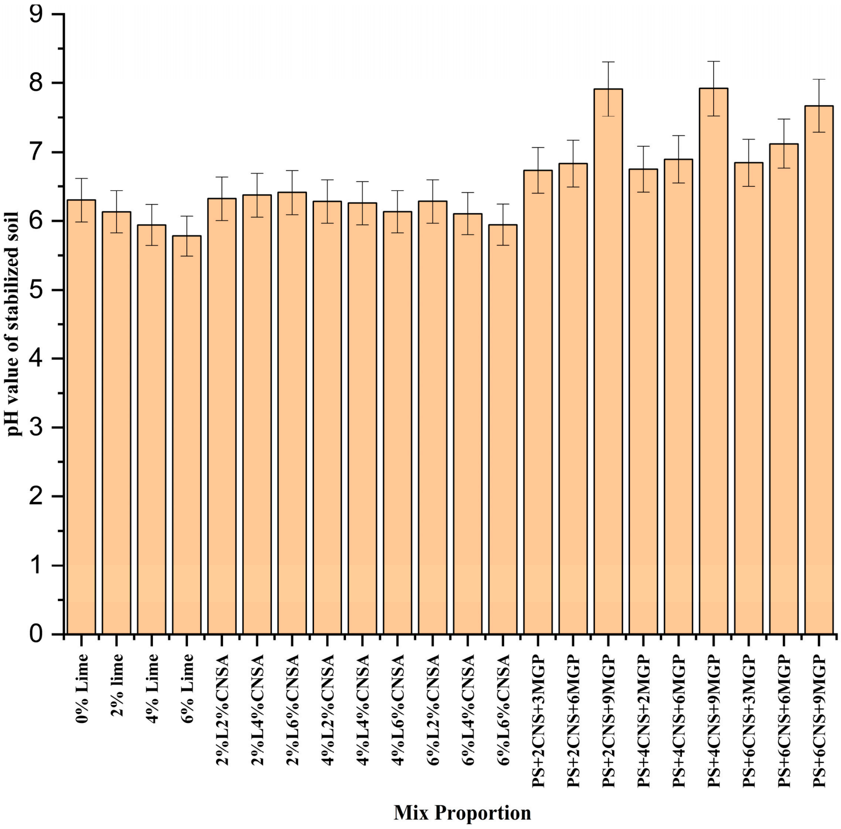


Figure 11. pH value of stabilized soil.

Similar to the case of untreated soils, the pH values of geopolymer-treated soils are higher, most notably when CNSA is included. For instance, geopolymer with CNSA and higher molarities, such as the combination of PS + 6% CNSA + 9 M GP, yielded the highest pH of approximately 8.5–8.8 and supported the strongly alkaline environment of the geopolymer matrix. This is caused by the enhancement of aluminosilicate phases in CNSA through the highly alkaline geopolymer solution to form a strong and interconnected matrix. The swing in the pH levels demonstrates the efficiency of CNSA through chemically stabilizing the soils that have been worked on. The higher pH in the geopolymer-stabilized soils with CNSA offers better setting and proper cementation/hardening, in which the UCS is beneficial. The outcome of the research proves that the integration of geopolymer and CNSA not only improves the mechanical properties of the soil but also alters the chemical properties of the soil in a way that could be more suitable for long-term stability and durability.

3.2.2. Atterberg Limit

Figure 12 shows the change in the Atterberg limits, load limit (LL), plastic limit (PL), and plasticity index (PI) depending on the stabilized type and the use of the Cashew nut Shell Ash (CNSA) additives, lime stabilization, and geopolymer stabilization, which were tested after 28 days of curing, with a 5% error bar from the experimental replicates. It was found that the use of lime, CNSA, and geopolymer has been associated with a decrease in the liquid limit and the plasticity index while the value of the plastic limit increases, thus increasing the workability and stability of the soil. As for its liquidity limit, it decreases gradually with an increase in lime content and reaches the minimum at 6% of lime content equal from 59% of untreated soil to about 56%. There is a slight rise in the plastic limit from about 24% to around 27% and a decrease in the plasticity index from around 35% to roughly 29%, suggesting the change to less swelling-shrinking or better workable soil.

