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Research Article

Effect of Selected Nanospheres on the Mechanical Strength of Lime-Stabilized High-Plasticity Clay Soils

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The proper design of protective structures may start from improving the characteristics of soils. In order to obtain reasonable safety criteria, several research studies have recently been dedicated to enhancing complex civil engineering structural systems with the use of nanotechnology. Thus, the following paper investigates the effect of nanospheres, including nanosilica (nano-SiO_2) and nano zinc oxide (nano-ZnO), on lime-stabilized high-plasticity clay soil. For this purpose, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were performed on samples. The results showed that the use of the selected nanospheres greatly increased the UCS of the samples compared to untreated soil. The UCS value of samples containing 6% lime and 1.5% nano-ZnO after 28 days of treatment increased by 5-fold compared to the UCS of untreated samples. In addition, the samples containing 6% lime and 2% nano-SiO_2, with similar curing conditions, experienced a 5.3-fold increase in their UCS value compared to the untreated samples. These compounds were considered as the optimal amounts and showed the highest mechanical strength in both UCS and CBR tests. The same trend was achieved in the CBR test, in which the CBR value for the optimal mixtures containing nano-ZnO and nano-SiO_2 was 14.8 and 16.6 times higher than that of high-plasticity clay soil, respectively. Finally, the results obtained from scanning electron microscopy (SEM) analysis revealed that the nanospheres caused a dense and compact matrix to form in the soil, which led to the enhancement of the mechanical strength of the treated samples.

1. Introduction

When designing protective structures, high-plasticity clay soils, which are widely scattered throughout the world, are very problematic. This is mainly due to the fact that they are highly sensitive after being exposed to moisture. The presence of these soils in construction projects should be specifically addressed and treated if necessary due to their undesirable behaviour such as swelling, shrinkage, dispersion, low mechanical strength, and high level of settlement [1–3]. To overcome such problems, several approaches are available to treat them, including the use of geosynthetics, piles, electroosmosis techniques, and stabilization [4–14]. These methods can lead to increased mechanical strength, reduced settlement, and controlled swelling or shrinking of soils, as well as providing a suitable site for the construction of structures. Among these methods, stabilization with the use of chemical additives, most notably lime and cement, is considered as one of the most effective techniques to improve the characteristics of soil [15–18].

In the past few decades, many studies have been conducted on the chemical stabilization of soils using these traditional materials [19–26]. The use of such stabilizers increases the soil pH up to about 12, which in turn provides long-term reactions. Khemissa and Mahamedi [27] determined the physicochemical and mechanical parameters of high-plasticity clay stabilized with a mixture of Portland cement and extinct lime. They found that the geotechnical parameters are consistent and confirmed the enhancement of the bearing capacity of high-plasticity clay soil, which is interpreted by a substantial increase in its mechanical strength and durability. A summary of recent studies on soil stabilization by other researchers is presented in Table 1. Despite ongoing research on soil stabilization with traditional materials, there is a need to find new and better performing materials to replace conventional additives.

In order to obtain reasonable safety criteria, several research studies have recently been dedicated to enhancing complex civil engineering structural systems using nanotechnology. Nanodimension stabilizers are highly effective in soil stabilization from both physical and chemical viewpoints. Nanospheres have a particularly high specific surface area and are therefore more involved in chemical reactions [31]. Moreover, the very fine particles of nanospheres may improve the characteristics of soil [37].

Nano-SiO_2 and nano-ZnO are two types of additives that have very good properties in combination with soil. In recent years, these nanospheres have attracted great research interest because of their high pozzolanic activity in cement-based systems. According to Mostafa et al. [38], the addition of nano- and micro-SiO_2 to lime-stabilized soil improved its mechanical strength values and its compressive strength increased with a lower nano-SiO_2 content compared to silica fume. Saleh et al. [39] showed that the addition of nano-SiO_2 and nano-ZnO improves soil behaviour. Similar results have been reported by other researchers when using these materials, as can be seen in Table 1. Despite the numerous studies on the use of these materials in soil stabilization, less attention has been paid to their combination with lime. In addition, it should be noted that the application of these effective additives on the mechanical properties of high-plasticity clay soils has not yet been investigated.

