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Utilization of Nano Silica and Plantain Leaf Ash for Improving Strength Properties of Expansive Soil

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Abstract: This study investigates the effect of nanosilica and plantain leaf ash on the sustainable stabilization of expansive soil. This study conducted various strength tests, including Unconfined Compressive Strength (UCS), direct shear, and California Bearing Ratio (CBR) tests, to analyze the enhancement of mechanical properties by adding nano silica and plantain leaf ash. Scanning Electron Microscopy (SEM) analysis was conducted to investigate the interaction mechanism between the soil and the combination of nano silica and plantain leaf ash. Three different combinations of plantain leaf ash were utilized, ranging from 5% to 15%, alongside nano silica ranging from 0.4% to 1.2%. The reinforced soil's compressive strength, shear strength, and bearing capacity were assessed through UCS, direct shear, and CBR tests. The results demonstrated significant improvements in compressive strength, up to 4.6 times, and enhancements in cohesion and frictional angle, up to 3.3 and 1.6 times, respectively, at 28 days. Moreover, the addition of nano silica and plantain leaf ash led to increased bearing capacity and reduced soil swelling potential, contributing to the overall stability and strength improvement in expansive soil. The SEM test results demonstrate that maximum bonding and compaction occur when 1.2% nano silica and 15% plantain leaf ash are added to the soil.

Keywords: nano silica; plantain leaf ash; expansive soil; soil stabilization; strength properties; structural analysis; SEM; sustainability

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1. Introduction

Expansive soils are naturally unstable and susceptible to volume changes affected by moisture content, which makes them major challenges in engineering and construction [1]. Cement and other non-renewable materials are frequently used in traditional techniques for stabilizing these soils, which reduces resources and increases environmental degradation [2]. As such, it is critical to find sustainable options to improve the strength characteristics of expansive soil.

Investigating environmentally friendly additives has recently gained popularity as a potential way to address soil stabilization while reducing environmental effects. Because of its ability to increase the strength and durability of soil, nano silica, which has been identified by its minute particle size and outstanding pozzolanic properties, has come into focus as a possible solution [3]. Plantain leaf ash, which is a byproduct of agriculture, has demonstrated potential as an additional stabilizing agent because of its high calcium concentration and natural pozzolanic reactivity [4]. In order to minimize environmental effects and promote environmentally friendly engineering techniques, sustainability is not just about improving soil qualities but also about decreasing reliance on non-renewable resources.

In recent years, scientists and engineers have been looking into new, environmentally friendly ways to reduce the adverse effects of expanding soils. Ijaz et al. [5] utilized lignosulphonate and hydrated lime for the sustainable treatment of expansive soil, and to improve the geotechnical properties of this soil. Kumar et al.'s study [6] involves the utilization of lime and fly ash in proportions of up to 10% and 20%, along with the addition of polyethylene terephthalate (PET) fibers up to 2%, for the sustainable soil stabilization of expansive soil. The results demonstrate an increase in both the Unconfined Compressive Strength (UCS) and tensile strength of the soil due to the incorporation of these additives. In another study, leaf ash was employed for the soil stabilization of expansive soil. The results indicated a noticeable increase in both the UCS and California Bearing Ratio (CBR) values of the soil upon the addition of leaf ash [7,8].

There has been an increase in interest recently in creating sustainable and economical methods for stabilizing expansive soils [9,10]. The use of nanotechnology, namely the integration of nano silica particles, in combination with waste products like ash, is one viable route in this respect. Nano silica, with its special properties, may be useful in modifying the mechanical and hydraulic properties of expansive soils [11,12], whereas waste products like ash, which are widely available from various industrial processes, offer a chance to lessen environmental waste and improve soil.

Mostafa et al. [13] utilized up to 15% silica fume and up to 3% nano silica in combination with lime for the stabilization of expansive soil. The results demonstrated that increasing the amounts of silica fume and nano silica, in conjunction with lime, led to a remarkable improvement in the California Bearing Ratio (CBR) value, which increased threefold, and the Unconfined Compressive Strength (UCS) value, which doubled. Buazar [14] utilized green nano silica and observed that, by using 1.5% nano silica, there was a 5.8 times increase in the CBR value of expansive soil. Another study demonstrated that, by utilizing nano silica in conjunction with other binding materials like cement, there is an increase in the UCS value of the expansive soil [15]. Al-Gharbawi et al.'s study [16] demonstrated that incorporating lime, cement, and nano silica, at levels of up to 9%, in expansive soil resulted in significant improvements. The results indicated a reduction in swelling pressure by up to 76% and an increase in bearing capacity by up to 82%. Another research study utilized both nano and crystalline silica to observe a reduction in the swelling and shrinkage of expansive soil [17]. Alshami et al. [18] utilized micro and nano silica as additives for expansive clay, with concentrations of up to 7%. The study aimed to analyze the increase in the Unconfined Compressive Strength (UCS) value resulting from the addition of these additives to the soil. However, Eissa et al. [19] employed cement and slag at concentrations of up to 20%, along with up to 2.4% nano silica, for enhancing expansive soil. The results demonstrated improvements in both performance and cost-effectiveness. Some recent studies utilized agricultural waste and biomass in construction [20,21]. For instance, the study conducted by Rahgozar et al. [22] utilized up to 8% rice husk ash to improve the strength properties of soil. Similarly, Sharma and Sharma [23] conducted a study on lime-stabilized soil using the same approach. Furthermore, Gidebo et al.'s [24] study utilized a variety of agricultural waste materials, such as rice, wheat, sugarcane, and bamboo ash, for the stabilization of expansive soil.

Previous research has primarily focused on the impact of nano silica on expansive soil. However, there is a noticeable gap in the literature when it comes to analyzing the combined effects of leaf ash and nano silica on soil stabilization. This study aims to bridge this gap by utilizing nano silica and plantain leaf ash, with a specific focus on achieving sustainable soil improvement in fat clay soil through the utilization of waste materials.

2. Materials and Methods

2.1. Materials

2.1.1. Expansive Soil

In this study, expansive soil was obtained from an urban area characterized by high plasticity. The physical properties, mineralogical, and chemical composition of the expansive soil used are listed in Tables 1 and 2, respectively. The testing method described in ASTM D4318 [25] was used to determine the Atterberg limits (liquid and plastic limits) of the expansive soil used. The results showed that the liquid limit and plastic limit for the expansive soil used were 74% and 39%, respectively. According to the Unified Soil

Classification System (USCS), the expansive soil used can be classified as CH (highly plastic clays).

2.1.2. Nano Silica

Nano silica powder, obtained from a local ceramic industry company, was used in this study. Typically, nano silica powder is seen as a fine, white powder. It frequently has a smooth texture [26]. When combined with liquids, the extremely dispersible powder can create solutions [27]. Nano silica particles are very small, homogeneous particles that range in size from 1 to 100 nanometers. They are frequently spherical or irregular in shape [28]. The physical properties of this nano silica are detailed in Table 3.

2.1.3. Plantain Leaf Ash

Dry plantain leaves were gathered from an agricultural area and then underwent a heating process in an oven and calcination was carried out in a makeup container below 650 °C to produce ash [29]. Afterward, they were cooled to room temperature and ground using a grinder machine to produce ash. The chemical composition of the leaf ash is presented in Table 4. A composition analysis indicated a predominant presence of calcium oxide (CaO) at 47.31% of the total leaf ash composition. Additionally, silica, calcium, and potassium were significant contributors to the composition.

Table 1. Physical properties of the expansive soil used.

Parameters	Value	Standard
Liquid Limit (%)	74	ASTM D4318 [25]
Plastic Limit (%)	39	ASTM D4318 [25]
Plastic Index (%)	35	ASTM D4318 [25]
Soil Classification (USCS)	CH	ASTM D2487 [30]
Unconfined Compressive Strength (MPa)	0.68	ASTM D2166 [31]
Swelling Potential (%)	72	ASTM D4546 [32]
Specific Gravity (G_s)	2.68	ASTM D854 [33]
Optimum Moisture Content (OMC) (%)	27.4	ASTM D1557 [34]
Maximum Dry Density (g/cm^3)	1.2	ASTM D1557 [34]

Table 2. Mineralogical and chemical composition of the expansive soil used.

Parameters	Percentage (%)
Mineralogical Composition %	
Quartz	46.1
Montmorillonite	34.7
Kaolinite	11.4
Feldspar	3.1
Other	4.7
Chemical Composition %	
SiO_2	59.34
Al_2O_3	23.42
FeO	9.31
CaO	3.07
MgO	1.94
TiO_2	1.78
K_2O	0.71
$Na_2O + P_2O_5$	0.43

Table 3. Physical properties of the nano silica used.

Parameters	Values
Color	White
Form	Powder
Surface Area	200 (m^2/g)
Refractive Index	1.46 (lit.)
Average Particle Size	200–300 (nm)
Density	2.31 (b/cu.ft)

Table 4. Chemical composition of the plantain leaf ash used.