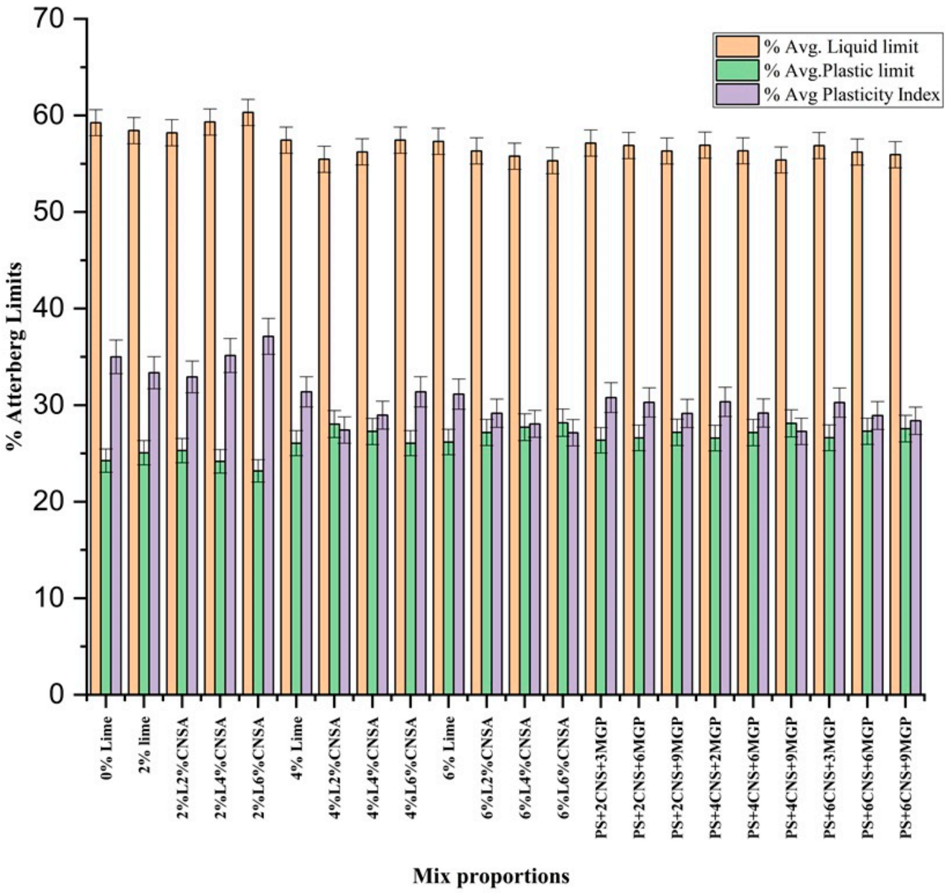


Figure 12. % Atterberg Limits of Stabilized Soil.

Incorporation of CNSA doubles these effects. For example, the soils containing 6% lime and 4% CNSA have a liquid limit of 55%, a plastic limit of 28%, and a plasticity index of 27%. This is attributed to the pozzolanic reactions between the lime and CNSA, which cause the enhancement of the soil particles binding and reduction of water trapped. The pertaining analyses also indicate that the combined use of geopolymer with CNSA applied on the soils shows the maximum enhancement. For instance, the blend produced using 9 M geopolymer and 6% CNSA has a liquid limit of around 52%, a plastic limit of around 30%, and a plasticity index of around 22%. This goes a long way to explaining how geopolymerization is able to create a denser soil structure with less plasticity and higher resistance to deformation. These variations can be explained on the basis of the chemical and physical activity of lime, CNSA, and geopolymer with soil particles to affect the availability of free water for swelling and to enhance the mechanical strength and structural stability of the soil. The outcomes support that geopolymer together with CNSA is the best stabilizer for improving the characteristics of the soil.

3.2.3. Loss of Ignition

The percentage of weight reduction in the soil at elevated temperatures directly correlates with the strength and durability of the stabilized soil. The loss of Ignition (LOI) test is commonly used to measure curing, which involves the emission of volatile compounds and moisture, burning of organic matter, and breakdown of carbonate substances in the stabilized soil. The key factors influencing the percentage weight reduction during high-temperature curing include the amount of binding agent added, initial organic content, and curing duration. In this study, we subjected the stabilized samples to high temperatures between 600 °C, 750 °C, and 900 °C for a period of 2 h in a muffle furnace with an initial LOI value of 0.12. Loss of ignition (LOI) was determined by comparing the initial and post-burn weights of the soil samples.