The high-plasticity clay soil in the present study does not have a sufficient mechanical strength and causes severe damage to a construction built on it due to the weak structure of soil particles. Therefore, finding a reliable and practical technique was the main goal of this research. In this study, the effect of nano-SiO_2 and nano-ZnO on the mechanical strength parameters of high-plasticity clay soil stabilized with lime was investigated and their microstructural changes were carefully considered. For this purpose, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests were performed on samples. In addition, scanning electron microscopy (SEM) analysis was applied to observe the microstructural properties.

2. Materials and Methods

2.1. Properties of High-Plasticity Clay Soil. The high-plasticity clay soil that was used in this study was collected from a depth of 1 m at an excavation site within the University of Guilan (5th kilometer of the Rasht-Tehran road). Based on the UCS value obtained from the studied clay (174.55 kPa), it was stated that the soil of this region exhibits very low strength and consequently would not withstand the loads imposed upon it. Moreover, the poor particle-size distribution shown in Figure 1 indicates the lack of mechanical strength of the soil and the necessity of soil stabilization before any further operations. Due to the low mechanical strength and high compressibility of soil in this region, the soil is considered to be problematic. Since the soil in this area is subjected to heavy loads during the construction of high-rise buildings, it is important to improve its mechanical strength properties. Figure 1 shows the particle-size distribution of the studied high-plasticity clay soil according to ASTM D2487-11 [40]. Some of the properties of the studied soil, determined based on ASTM D4318 [41], are presented in Table 2. Moreover, the standard compaction test was carried out according to ASTM D698 [42]; and the maximum dry density (MDD) and optimum moisture content (OMC) of the samples were 1470 kg/m^3 and 23%, respectively. The results of the chemical analysis obtained from X-ray fluorescence analysis are presented in Table 3.

2.2. Properties of Hydrated Lime. The hydrated lime used in this study was obtained from Qom Limestone Factory and contained about 51% quick lime (CaO) with particles finer than sieve No. 60 (0.250 mm). Table 4 shows the chemical properties of the lime, which were provided by the manufacturer.

2.2.1. Properties of the Studied Nanospheres. In this study, lime was replaced by 1, 1.5, and 2% of nanospheres including nano-SiO_2 and nano-ZnO with average sizes of 20–30 and 30–50 nm and surface areas of 220 m^2/g and 50 m^2/g, respectively. In this research, regardless of the specifications given by the nanomaterial manufacturer, the specific surface area of the nanospheres was measured by nitrogen adsorption at 77 K by using the Brunauer–Emmett–Teller (BET) method. The nanospheres were obtained from the Iranian Pishgaman Nanomaterial Company. In this study, particle-size distribution was calculated for each nanosphere sample from the SEM images by using ImageJ software. Then, the number of pixels occupied by the number of particles was counted. It should be noted that ImageJ software has been used for postprocessing and particle analysis by many researchers. Figure 2 shows the SEM microstructure and the particle size of nano-SiO_2 and nano-ZnO. The properties of both nanospheres are given in Table 5.

2.3. Description of Conducted Laboratory Tests

2.3.1. Sample Preparation Process. The results of previous studies have shown that the characteristics of soil improve to a certain extent, with the use of additives, and that higher amounts of them can have adverse effects on soil strength. In order to obtain the most favourable mixture of lime-nanospheres, the ratio of cementitious materials should be strongly considered due to the fact that the replacement of larger amounts of lime-nanospheres can lead to a poor mixture with lower strength. Therefore, the optimum amount of nanospheres as a substitute for lime can only be determined by trial and error. By and large, based on the results of previous studies, the optimum amount of lime in

Table 1: Examples of recent soil stabilization research.

Reference	Soil type	Stabilizer type	Curing time (days)	Tests
Yi et al. [28]	Soft high-plasticity clay	Lime, GGBS	7, 28, 90	UCS, MIP
Ghorbani et al. [22]	Sulfate silty sand	Lime, micro-SiO_2	7, 28	UCS, CBR
Choobbasti et al. [29]	Sandy soil	Cement, nano-SiO_2	7	UCS
Bahmani et al. [30]	High-plasticity clay soil	Cement, nano-SiO_2	7, 14, 28	UCS
Ghasabkolaei et al. [31]	High-plasticity clay soil	Cement, nano-SiO_2	7, 14, 28	UCS, CBR
Yoobanpot et al. [32]	Soft high-plasticity clay	Cement, fly ash residue	3, 7, 28, 90	UCS
Alnahhal et al. [33]	Sand	OPC, CKD, nano-CKD	7, 28, 56	UCS
García et al. [34]	Soft high-plasticity clay	Nano-SiO_2	—	UCS
Sharma et al. [25]	High-plasticity clayey sand	Lime, cement	1, 3, 7, 14, 21, 28	UCS, shear strength
Abbasi et al. [35]	Dispersive high-plasticity clayey soils	Nano-high-plasticity clay	1, 3, 7	Pinhole
Choobbasti et al. [36]	Sand	Cement, nano-SiO_2	7	UCS, triaxial