Parameters	Percentage (%)
CaO	47.31
SiO_2	17.54
K_2O	16.92
Al_2O_3	4.08
Fe_2O_3	3.87
P_2O_5	3.14
SO_3	2.69
MgO	1.47
LOI	0.28
Others	2.70

2.2. Preparation of Soil Samples

Ten types of soil samples were prepared by varying the ratio of reinforced materials mixed with the soil. The Optimum Moisture Content (OMC) for making each sample was determined by the compaction test, as shown in Table 5. The process for preparing the reinforced soil samples, involving plantain leaf ash and nano silica, mirrored that of the unreinforced soil samples. Plantain leaf ash was used in mixtures ranging from 0 to 15%, while nano silica ranged from 0 to 1.2%. The dosage of nano silica in mixes can vary depending on its intended use, soil type, the other materials it is combined with, economic considerations, the desired soil strength achievement, and also on previous literature. When nano silica is incorporated alongside ash, a lower dosage may be sufficient [3]. This is because the ash itself often contributes to pozzolanic reactions, synergistically enhancing the properties of the mixture [35]. A study conducted by Munda et al. [36] showed that cooperating nano silica percentages up to 1.5% with fly ash show the maximum improvement in expansive soil strength. After 1.5%, the strength decreases. The study by Munawar et al. [37] analyzed the use of up to 1.2% nano silica with rice husk ash and showed the maximum improvement in expansive clay soil strength. The study by Kulanthaivel et al. [38] utilized up to 1% nano silica with PET fiber and fly ash and showed maximum improvement in expansive clay soil. However, the dosage of plantain leaf ash is also decided according to previous literature. The study by Ezema, Adinna, and Anayo [4] shows maximum improvement in soil strength by utilizing up to 10% plantain leaf ash. Another study utilized up to 10% of plantain peel ash for improving the strength properties of soil [39]. After sample preparation, strength tests were conducted to analyze how different proportions of plantain leaf ash and nano silica affected the strength properties of expansive soil. Table 5 illustrates the variations in soil samples corresponding to different ratios of plantain leaf ash and nano silica. Figure 1 displays the preparation of a reinforced soil sample by mixing reinforced materials with soil.

Table 5. Reinforced soil samples with different percentages of nano silica and plantain leaf ash.

No.	Mixed Ratios of Samples	Designation	Soil (%)	Plantain Leaf Ash (%)	Nano Silica (%)	Total (%)	OMC (%)
1	Soil + 0% Plantain leaf ash + 0% Nano silica	PN0	100	0	0	100	27.4
2	Soil + 5% Plantain leaf ash + 0.4% Nano silica	PN1	94.6	5	0.4	100	16.3
3	Soil + 10% Plantain leaf ash + 0.4% Nano silica	PN2	89.6	10	0.4	100	17.1
4	Soil + 15% Plantain leaf ash + 0.4% Nano silica	PN3	84.6	15	0.4	100	18.6
5	Soil + 5% Plantain leaf ash + 0.8% Nano silica	PN4	94.2	5	0.8	100	21.9
6	Soil + 10% Plantain leaf ash + 0.8% Nano silica	PN5	89.2	10	0.8	100	22.4
7	Soil + 15% Plantain leaf ash + 0.8% Nano silica	PN6	84.2	15	0.8	100	23.7
8	Soil + 5% Plantain leaf ash + 1.2% Nano silica	PN7	93.8	5	1.2	100	26.8
9	Soil + 10% Plantain leaf ash + 1.2% Nano silica	PN8	88.8	10	1.2	100	28.2
10	Soil + 15% Plantain leaf ash + 1.2% Nano silica	PN9	83.8	15	1.2	100	28.9

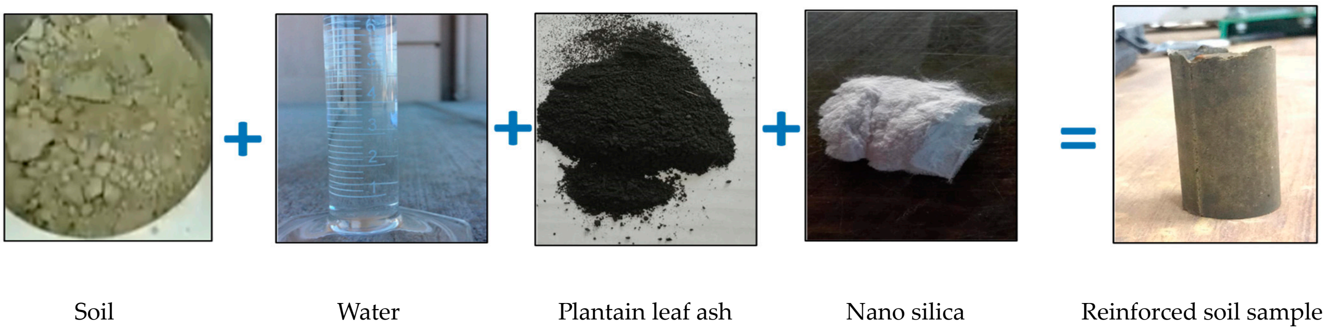


Figure 1. Preparation of reinforced soil sample.

2.3. Test Methods

The methodology employed in this study is depicted in Figure 2. The procedures for these tests are explained in the following sections. The experimental apparatus is shown in the Supplementary Data in Figure S1.

2.3.1. Compaction Test

A soil sample weighing 5 kg was used to conduct the modified Proctor test following ASTM D1557 [34] standards. The soil was thoroughly mixed with water. Subsequently, a modified Proctor test was conducted. The mold was filled with five layers, each subjected to 25 blows with a hammer weighing 4.5 kg and dropped from a height of 45 cm. The test provided the optimum moisture content and maximum dry density. The determined optimum moisture content was utilized in preparing the UCS samples.

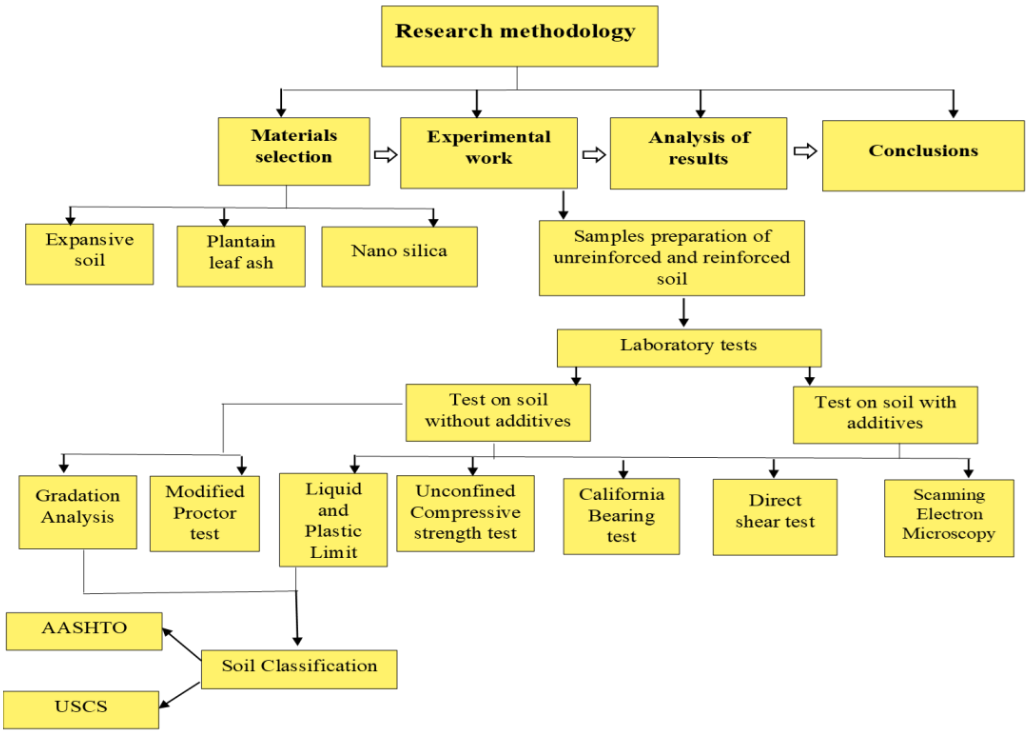


Figure 2. Research methodology.

2.3.2. UCS Test

The Unconfined Compressive tests for both unreinforced and reinforced soil samples were conducted following ASTM D2166 [31] standards. A modified Proctor test was performed to determine the optimum moisture content, which was subsequently used in creating samples with varying ratios of plantain leaf ash and nano silica. The height and weight of the prepared samples removed from the mold were 7.6 cm and 3.7 cm. These samples underwent curing for 7, 14, 21, and 28 days before the UCS tests were conducted. To maintain moisture levels, the samples were wrapped in plastic throughout the testing period. Data collected during the UCS tests, including maximum load sustained and corresponding deformation, were meticulously recorded in compliance with ASTM standards for test methods and practices.