Figure 13 illustrates the assessment of the percentage loss of organic matter and shows the % LOI of lime-stabilized and geopolymer-stabilized soil with and without CNSA at 600 °C, 750 °C, and 900 °C. The LOI values in general decrease with increasing temperature of the treatment, suggesting enhanced thermal stability. The percentage LOI of the lime-treated soils without CNSA is approximately 0.25 at 600 °C, indicating lower thermal stability owing to the decomposition of lime and the absence of any considerable pozzolanic reaction. The involvement of CNSA brings the LOI percentage down to around 0.22–0.23% due to pozzolanic chemistry that infused a more compact and sound matrix. However, the percentage LOI of the geopolymer-stabilized samples is lower and more stable, ranging from around 0.21% at 600 °C to 0.17% at 900 °C in PS + CNS + 6 M GP. This indicates that the inorganic binder system of the geopolymer provides enhanced thermal stability. The lower percentage LOI in geopolymer-treated soils is due to the aluminosilicate framework formed during geopolymerization that is thermally stable, complemented by the CNSA that provides reactive silica and alumina. Although there is some enhancement in the CNSA and lime-stabilized samples, the thermal profile is poorer as compared to geopolymer-treated samples. These results explain the effectiveness of the integration of geopolymer and CNSA in applications where higher thermal stability is required. Furthermore, the decrease in LOI value in stabilized soil indicates the removal of the extent of organic content and volatile elements that evaporated during heat treatment. This reduction does not affect the strength of the soil in any way as a result of pozzolanic reactions that occur and the creation of a dense geopolymer matrix that offers enhanced strength in place of the lost weight. The stabilization process also improves the other properties of the composite, such as durability and the mechanical properties that provide stability.

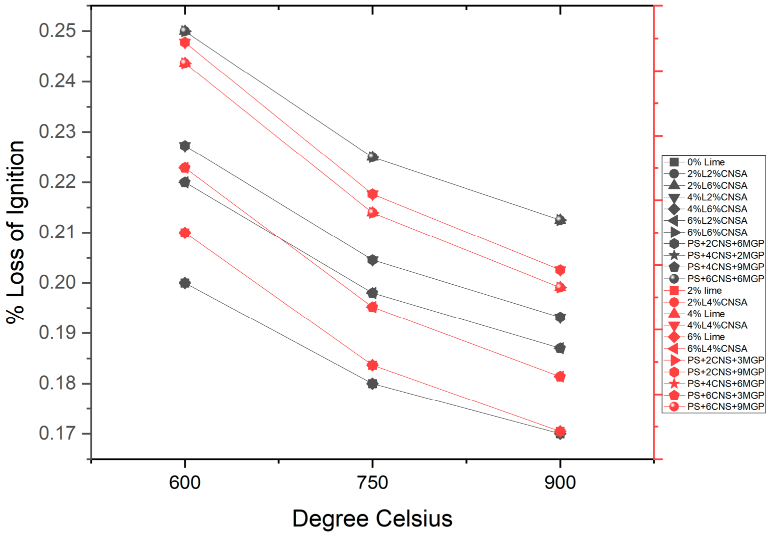


Figure 13. Loss of Ignition of Stabilized Soil.

3.3. Microstructural Behavior of Stabilized Soil

Figure 14 shows the FESEM images of the unconfined compressive strength (UCS) at 340× magnification to help explain the changes in the microstructure of lime-stabilized and geopolymer-stabilized soils with and without CNSA. Figure 14a, lime-treated clay soil without CNSA shows a good porous structure with numerous gaps and low interparticle forces. This corresponds with the poor UCS. This structure does not contain compact reaction products, which makes it less capable of withstanding external forces. In the CNSA case, Figure 14b shows that lime-treated soil has low porosity and high connectivity of particles as a result of pozzolanic reactions that lead to the conversion of Lime–CNSA to C-S-H and C-A-H. This holds the key to explaining the observed moderate UCS increases due to the densification of the matrix and enhancing load transfer between particles. Figure 14c consists of soil that has been treated with geopolymer but does not contain CNSA and shows a more compact and stronger structure of the chemical bonds with the network of the aluminosilicate gel being formed. The microstructure also substantially decreases porosity and increases the UCS because the particle linkages through geopolymerization are strong and restrict microcracking. Lastly, Figure 14d presenting the geopolymer-treated soil with CNSA, has the least number of pores and evenly disseminated reaction products due to favorable compatibility between geopolymer and CNSA Si/Al phases. This structure provides the highest UCS and geometries that suggest enhanced mechanical performance and thermal insulation properties. The microstructural differences have been further amplified; a clear relation is evident between these changes and the mechanical enhancements, thus confirming the effectiveness of CNSA and geopolymer for the stabilization of soils.