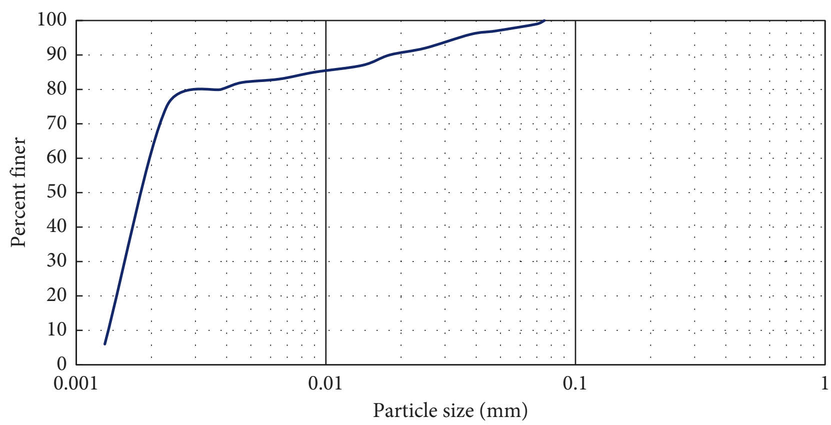


Figure 1: Particle-size distribution of the studied high-plasticity clay soil (obtained according to ASTM D2487-11 [40]).

Table 2: Physical properties and Atterberg limits of the studied high-plasticity clay soil.

Parameter	Value
G_s	2.7
Liquid limit (LL) (%)	62.5
Plastic limit (PL) (%)	30.11
Plasticity index (PI) (%)	32.39
Maximum dry density (MDD) (kg/m^3)	1470
Optimum moisture content (OMC) (%)	23
Unconfined compressive strength (UCS) (kPa)	174.55
Unsoaked California bearing ratio (CBR) (%)	4.9

Table 3: Chemical compositions of the studied high-plasticity clay soil (obtained from X-ray fluorescence analysis).

Formula	Content (%)
SiO_2	53.9
Al_2O_3	16.4
CaO	3.14
Fe_2O_3	8.8
MgO	2.0
K_2O	5.2
Na_2O	0.57
P_2O_5	0.1
TiO_2	0.79
Other particles	0.2
L.O.I	8.9

Table 4: Chemical compositions of hydrated lime (provided by the manufacturer).

Formula	Content (%)
K_2O	4
SO_3	0.8
MgO	2.65
CaO	51.64
Fe_2O_3	0.13
Al_2O_3	0.24
SiO_2	1.36
L.O.I	39.18

clay soil stabilization has been reported to be between 4 and 8 [23, 43–45], which is consistent with the specified values in this study. Thus, the amounts of 3, 6, and 9% by weight of lime were added to the soil to determine the optimum amount of lime. Based on the results, 6% lime content had the highest mechanical strength and was considered as the optimum value. Then, the amounts of 1, 1.5, and 2% by weight of nano-SiO_2 or nano-ZnO with the optimum amount of lime (6%) were added to the soil, as presented in Table 6. The dry soil and additives (lime and nanospheres) were stirred with about 50% of the total amount of water needed to obtain the optimum moisture content. After that, the soil and admixture were mixed manually and the remaining water was added to bring the sample to the