2.3.3. Direct Shear Test

The ASTM D3080 [40] guidelines were followed to determine the frictional angle and soil cohesiveness during a direct shear test. As per ASTM rules, a soil specimen, generally square and approximately 61 mm by 61 mm, was prepared and placed inside a shear box apparatus for the experiment. After that, in order to replicate real-world circumstances, the soil specimen was exposed to controlled stresses, usually at a constant normal stress of 100 kPa. The specimen was subjected to a regulated rate of incremental shear stress applied horizontally until failure occurred. The cohesiveness and frictional angle of the soil were determined by carefully examining the test results in accordance with ASTM guidelines. The intercept of the shear stress–displacement curve at zero displacement was used to calculate cohesiveness, which is a measure of the intrinsic strength of the soil [41,42]. In the meantime, the slope of the linear section of the curve after peak failure was used to calculate the frictional angle, which is a measure of the soil's resistance to sliding [43].

2.3.4. CBR Test

The California Bearing Ratio (CBR) tests were conducted in accordance with ASTM D1883 and D4546 [32,44] standards to assess both unreinforced and reinforced soil samples. Unsoaked samples, measuring 15 mm in diameter and 18 cm in height, were compacted at their optimum moisture content within the mold. CBR testing was carried out at intervals of 7, 14, 21, and 28 days under a surcharge of 2500 Pa to determine the samples' load-bearing capacity. For the soaked CBR tests, the same preparation method was followed initially. Subsequently, these samples underwent soaking in water to induce swelling. Swelling behavior was monitored using a dial gauge at various time intervals until the swelling ceased. The swell potential was quantified based on these observations.

2.3.5. SEM Test

For microstructural analysis, the soil samples underwent SEM testing in accordance with ASTM E2809 standards [45]. Fractured pieces from unreinforced soil samples, soil samples reinforced with 1.2% nano silica, and soil reinforced with 1.2% nano silica and 15% plantain leaf ash were extracted from the UCS test after 28 days. Before SEM imaging, both reinforced and unreinforced samples were dried at room temperature (35 °C). Subsequently, SEM images were captured to analyze the interaction behavior among these particles.

3. Results and Discussion

3.1. Effect of Nano Silica and Plantain Leaf Ash on Atterberg Limits

In Figure 3, the impact of increased quantities of nano silica and plantain leaf ash on the Atterberg limits of the samples is illustrated. It is evident that, as the nano silica content rises to 1.2% and the plantain leaf ash content increases up to 15%, the liquid limit of the unreinforced soil sample decreases by a factor of 1.5, while the plastic limit decreases by a factor of 1.3. The liquid and plastic limits of expansive soil can be efficiently reduced by mixing with plantain leaf ash and nano silica. Compounds in plantain leaf ash improve the binding qualities of the soil, which helps to change its structure [29]. By filling in the spaces in the soil, the ash particles lower the amount of water needed to reach the liquid limit [4]. Furthermore, because of its small particle size, nano silica reduces the flexibility of the soil by filling in the spaces between particles within the soil matrix. The filling impact lowers the plastic limit by decreasing the soil's capacity to absorb water [46,47].

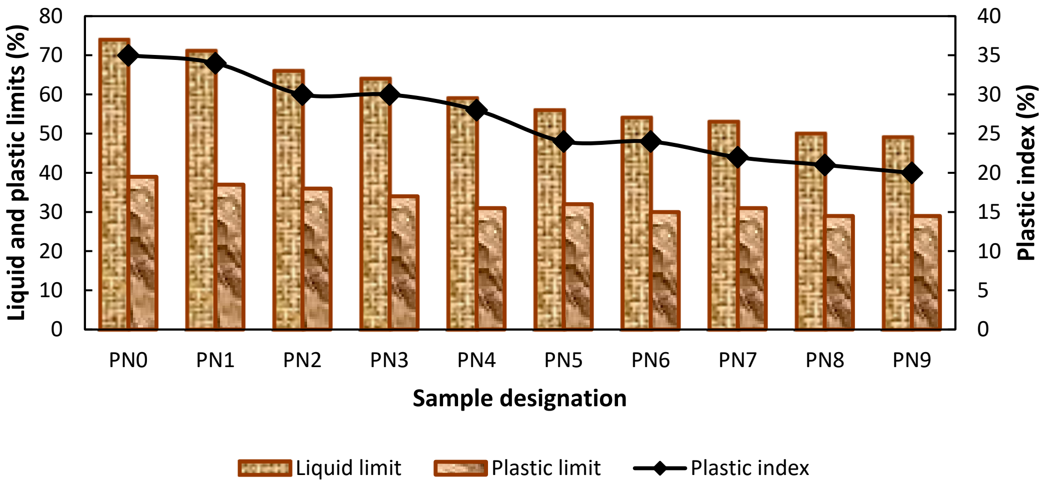
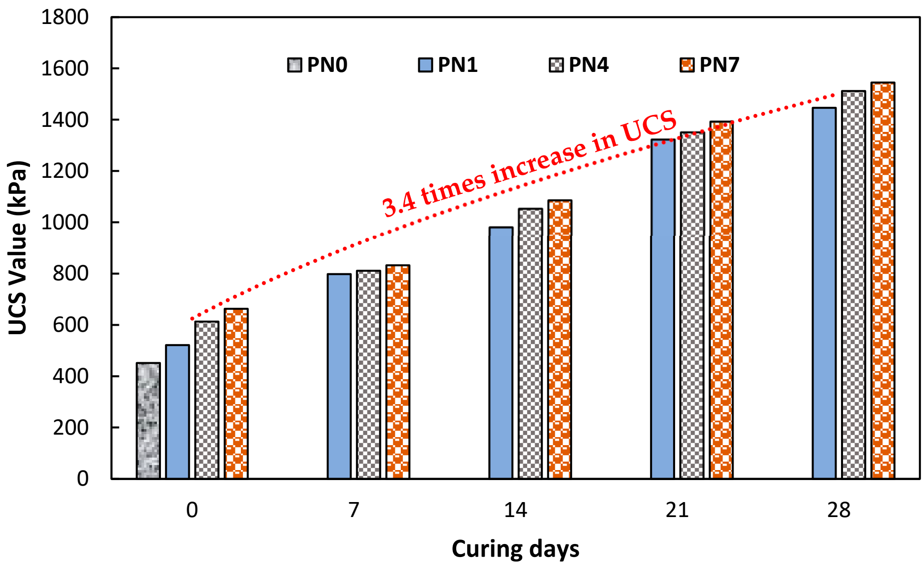


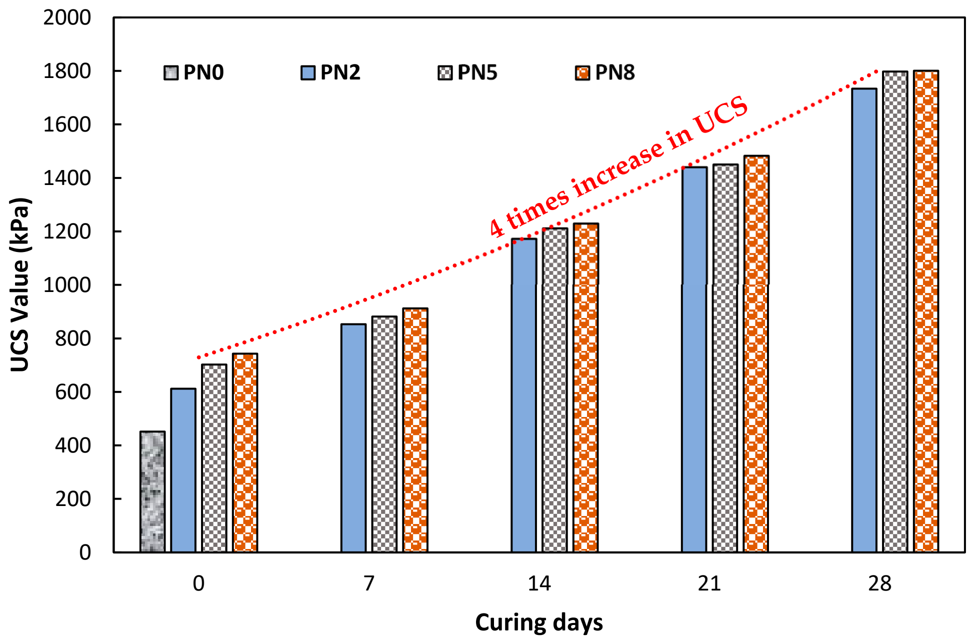
Figure 3. Effect of nano silica and plantain leaf ash on the Atterberg limits of soil.