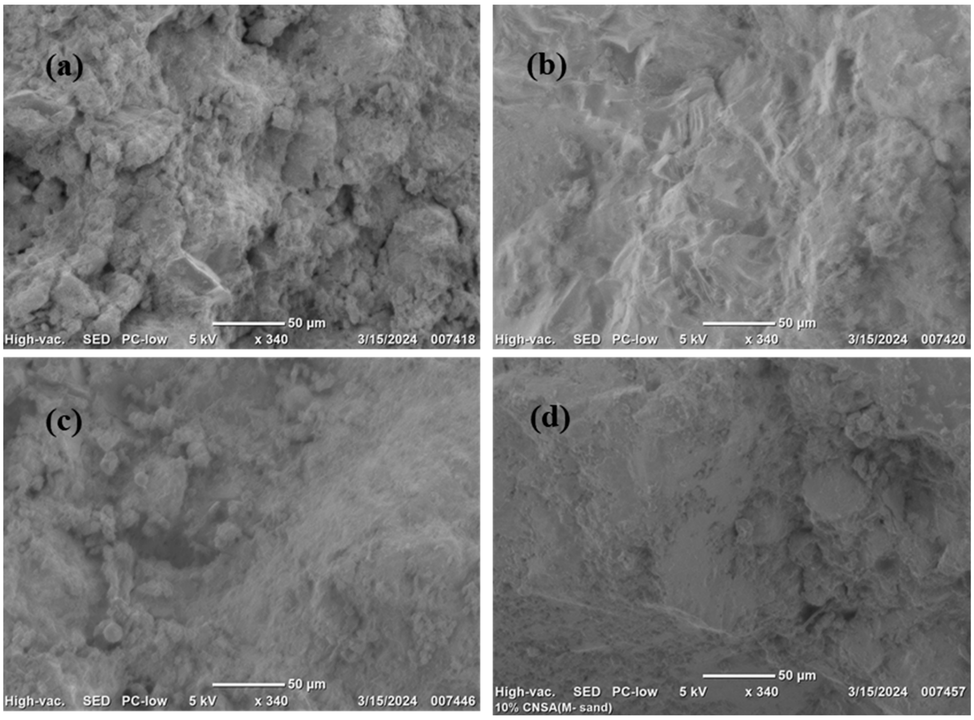


Figure 14. FESEM Analysis of Stabilized Soil (**a**) Plain Soil (**b**) Plain soil with 4% Lime (**c**) Plain soil with 6% Lime + 4% CNSA (**d**) Plain soil with 9 M GP + 2% CNSA (at 340×).

4. Conclusions

Based on the comprehensive experimental study, the following conclusions can be drawn:

1. For effective stabilization with CNSA, geopolymer-stabilized soils gained a significantly higher Unconfined Compressive Strength (UCS) than lime-stabilized soils. Consequently, soil treated with geopolymer with 9 M NaOH and 4% CNSA provided the highest UCS value, which is about 1900 kPa, compared to that of lime-stabilized soil, which was only 1400 kPa with 6% lime and 4% CNSA. This shows the enhanced chemistry between the geopolymer and CNSA system such as bonding and formation of new compounds.
2. Generally, soil samples that received geopolymer treatment have better proven resistance to degradation from water immersion, as evident from the approximately 18% reduction in strength for geopolymer with CNSA after the capillary soaking test as compared to an approximately 25% reduction in strength for lime-only-treated soil. Hence, there is an increase in the density of the created geopolymer matrix, and the permeability of the material is reduced due to CNSA pozzolanic reactions.

3. The thermal stability of the geopolymer-stabilized soils is further evident from the Loss of Ignition (LOI) results wherein the LOI values have decreased with temperature 0.17% at 900 °C for geopolymer + CNSA for geopolymer-stabilized soils, while the lime-treated CNSA-stabilized soil samples have much higher LOI values of 0.25% at 600 °C. The higher thermal resistances of the geopolymer-CNSA-treated soils can be explained by the progressive consolidation of the aluminosilicate framework of the geopolymer and the increased reactivity of CNSA.
4. FESEM analysis established that the soils treated with geopolymer-CNSA had a higher density and uniformity, free from pores, and a uniform distribution of reaction products. This was different from the lime-stabilized soils, which have shown porous and less compact structures. In addition, the improvement of the microstructure of geopolymer-treated soils explains the increased mechanical and thermal performance.
5. The incorporation of CNSA and geopolymer has led to a decrease in the value of the plasticity index and liquid limit and an increase in that of the plastic limit, which makes the soil more suitable for construction as its volume does not expand or shrink severely when it is being compacted. This characteristic is useful for engineering applications where the dimensional stability of the material is desired.

Therefore, CNSA, when used as a pozzolanic material alongside a geopolymer shows a more environmentally friendly and sustainable method of operation than the regular lime and cement stabilizers. This also reduces carbon emissions while putting industrial by-products into proper use. Therefore, the integration of a geopolymer and CNSA in the stabilization of soils is an effective and sustainable solution that can provide additional strength, durability, and thermal stability and is eco-friendly when compared with lime treatment. This study reveals the possibility of employing CNSA-based geopolymers in the civil engineering and construction industries.

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