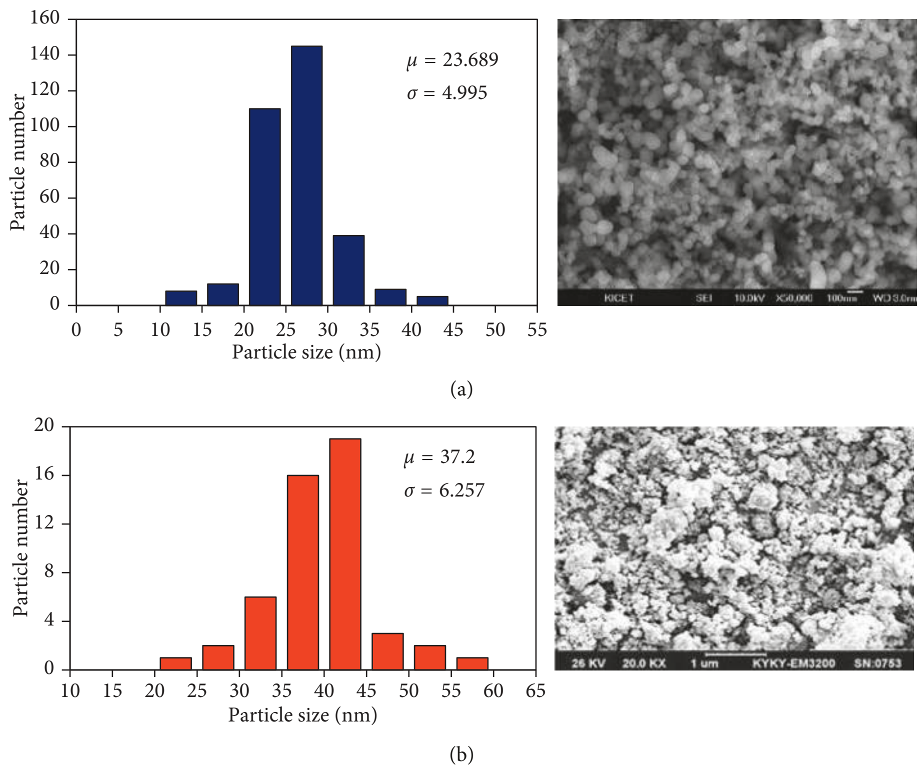


Figure 2: SEM microstructure and particle size of nanospheres: (a) nano-SiO_2 and (b) nano-ZnO.

Table 5: Selected properties of studied nanospheres.

Name of the property	Nano-SiO_2	Nano-ZnO
Color	White	White
Average particle sizes (nm)	20–30	30–50
pH	7	6
Specific surface area (SSA) (m^2/kg)	220000	50000
Purity (%)	98.31	99.14

Table 6: Mixture proportions of used materials.

Test no.	Lime (%)	Nano-SiO_2 (%)	Nano-ZnO (%)
1	3	0	0
2	6	0	0
3	9	0	0
4	6	1	0
5	6	1.5	0
6	6	2	0
7	6	0	1
8	6	0	1.5
9	6	0	2

Each test was performed three times.

desired moisture content. It should be noted that all the samples were prepared at maximum dry density and optimum moisture content. Finally, SEM analysis (model VEGA/TESCAN) was applied to the samples in order to observe changes in soil microstructure and to investigate the interaction between the soil and additives. For SEM observation, the samples were mounted on stubs with aluminum tape and then coated in a sputter coater with 20 nm of gold at an accelerating voltage of 10–15 kV.

2.3.2. Unconfined Compressive Strength. To carry out the unconfined compressive strength test according to ASTM D2166-91 [46], the soil, additives, and water were mixed with different proportions and then compacted into a mould in three layers with 25 blows/layer. The mould had a height and diameter of 9.8 and 4.9 cm, respectively. The samples were packed into airtight containers and stored at 25°C with respect to the curing time of 7, 14, and 28 days. The unconfined compressive strength (UCS) loading was carried out with a fixed displacement rate of 1 mm/min and continued until the initial failure of the samples. Figure 3 shows the cylindrical mould, the prepared samples, and the sample under loading in the UCS test.

2.3.3. California Bearing Ratio Tests. To carry out the unsoaked California bearing ratio (CBR) test according to ASTM D1883-16 [47], the dry soil and additives were mixed for each sample individually and then water was added to them to achieve the optimum moisture content. After that, they were thoroughly mixed to obtain uniform samples. A cylindrical mould with a diameter of 6 inches and a height of 4.8 inches was used to perform the tests. The compounds were placed into the mould in 5 layers so that each layer was packed with 56 blows of a 4.5 kg hammer dropped from a height of 457 mm, according to ASTM D1557 [48]. Then, the

(a) (b) (c)

Figure 3: Unconfined compressive strength test: (a) mould, (b) prepared samples, and (c) sample under loading.

mould containing the materials was placed in an airtight plastic bag to ensure that no moisture was lost. Finally, the mould was placed inside the CBR apparatus, and the test was conducted with a penetration rate of 1.27 mm/min after 7 days of treatment. According to Spanish legislation, the CBR index has been referred to as the only way of evaluating the bearing capacity of treated soil with chemical additives, and the minimum CBR index is considered to be higher than or equal to 20 after 7 days [49]. Therefore, a 7-day treatment was conducted in order to evaluate and compare the CBR results. Figure 4 shows the mould, the prepared samples after 7 days of curing, and the CBR apparatus used in the study.