3.2. Effect of Nano Silica and Plantain Leaf Ash on UCS

Figure 4 presents the results of the unconfined compressive test conducted on soil samples reinforced with up to 1.2% nano silica and up to 15% plantain leaf ash for various curing periods (0, 7, 14, 21, and 28 days). In Figure 4a, the unconfined compressive strength (UCS) test results for both unreinforced and reinforced soil are shown, with nano silica ratios of 0.4%, 0.8%, and 1.2%, along with 5% plantain leaf ash. It is observed that a maximum improvement of approximately 3.4 times the initial unreinforced sample value is achieved by utilizing 1.2% nano silica after 28 days on the PN7 soil sample. In Figure 4b, the UCS test results for unreinforced and reinforced soil are presented with nano silica ratios of 0.4%, 0.8%, and 1.2%, and 10% plantain leaf ash. A maximum improvement of about four times the initial unreinforced sample value is observed with the utilization of 1.2% nano silica after 28 days on the PN8 soil sample. Figure 4c displays the UCS test results for unreinforced and reinforced soil, employing nano silica ratios of 0.4%, 0.8%, and 1.2%, along with 15% plantain leaf ash. It is noted that a maximum improvement of approximately 4.6 times the initial unreinforced sample value is achieved by utilizing 1.2% nano silica after 28 days on the PN9 soil sample.

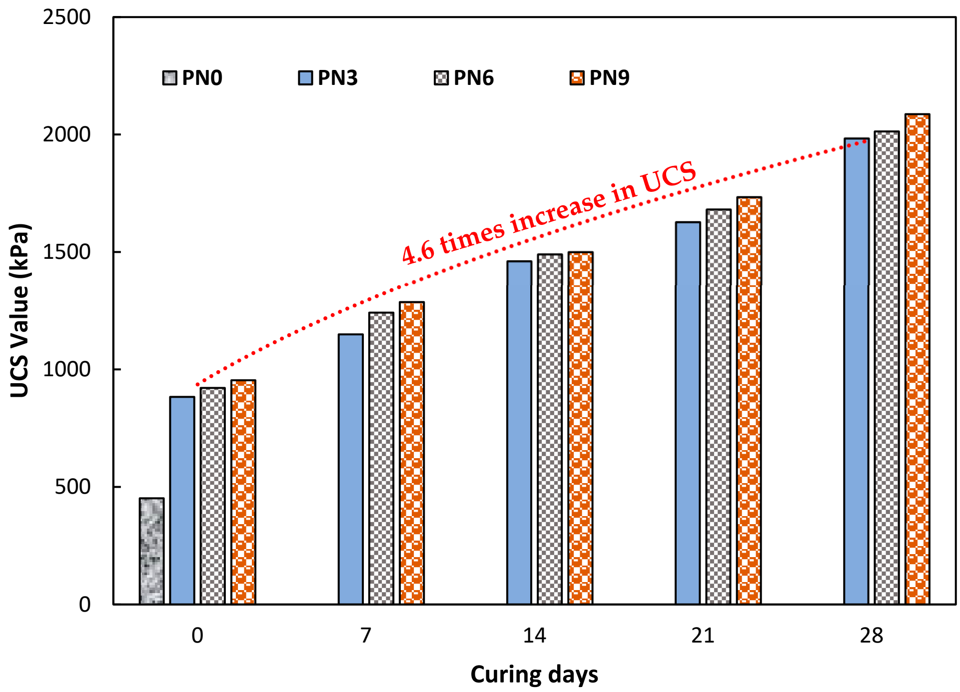


(**a**)



(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. UCS test results of soil samples reinforced with different percentages of nano silica and (**a**) 5% plantain leaf ash, (**b**) 10% plantain leaf ash, and (**c**) 15% plantain leaf ash.

Increasing the nano silica and plantain leaf ash enhances the compressive strength of the soil. Bahmani et al.'s [48] study utilized up to 1.2% nano silica and analyzed that the maximum improvement in compressive strength was observed at 28 days. Ghavami, Naseri, Jahanbakhsh, and Nejad [3] conducted another study, employing nano silica and silica fumes to analyze the enhancement in the strength properties of clayey soil. The analysis revealed that the maximum improvement in compressive strength occurred when using 1% nano silica and 15% silica fumes after 28 days. The study carried out by Bahmani et al. [49] analyzed an increase in compressive strength of up to 80% by utilizing nano silica in cement-stabilized soil. Incorporating leaf ash into soil provides stabilizing properties due to its richness in organic compounds and minerals [50]. Compressive strength is increased as a result of improved soil compaction, decreased flexibility, and increased soil particle binding capacity [51–53]. The tiny particle size of nano silica allows it to micro-fill in the spaces between soil particles, strengthening the structure of the soil. It improves the soil's overall stability and compressive strength by forming a denser matrix [54,55].

The Supplementary Data provide a comparative analysis of plantain leaf ash and nano silica incorporated into the soil, as depicted in Figures S2 and S3 and Tables S1 and S2.

Figure 5 displays the failure of the unreinforced sample and the sample reinforced with 1.2% nano silica and 15% plantain leaf ash at 28 days. The sample exhibits a bulging failure on the first day; this occurs because the soil lacks internal support to withstand the applied stress uniformly, leading to lateral expansion and deformation [56], whereas the sample at 28 days reinforced with 1.2% nano silica and 15% plantain leaf ash shows shear failure in the UCS test. This phenomenon is attributed to the reinforcement's ability to provide lateral confinement and internal support, effectively resisting bulging and promoting a more defined failure plane [57].

(**a**) (**b**)

Figure 5. Failure of soil sample in UCS test: (**a**) unreinforced and (**b**) reinforced with 1.2% nano silica and 15% plantain leaf ash at 28 days.

3.3. Effect of Nano Silica and Plantain Leaf Ash on Shear Strength Parameters

A direct shear test was performed to assess the shear strength parameters of the samples. Table 6 illustrates the enhancement in shear strength parameters due to the incorporation of nano silica and plantain leaf ash. The unreinforced soil displays a cohesion of 13.6 kPa and a frictional angle of 18.7°. With the addition of 0.4% nano silica and a 5% increment in plantain leaf ash, there is a maximum improvement in cohesion of about 2 times and in the frictional angle by approximately 1.2 times when utilizing 15% plantain leaf ash. Increasing the nano silica to 0.8% with the same 5% increment in plantain leaf ash results in a cohesion enhancement of about 3.1 times and a frictional angle improvement of around 1.3 times with 15% plantain leaf ash. At 1.2% nano silica with a 5% incremental rise in plantain leaf ash, the maximum enhancement in cohesion reaches about 3.3 times, while the frictional angle improves by about 1.6 times at 15% plantain leaf ash. Kalhor et al.'s [58] study analyzed how, by increasing the nano silica up to 3%, there was an increase in both the friction angle and cohesion of the soil. The study conducted by Changizi and Haddad [59] analyzed how, by using up to 1% nano silica, there was an increase in the shear strength parameters of cohesive soil. Another study indicated that utilizing carbon fiber and up to 3% nano silica increases the shear strength parameters of silty soil [60], while the study carried out by Inim et al. [61] analyzed how a 5% increment in bamboo leaf ash increased both the cohesion and the frictional angle value. Meanwhile, another study utilized up to 2% leaf ash with plastic and analyzed the improvement in the shear strength parameters of soil [62]. The addition of plantain leaf ash and nano silica is advantageous for expansive soil, enhancing its engineering properties [4]. Rich in minerals and silica, plantain leaf ash strengthens soil bonding and increases the soil's frictional angle. Nano silica fills spaces between soil particles, enhancing cohesion and overall strength [63,64]. By using these procedures together, the soil's susceptibility to changes in moisture content may be decreased.

Table 6. Improvement in shear strength parameters in soil reinforced with nano silica and plantain leaf ash.

Sample Designation	Nano Silica (%)	Plantain Leaf Ash (%)	Frictional Angle (°)	Cohesion (kPa)
PN0	0	0	18.7	13.6
PN1	0.4	5	19.3	18.1
PN2		10	21.1	24.7
PN3		15	21.9	26.8
PN4	0.8	5	22.6	32.5
PN5		10	23.1	38.3
PN6		15	24.2	42.9
PN7	1.2	5	25.7	38.4
PN8		10	28.6	43.7
PN9		15	29.2	45.2

3.4. Effect of Nano Silica and Plantain Leaf Ash on CBR

Figure 6a depicts the CBR test results for unsoaked samples reinforced with 0.4% nano silica, exhibiting a 5% increment in plantain leaf ash. It was observed that there was a maximum improvement of approximately 4.4 times the initial CBR value of unreinforced soil, which is 7%, achieved by adding 0.4% nano silica and 15% plantain leaf ash (PN3). Figure 6b displays the CBR test outcomes for unsoaked samples reinforced with 0.8% nano silica, accompanied by a 5% increment in plantain leaf ash. It was noted that a maximum improvement of about 4.8 times compared to the initial CBR value of unreinforced soil (which is 7%) was seen in PN6. Furthermore, Figure 6c exhibits the CBR test results for unsoaked samples reinforced with 1.2% nano silica, along with a 5% increment in plantain leaf ash. In this case, a maximum improvement of approximately 5.8 times the initial CBR value of unreinforced soil (which is 7%) was observed in the PN9 sample type. Patro and Sahoo [65] noted a similar observation, employing nano silica at a concentration of up to 1.5% to analyze the enhancement in the CBR of soil. Another study, conducted by Alireza et al. [66], demonstrated that utilizing the optimum combination of 5% lime and 3% nano silica significantly increased the CBR value of the weak soil. One study utilized both fly ash and nano silica and observed an improvement in the CBR value of the soil [67]. Munda, Padhi, and Mohanty's [36] study revealed that the CBR value of unsoaked samples increased by 5.1 times when employing nano silica and fly ash in expansive soil. Eshaghzadeh et al.'s [68] study indicated that an increase in nano silica in fiber-reinforced soil has a negative impact on the CBR value of silty sand. An increase in the amount of nano silica and plantain leaf ash leads to an enhancement in the bearing capacity of the soil.