3. Results and Discussion

3.1. Effect of Nanospheres on Unconfined Compressive Strength. Figure 5 illustrates the effect of lime on the unconfined compressive strength (UCS) of high-plasticity clay soil over curing time. As can be seen, the UCS increased and reached its maximum resistance with the addition of lime of up to 6%, whereas the UCS value was reduced for higher amounts of lime. The presence of lime in the samples increased the pH value of the soil and provided the conditions for long-term pozzolanic reactions. Moreover, the increase in curing time also resulted in an improved mechanical strength in all the samples, which was due to the completion of chemical reactions. The maximum strength was recorded as 876 kPa after 28 days of treatment for the sample containing 6% lime. Higher amounts of lime, however, reduce the UCS of the soil due to the lack of significant friction and low cohesion [50]. Moreover, the MDD and OMC values of untreated soil change as soon as additives are added to the soil. This may also affect the optimum lime content, and as a result, the UCS values reduce for a higher lime content. Finally, it can be concluded that the optimum amount of lime for pozzolanic reactions in the soil samples was determined to be 6%, and this amount was selected for subsequent experiments with nanospheres.

Figures 6 and 7 show the variations of soil UCS for various combinations of lime with nano-zinc and nano-SiO_2

(a) (b) (c)

Figure 4: California bearing ratio test: (a) mould, (b) samples after 7 days of curing, and (c) California bearing ratio test apparatus.

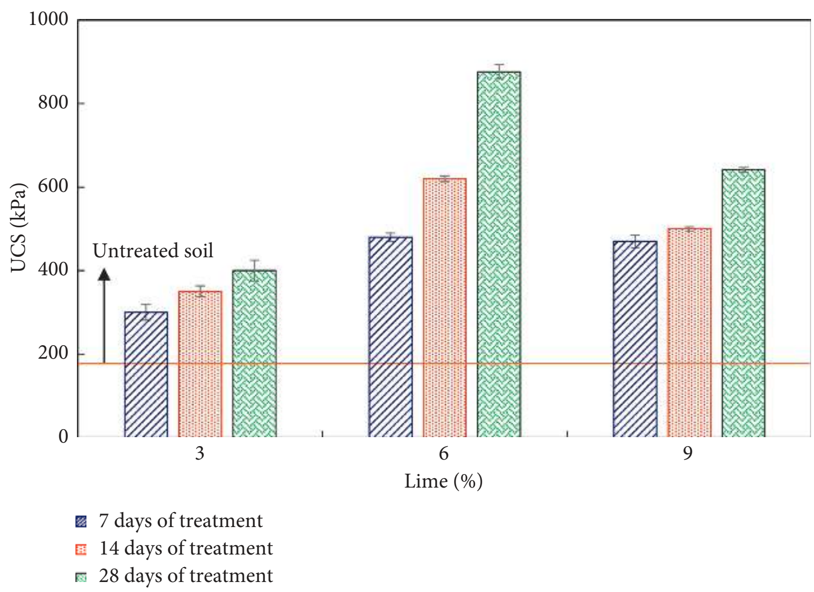


Figure 5: Effect of lime on the UCS of soil after a curing time of up to 28 days.

during different treatment periods, respectively. The UCS value increased in all the samples with the increase of curing time, and therefore, the sample containing 6% lime with 1% nano-ZnO had a strength equal to 867 and 500 kPa after 7 and 28 days of treatment, respectively. These values were equal to 881 and 598 kPa for the same samples of nano-SiO_2, respectively. Based on Figure 6, the addition of 1.5% of nano-ZnO to the samples increased the UCS to a maximum value. By adding further amounts of nano-ZnO, the strength decreased slightly. Therefore, the optimum amount of nano-ZnO in combination with 6% lime was reported as 1.5%, which resulted in a 5-fold increase after 28 days of treatment compared to the untreated soil. Moreover, the UCS increased by adding up to 2% of nano-SiO_2 to the optimum lime content (6%) so that it reached the highest level of 1000 kPa after 28 days of treatment, which is equivalent to an increase of about 5.3 times compared to that of untreated soil.

In general, the increase of UCS by adding different compounds can be attributed to short- and long-term reactions. Pozzolanic reactions lead to the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) gels that fill the voids and thus increase the UCS of the samples [51, 52]. Based on the Figures 6 and 7, the optimum value of nano-ZnO and nano-SiO_2 in combination with 6% lime was reported at 1.5 and 2%, respectively. Moreover, the results indicated a better performance of nano-SiO_2 than nano-ZnO.

3.2. Effect of Additives on CBR. In this study, the CBR test was performed after 7 days of treatment in order to more

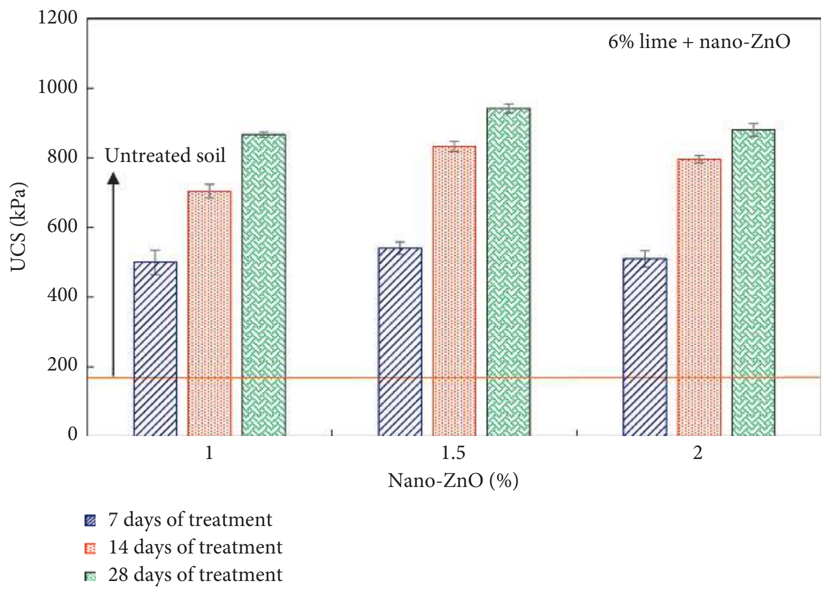


Figure 6: Effect of nano-ZnO on the UCS of lime-stabilized soil after a curing time of up to 28 days.

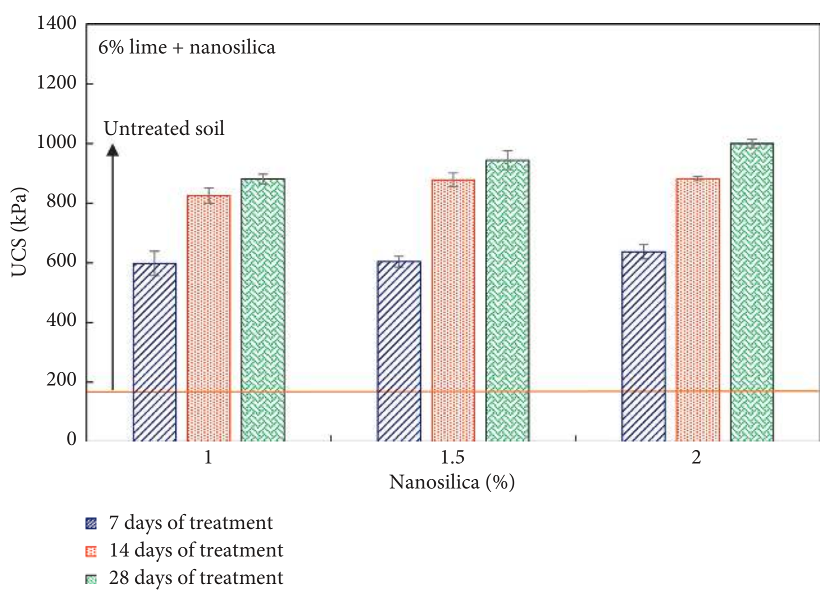


Figure 7: Effect of nano-SiO_2 on the UCS of lime-stabilized soil after a curing time of up to 28 days.

accurately evaluate the mechanical strength behaviour in all the samples. Figure 8 shows the results of the CBR for the lime-stabilized samples, and it can be seen that adding the lime increased the CBR, which demonstrated a peak for the lime content of 6%. The CBR value for this optimum amount of lime was reported at about 56.9%. Afterwards, the CBR value was reduced by adding more lime, which was similar to the trend of UCS values. A CBR of about 50% was obtained for the sample containing 9% lime, which was about 10 times higher than that of untreated soil.