Figure 7 displays the results of the swell potential via the soaked CBR test. An increase in nano silica and plantain leaf ash resulted in a decrease in the swell potential of expansive soil. The maximum reduction in swell potential of 74% was observed in PN9 soil after 28 days. Because of the small size of its particles, nano silica can fill in the spaces between the particles in the soil, minimizing the amount of space between them and preventing water from interacting with the larger clay particles [69,70]. Because of this, the soil absorbs less water, which lowers the possibility of swell. However, the pozzolanic qualities of plantain leaf ash are well known. When combined with calcium hydroxide in the presence of water, these capabilities produce more binding compounds [29,71–73]. Soil is strengthened and stabilized as a result, and it is less likely to expand when it becomes moist. By improving soil microstructure, reducing water permeability, and enhancing soil stability, the combined effects of nano silica and plantain leaf ash reduce the potential for swell. Figure 8 depicts the CBR test results of soil samples, showing both the soaked and unsoaked conditions.

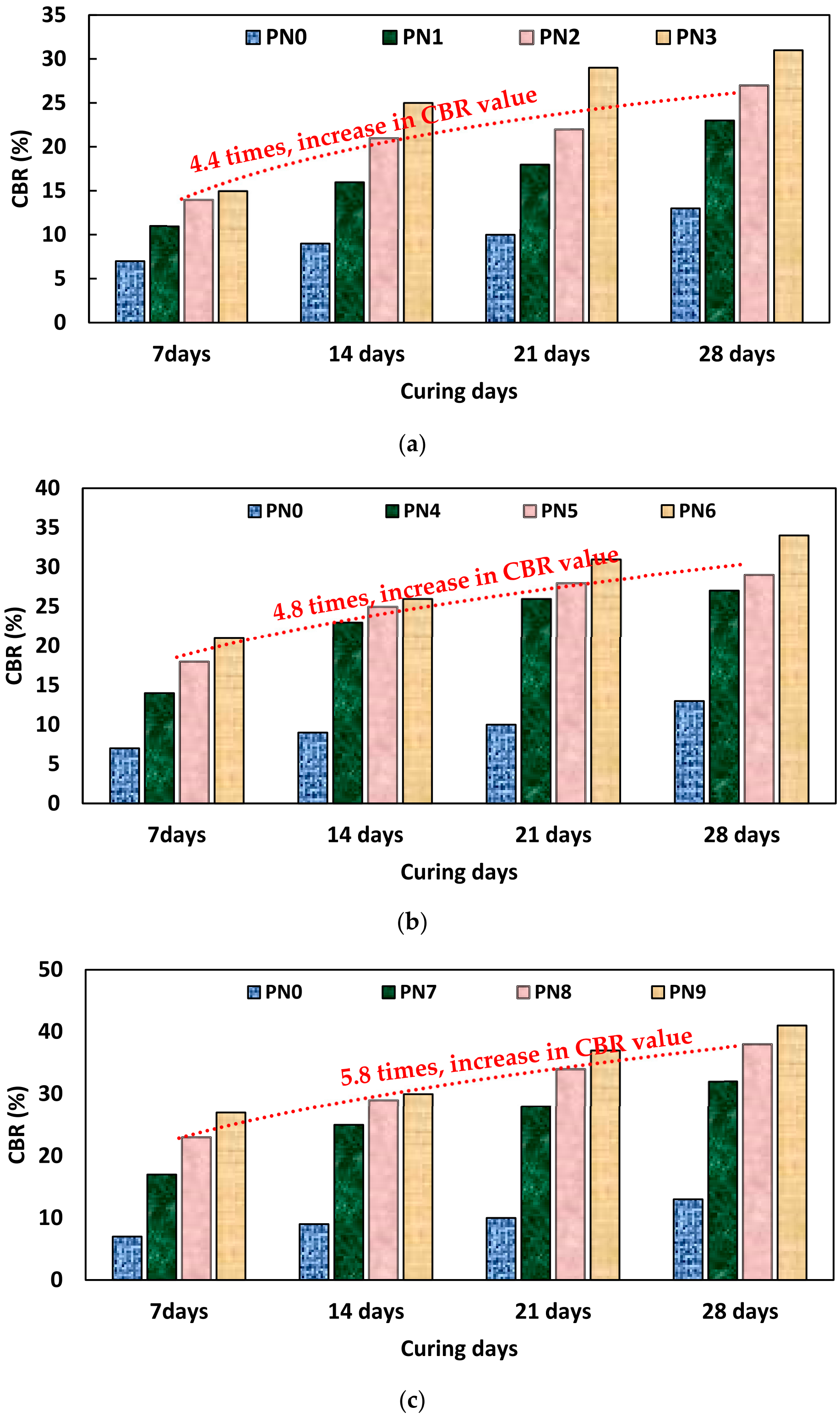


Figure 6. CBR test results for unsoaked samples reinforced with (**a**) 0.4% nano silica, (**b**) 0.8% nano silica, and (**c**) 1.2% nano silica.

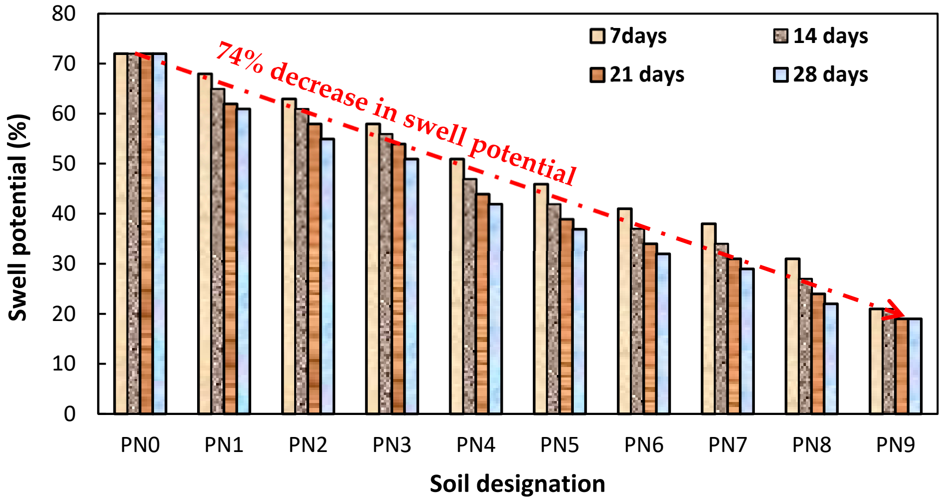


Figure 7. Comparison of swell potential in soaked CBR tests.

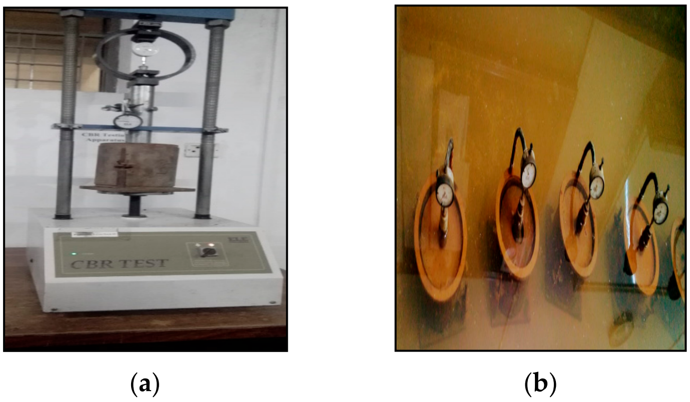


Figure 8. CBR test for soil samples: (**a**) unsoaked and (**b**) soaked.

3.5. Effect of Nano Silica and Plantain Leaf Ash on Microstructure Analysis

The SEM (Scanning Electron Microscope) test results most likely show a loose, uneven, and unstable soil structure in Figure 9a, which depicts expansive soil without reinforcement. The expansive clay minerals in the soil are easily identified, giving rise to the soil's tendency to expand and contract in response to variations in moisture. Comparing Figure 9b to Figure 9a, which shows expansive soil reinforced with nano silica, the SEM results indicate a more compacted and organized look. It is possible to see nano silica particles forming a network or link that strengthens the soil matrix between soil particles. The increased cohesiveness and decreased swelling potential as a result of this reinforcement produce a more stable and organized soil microstructure. A further improved soil structure is shown in Figure 9c, which shows expansive soil reinforced by a combination of nano silica and plantain leaf ash. The combined action of nano silica and plantain leaf ash may result in a more refined and interconnected network, as shown in the SEM pictures. As a supplemental element, plantain leaf ash helps to promote compaction and reinforce the soil structure. As a result, Figure 9c shows a well-organized, tightly packed soil matrix with fewer voids and greater stability.

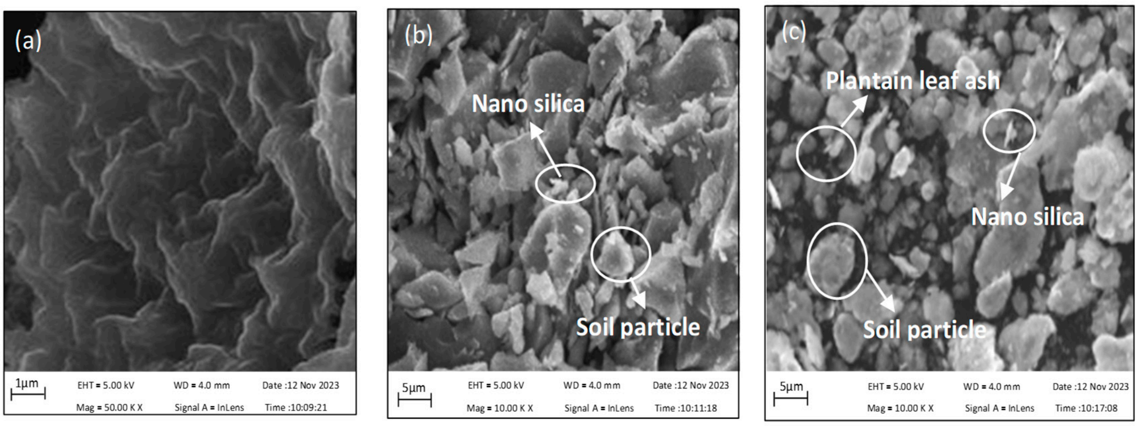


Figure 9. SEM test results (**a**) soil sample, (**b**) soil sample + 1.2% nano silica, and (**c**) soil sample + 1.2% nano silica + 15% plantain leaf ash.

4. Interaction Mechanism between Soil, Plantain Leaf Ash, and Nano Silica

Figure 10 shows the interaction mechanism of nano silica, plantain leaf ash, and soil. The stabilization of soil involves a physical and chemical interaction between plantain leaf ash, nano silica, and the soil. Rich in minerals like silica and potassium oxide, plantain leaf ash combines chemically with soil particles to form connections that improve soil cohesiveness when it is added to the soil [74]. Due to its high reactivity, nano silica interacts with soil constituents simultaneously to generate cementitious compounds, such as calcium silicate hydrates (C-S-H), which strengthen the soil's structure [75]. To improve soil strength and stability, plantain leaf ash and nano silica both help to change the way soil particles are arranged, fill in gaps, and increase soil density. Furthermore, ash's strength in increasing the soil's cation exchange capacity enhances nutrient retention, and the combined action of these additions lessens soil swelling and plasticity [76]. When all of these activities come together, they create micro aggregates and improve soil particle adhesion, which promotes long-term stability and durability against weathering and erosion.

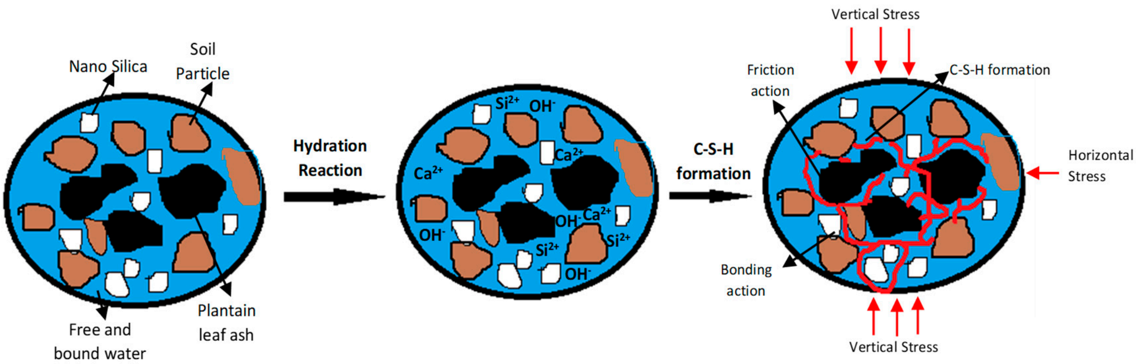


Figure 10. Interaction mechanism of nano silica, plantain leaf ash, and soil.

5. Conclusions

This study investigates the stabilization of expansive soil using a combination of nano silica and plantain leaf ash. The findings reveal that introducing up to 1.2%nano silica and up to 15% plantain leaf ash leads to a notable reduction in both the liquid and plastic limits of the soil, decreasing them by factors of 1.5 and 1.3, respectively. The observed reductions in both liquid and plastic limits signify a reduction in the soil's propensity for volumetric changes, thereby mitigating issues related to swelling and shrinkage.

Moreover, the UCS test results demonstrate significant enhancements in the soil's compressive strength. Specifically, incorporating 1.2% nano silica and 15% plantain leaf ash increases the compressive strength by up to 4.6 times compared to untreated soil over 28 days. The considerable increase in compressive strength highlights the enhanced load-bearing capacity of the stabilized soil.

Furthermore, improvements in the soil's shear strength parameters are observed. The cohesion of the soil increases by a maximum of about 3.3 times with the addition of 1.2% nano silica and 15% plantain leaf ash. Additionally, the frictional angle improves by up to 1.6 times when 1.2% nano silica and 15% plantain leaf ash are added to the untreated soil. It indicates the soil's increased resistance to shear stresses. This is particularly important in scenarios where the soil is subjected to lateral forces, such as those experienced in embankments.

In terms of the CBR test, the unsoaked condition reveals a substantial increase in bearing capacity, with the maximum improvement reaching about 5.8 times for the sample treated with 1.2% nano silica and 15% plantain leaf ash at 28 days. Furthermore, the soaked CBR test indicates a reduction in the swelling potential of up to 74% after the addition of nano silica and plantain leaf ash over the same period. The SEM analysis illustrates that the addition of nano silica and plantain leaf ash densifies the soil structure, indicating enhanced bonding within the sample. This densification suggests an improvement in the overall soil structure.

Nano silica, with its ultrafine particles, enhances the soil's mechanical properties by filling in pore spaces and increasing cohesion, thereby reducing swelling and improving stability. Plantain leaf ash, on the other hand, acts as a natural pozzolan, reacting with calcium hydroxide in the soil to form additional binding compounds, further enhancing strength and reducing susceptibility to volume changes. Together, the composite creates a synergistic effect, providing long-term stabilization.

The limitations of this study involve the economic feasibility of this study, alongside its sustainability. Future investigations could focus on optimizing the dosage and combination of stabilizing agents, assessing long-term performance under different environmental conditions, and evaluating the feasibility of large-scale implementation in real-world engineering projects. Additionally, comparative studies with conventional stabilization methods would provide valuable insights into the cost-effectiveness and sustainability of the proposed approach.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16052157/s1, Figure S1: Experimental apparatus; Figure S2: UCS test results of unreinforced soil and soil reinforced with 5, 10 and 15% Plantain leaf ash at 0 day; Figure S3: UCS test results of unreinforced soil and soil reinforced with 0.4, 0.8 and 1.2% Nano Silica at 0 day; Table S1: UCS test results of unreinforced soil and soil reinforced with 5, 10 and 15% Plantain leaf ash (PLA) at 0 day; Table S2: UCS test results of soil reinforced with 0.4, 0.8 and 1.2% Nano Silica (NS) at 0 day.