For samples containing nano-ZnO, the CBR value increased with an increasing amount of nanospheres, as shown in Figure 9. The sample containing 1.5% of nano-ZnO exhibited the highest CBR (about 72.6%), which was consistent with the UCS test. Increasing the nano-ZnO content by more than 1.5% resulted in a decrease in the CBR value to about 62.8%. However, in the samples containing up to 2% nano-SiO_2 content, the amount of CBR continued to increase, reaching a peak of about 81.4%, as illustrated in Figure 10. This amount was reported to be about 74.3% and 77.9% for the content of 1% and 1.5% of nano-SiO_2, respectively, which showed a significant increase compared to the untreated soil. Similar to what was observed for the UCS, the performance of nano-SiO_2 was also slightly better than that of nano-ZnO.

3.3. Effect of Nanospheres on the Microstructure. In this study, the SEM technique was applied to monitor structural

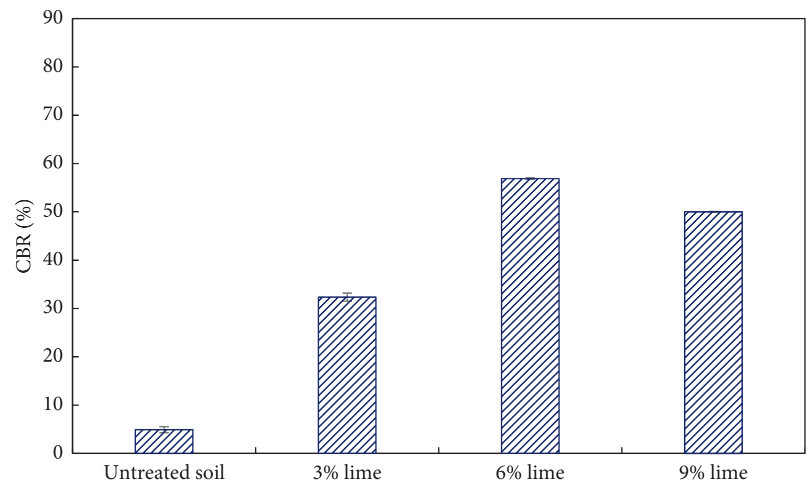


Figure 8: Effect of lime on the CBR of soil after 7 days of treatment.

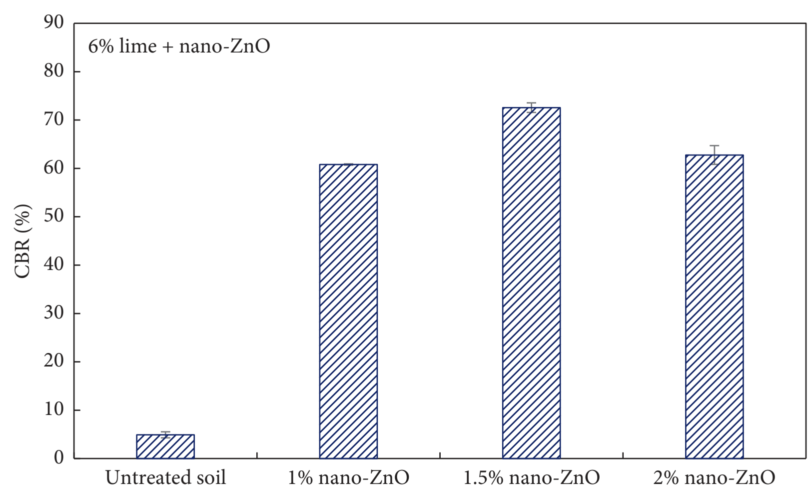


Figure 9: Effect of nano-ZnO on the CBR of lime-stabilized soil after 7 days of treatment.