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References

1. Chen, F.H. *Foundations on Expansive Soils*; Elsevier: Amsterdam, The Netherlands, 2012; Volume 12.
2. Mohamad, N.; Muthusamy, K.; Embong, R.; Kusbiantoro, A.; Hashim, M.H. Environmental impact of cement production and Solutions: A review. *Mater. Today Proc.* **2022**, *48*, 741–746. [CrossRef]
3. Ghavami, S.; Naseri, H.; Jahanbakhsh, H.; Nejad, F.M. The impacts of nano-SiO_2 and silica fume on cement kiln dust treated soil as a sustainable cement-free stabilizer. *Constr. Build. Mater.* **2021**, *285*, 122918. [CrossRef]

4. Ezema, N.; Adinna, B.; Anayo, C. Effect of sugarcane bagasse ash and plantain leaf ash on geotechnical properties of clay soil from Efab Estate, Awka, Anambra State. *Niger. J. Technol.* **2022**, *41*, 949–954. [CrossRef]
5. Ijaz, N.; Dai, F.; Meng, L.; ur Rehman, Z.; Zhang, H. Integrating lignosulphonate and hydrated lime for the amelioration of expansive soil: A sustainable waste solution. *J. Clean. Prod.* **2020**, *254*, 119985. [CrossRef]
6. Kumar, A.; Walia, B.S.; Bajaj, A. Influence of fly ash, lime, and polyester fibers on compaction and strength properties of expansive soil. *J. Mater. Civ. Eng.* **2007**, *19*, 242–248. [CrossRef]
7. Wijaya, W.; Ismanti, S.; Rifa'i, A. Soft Clay Improvement Using Bamboo Leaf Ash on CBR Values. *J. Phys. Conf. Ser.* **2020**, *1625*, 012007. [CrossRef]
8. Khalid, B.; Alshawmar, F. Exploring the Feasibility of Using Recycled PET Strips with Palm Leaf Ash for Sustainable Soil Stabilization. *Sustainability* **2023**, *15*, 13542. [CrossRef]
9. Zada, U.; Jamal, A.; Iqbal, M.; Eldin, S.M.; Almoshaogeh, M.; Bekkouche, S.R.; Almuaythir, S. Recent advances in expansive soil stabilization using admixtures: Current challenges and opportunities. *Case Stud. Constr. Mater.* **2023**, *18*, e01985. [CrossRef]
10. Petry, T.M.; Little, D.N. Review of stabilization of clays and expansive soils in pavements and lightly loaded structures—History, practice, and future. *J. Mater. Civ. Eng.* **2002**, *14*, 447–460. [CrossRef]
11. Luo, X.; Kong, L.; Bai, W. Effect of Superhydrophobic Nano-SiO_2 on the Hydraulic Conductivity of Expansive Soil and Analysis of Its Mechanism. *Appl. Sci.* **2023**, *13*, 8198. [CrossRef]
12. Ghasabkolaei, N.; Choobbasti, A.J.; Roshan, N.; Ghasemi, S.E. Geotechnical properties of the soils modified with nanomaterials: A comprehensive review. *Arch. Civ. Mech. Eng.* **2017**, *17*, 639–650. [CrossRef]
13. Mostafa, A.; Ouf, M.S.; Elgendy, M. Stabilization of subgrade pavement layer using silica fume and nano silica. *Int. J. Sci. Eng. Res.* **2016**, *7*, 573–581.
14. Buazar, F. Impact of biocompatible nanosilica on green stabilization of subgrade soil. *Sci. Rep.* **2019**, *9*, 15147. [CrossRef] [PubMed]
15. Awadalseed, W.; Zhang, J.; Zhao, H. Experimental Study on Nano SiO_2 and Cement Modified Expansive Soil. In Proceedings of the GeoShanghai 2018 International Conference: Fundamentals of Soil Behaviours, Shanghai, China, 27–30 May 2018; Springer: Berlin/Heidelberg, Germany, 2018; pp. 209–217.
16. Al-Gharbawi, A.S.; Najemalden, A.M.; Fattah, M.Y. Expansive Soil Stabilization with Lime, Cement, and Silica Fume. *Appl. Sci.* **2022**, *13*, 436. [CrossRef]
17. Biswas, N.; Puppala, A.J.; Chakraborty, S. Role of Nano-and Crystalline Silica to Accelerate Chemical Treatment of Problematic Soil. *J. Geotech. Geoenviron. Eng.* **2023**, *149*, 04023044. [CrossRef]
18. Alshami, A.W.; Ismael, B.H.; Aswad, M.F.; Majdi, A.; Alshijlawi, M.; Aljumaily, M.M.; AlOmar, M.K.; Aidan, I.A.; Hameed, M.M. Compaction Curves and Strength of Clayey Soil Modified with Micro and Nano Silica. *Materials* **2022**, *15*, 7148. [CrossRef]
19. Eissa, A.; Bassuoni, M.; Ghazy, A.; Alfaro, M. Improving the properties of soft clay using cement, slag, and nanosilica: Experimental and statistical modeling. *J. Mater. Civ. Eng.* **2022**, *34*, 04022031. [CrossRef]
20. Akinwumi, I.; Onyeiwu, M.; Epelle, P.; Ajayi, V. Soil Improvement Using Blends of Coal Ash and Plantain Peel Ash as Road Pavement Layer Materials. *Resources* **2023**, *12*, 41. [CrossRef]
21. Naguib, H.M.; Hou, G. Exploitation of natural and recycled biomass resources to get eco-friendly polymer. *J. Polym. Environ.* **2023**, *31*, 533–540. [CrossRef]
22. Rahgozar, M.A.; Saberian, M.; Li, J. Soil stabilization with non-conventional eco-friendly agricultural waste materials: An experimental study. *Transp. Geotech.* **2018**, *14*, 52–60. [CrossRef]
23. Sharma, A.; Sharma, R. Sub-grade characteristics of soil stabilized with agricultural waste, constructional waste, and lime. *Bull. Eng. Geol. Environ.* **2021**, *80*, 2473–2484. [CrossRef]
24. Gidebo, F.A.; Yasuhara, H.; Kinoshita, N. Stabilization of expansive soil with agricultural waste additives: A review. *Int. J. Geo-Eng.* **2023**, *14*, 14. [CrossRef]
25. *ASTM D4318*; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International: West Conshohocken, PA, USA, 2017.
26. Mourhly, A.; Khachani, M.; Hamidi, A.E.; Kacimi, M.; Halim, M.; Arsalane, S. The synthesis and characterization of low-cost mesoporous silica SiO_2 from local pumice rock. *Nanomater. Nanotechnol.* **2015**, *5*, 35. [CrossRef]
27. Kho, K.; Hadinoto, K. Effects of excipient formulation on the morphology and aqueous re-dispersibility of dry-powder silica nano-aggregates. *Colloids Surf. A Physicochem. Eng. Asp.* **2010**, *359*, 71–81. [CrossRef]
28. Kong, D.; Corr, D.J.; Hou, P.; Yang, Y.; Shah, S.P. Influence of colloidal silica sol on fresh properties of cement paste as compared to nano-silica powder with agglomerates in micron-scale. *Cem. Concr. Compos.* **2015**, *63*, 30–41. [CrossRef]
29. Ugwu, J.; Ugwuanyi, D. Sustainability Performance of Plantain Leaf Ash and the Compressive Strength of Concrete. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Thessaloniki, Greece, 2020; p. 012112.
30. *ASTM D2487*; Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International: West Conshohocken, PA, USA, 2017.
31. *ASTM D2166*; Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International: West Conshohocken, PA, USA, 2006.
32. *ASTM D4546*; Standard Test Methods for One-Dimensional Swell or Collapse of Soils. ASTM International: West Conshohocken, PA, USA, 2021.

33. *ASTM D854*; Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method. ASTM International: West Conshohocken, PA, USA, 2023.
34. *ASTM D1557*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2700 kN-m/m^3)). ASTM International: West Conshohocken, PA, USA, 2021.
35. Wang, J.; Liu, M.; Wang, Y.; Zhou, Z.; Xu, D.; Du, P.; Cheng, X. Synergistic effects of nano-silica and fly ash on properties of cement-based composites. *Constr. Build. Mater.* **2020**, *262*, 120737. [CrossRef]
36. Munda, J.; Padhi, J.; Mohanty, S. Investigation on performance of expansive soil stabilized with fly ash and nano-SiO_2. *Mater. Today: Proc.* **2022**, *67*, 1268–1275. [CrossRef]
37. Munawar, M.; Khan, A.H.; Rehman, Z.U.; Rahim, A.; Aziz, M.; Almuaythir, S.; El Kheir, B.S.; Haider, F. Micro to Nanolevel Stabilization of Expansive Clay Using Agro-Wastes. *Adv. Civ. Eng.* **2023**, *2023*, 2753641. [CrossRef]
38. Kulanthaivel, P.; Selvakumar, S.; Soundara, B.; Kayalvizhi, V.; Bhuvaneshwari, S. Combined effect of nano-silica and randomly distributed fibers on the strength behavior of clay soil. *Nanotechnol. Environ. Eng.* **2022**, *7*, 23–34. [CrossRef]
39. Ishola, K.; Olawuyi, O.; Bello, A.; Yohanna, P. Effect of plantain peel ash on the strength properties of tropical red soil. *Niger. Res. J. Eng. Environ. Sci.* **2019**, *4*, 447–459.
40. *ASTM D3080*; Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. ASTM International: West Conshohocken, PA, USA, 2004.
41. Zumrawi, M.M.; Mohammed, L.A. Correlation of placement conditions and soil intrinsic properties with shear strength of cohesive soils. In Proceedings of the 7th Annual Conference for Postgraduate Studies and Scientific Research-Basic Sciences and Engineering Studies, Khartoum, Sudan, 20–23 February 2016.
42. Smalley, I.J. Cohesion of soil particles and the intrinsic resistance of simple soil systems to wind erosion. *J. Soil Sci.* **1970**, *21*, 154–161. [CrossRef]
43. Pul, S.; Ghaffari, A.; Öztekin, E.; Hüsem, M.; Demir, S. Experimental Determination of Cohesion and Internal Friction Angle on Conventional Concretes. *ACI Mater. J.* **2017**, *114*, 407. [CrossRef]
44. *ASTM D1883*; Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. ASTM International: West Conshohocken, PA, USA, 2021.
45. *ASTM E2809-22*; Standard Guide for Using Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy (SEM/EDS) in Forensic Polymer Examinations. ASTM International: West Conshohocken, PA, USA, 2022.
46. Jassim, N.W.; Hassan, H.A.; Mohammed, H.A.; Fattah, M.Y. Enhancement consistency and compaction characteristics of clayey soil using nano silica material. *Period. Eng. Nat. Sci.* **2023**, *10*, 77–83. [CrossRef]
47. Gao, Y.; Zhou, W.; Zeng, W.; Pei, G.; Duan, K. Preparation and flexural fatigue resistance of self-compacting road concrete incorporating nano-silica particles. *Constr. Build. Mater.* **2021**, *278*, 122380. [CrossRef]
48. Bahmani, S.H.; Farzadnia, N.; Asadi, A.; Huat, B.B. The effect of size and replacement content of nanosilica on strength development of cement treated residual soil. *Constr. Build. Mater.* **2016**, *118*, 294–306. [CrossRef]
49. Bahmani, S.H.; Huat, B.B.; Asadi, A.; Farzadnia, N. Stabilization of residual soil using SiO_2 nanoparticles and cement. *Constr. Build. Mater.* **2014**, *64*, 350–359. [CrossRef]
50. Nnochiri, E.S.; Ogundipe, O.M.; Ola, S.A. Geotechnical and microstructural properties of cement-treated laterites stabilized with rice husk ash and bamboo leaf ash. *Acta Polytech.* **2021**, *61*, 722–732. [CrossRef]
51. Mim, N.J.; Meraz, M.M.; Islam, M.H.; Farsangi, E.N.; Mehedi, M.T.; Arafin, S.A.K.; Shrestha, R.K. Eco-friendly and cost-effective self-compacting concrete using waste banana leaf ash. *J. Build. Eng.* **2023**, *64*, 105581. [CrossRef]
52. Amin, M.; Tayeh, B.A.; Kandil, M.A.; Agwa, I.S.; Abdelmagied, M.F. Effect of rice straw ash and palm leaf ash on the properties of ultrahigh-performance concrete. *Case Stud. Constr. Mater.* **2022**, *17*, e01266. [CrossRef]
53. Bello, A.A.; Ige, J.; Ibitoye, G.I. Geotechnical Properties of Lateritic Soil Stabilized with Cement-Bamboo Leaf Ash Admixture. *Int. J. Appl. Eng. Res.* **2014**, *9*, 9655–9665.
54. Shahin, S.S.; Fayed, L.; Ahmad, E.H. Review of Nano Additives in Stabilization of Soil. In Proceedings of the 7th International Conference on Nano-Technology in Construction, Sharm El-Sheikh, Egypt, 27–31 March 2015; pp. 1–11.
55. Kulanthaivel, P.; Soundara, B.; Velmurugan, S.; Naveenraj, V. Experimental investigation on stabilization of clay soil using nano-materials and white cement. *Mater. Today Proc.* **2021**, *45*, 507–511. [CrossRef]
56. Rajabi, A.M.; Ghorashi, S.; Yeganeh, M.M. The effect of polypropylene and glass fibers on strength and failure behavior of clayey sand soil. *Arab. J. Geosci.* **2023**, *16*, 6. [CrossRef]
57. Mirzababaei, M.; Miraftab, M.; Mohamed, M.; McMahon, P. Unconfined compression strength of reinforced clays with carpet waste fibers. *J. Geotech. Geoenviron. Eng.* **2013**, *139*, 483–493. [CrossRef]
58. Kalhor, A.; Ghazavi, M.; Roustaei, M. Impacts of nano-silica on physical properties and shear strength of clayey soil. *Arab. J. Sci. Eng.* **2022**, *47*, 5271–5279. [CrossRef]
59. Changizi, F.; Haddad, A. Effect of nano-SiO_2 on the geotechnical properties of cohesive soil. *Geotech. Geol. Eng.* **2016**, *34*, 725–733. [CrossRef]
60. Cui, H.; Jin, Z.; Bao, X.; Tang, W.; Dong, B. Effect of carbon fiber and nanosilica on shear properties of silty soil and the mechanisms. *Constr. Build. Mater.* **2018**, *189*, 286–295. [CrossRef]
61. Inim, I.J.; Affiah, U.E.; Eminue, O.O. Assessment of bamboo leaf ash/lime-stabilized lateritic soils as construction materials. *Innov. Infrastruct. Solut.* **2018**, *3*, 32. [CrossRef]

62. Yathushan, V.; Puswewala, U.G.A. Effectiveness of Pozzolanic Leaf Ashes and Plastics on Geotechnical Characteristics. *Int. J. Eng. Technol. Innov.* **2022**, *12*, 155–166. [CrossRef]
63. Maduka, E.J. *Geotechnical Properties of Lateritic Soil–Bentonite Mixture Treated with Bamboo Leaf Ash*; NAU Department of Civil Engineering Final Year Project & Postgraduate Portal; Nnamdi Azikiwe University: Awka, Nigeria, 2023; Volume 2.
64. Ishola, K.; Olawuyi, O.; Kareem, M. Compaction Characteristics of the Lateritic Soil-Mango Leaf Ash Admixed. *UNIOSUN J. Eng. Environ. Sci.* **2019**, *1*, 96–102. [CrossRef]
65. Patro, A.; Sahoo, R.R. Strength and Microstructure Evolution of Soft Soils by Using Nano-silica. In *Ground Characterization and Foundations: Proceedings of Indian Geotechnical Conference 2020 Volume 1*; Springer: Singapore, 2022; pp. 315–325.
66. Alireza, S.G.S.; Mohammad, M.S.; Hasan, B.M. Application of nanomaterial to stabilize a weak soil. In Proceedings of the 7th Conference of the International Conference on Case Histories in Geotechnical Engineering, Chicago, IN, USA, 2 May 2013.
67. Kulkarni, P.P.; Mandal, J.N. Performance assessment of stabilized soil with fly ash-nano material mixes. *J. Geotech. Transp. Eng.* **2017**, *3*, 35–46.
68. Eshaghzadeh, M.; Bayat, M.; Ajalloeian, R.; Hejazi, S.M. Mechanical behavior of silty sand reinforced with nanosilica-coated ceramic fibers. *J. Adhes. Sci. Technol.* **2021**, *35*, 2664–2683. [CrossRef]
69. Pham, H.; Nguyen, Q.P. Effect of silica nanoparticles on clay swelling and aqueous stability of nanoparticle dispersions. *J. Nanopart. Res.* **2014**, *16*, 2137. [CrossRef]
70. Omurlu, C.; Pham, H.; Nguyen, Q. Interaction of surface-modified silica nanoparticles with clay minerals. *Appl. Nanosci.* **2016**, *6*, 1167–1173. [CrossRef]
71. Ettu, L.; Mbarjiogu, S.; Arimanwa, J. Strength of blended cement sandcrete and soilcrete blocks containing cassava waste ash and plantain leaf ash. *Am. J. Eng. Res.* **2013**, *2*, 55–60.
72. Ettu, L.; Ezeh, J.; Anya, U.; Arimanwa, J.; Nwachukwu, K. Strength of binary blended cement composites containing plantain leaf ash. *IOSR J. Eng* **2013**, *3*, 54–59. [CrossRef]
73. Ettu, L.; Nwachukwu, K.; Arimanwa, J.; Awodiji, C.; Opara, H. Strength of Ternary Blended Cement Concrete Containing Oil Palm Bunch Ash and Plantain Leaf Ash. *Int. J. Comput. Eng. Res.* **2013**, *3*, 64–68.
74. Yerima, B.P.; Van Ranst, E. *Introduction to Soil Science: Soils of the Tropics*; Trafford Publishing: Victoria, BC, Canada, 2005.
75. Ramezanianpour, A.A.; Mortezaei, M.; Mirvalad, S. Synergic effect of nano-silica and natural pozzolans on transport and mechanical properties of blended cement mortars. *J. Build. Eng.* **2021**, *44*, 102667. [CrossRef]
76. Atahu, M.K. *The Effect of Coffee Husk Ash on Geotechnical Properties of Expansive Soil*; Universität Rostock: Rostock, Germany, 2020.