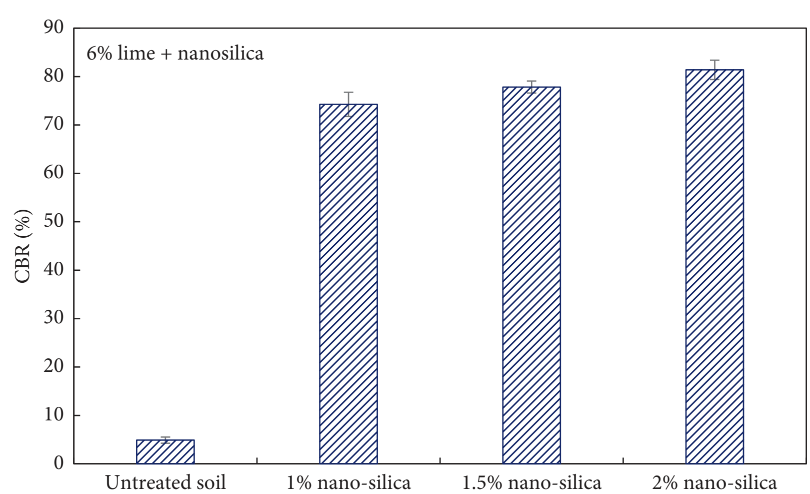
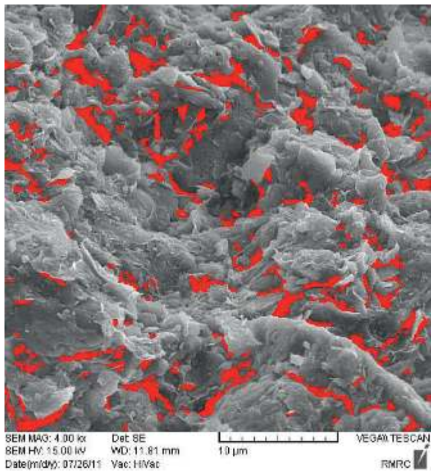
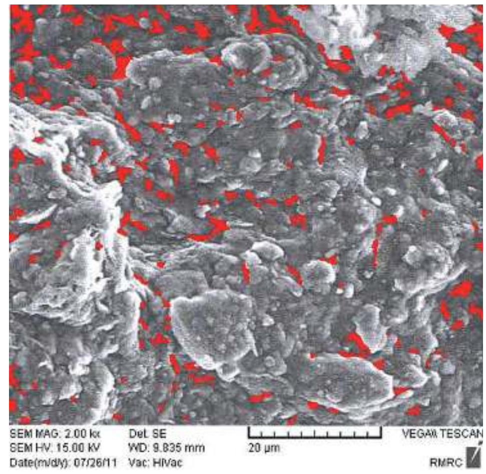


Figure 10: Effect of nano-SiO_2 on the CBR of lime-stabilized soil after 7 days of treatment.

changes and to better understand the interactions between the soil and additives. For this purpose, in addition to the untreated soil sample, two samples treated with additives that provided the highest mechanical strength (6% lime + 1.5% nano-ZnO and 6% lime + 2% nano-SiO_2) were analyzed. The SEM images of these three samples are shown



(a)



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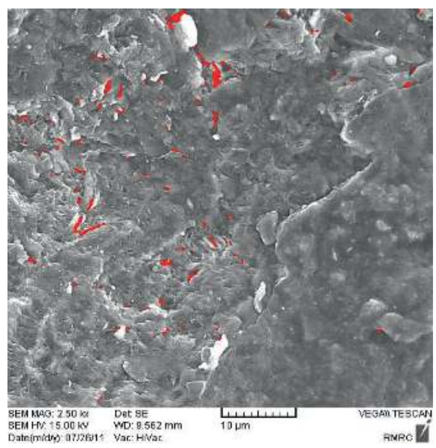

(c)

Figure 11: SEM micrographs: (a) the high-plasticity clay soil, (b) 6% lime + 1.5 nano-ZnO, and (c) 6% lime + 2% nano-SiO2.

in Figure 11 in such a way that the porosity is shown as red particles. As seen in Figure 11(a), the untreated soil texture is completely porous (about 9.03%), which leads to very poor results in UCS and CBR tests. Figure 11(b) shows that the increase of additive containing nano-ZnO to the untreated soil led to a decrease in porosity from 9.03% to 5.73%. This causes more friction between particles, resulting in much greater mechanical strength compared to the pure soil. Figure 11(c) shows the sample containing nano-SiO_2, which had the highest strength and the minimum porosity of approximately 0.82%. In this sample, the soil particles form a dense and compact matrix and are easily detected in the cementitious gel that covers the particles. On the one hand, nano-SiO_2 serves as a filler, and on the other hand, it acts as a very effective pozzolan with lime and improves the bond between particles [53, 54].

4. Conclusions

The purpose of this study was to evaluate the effect of nanoscale materials, including nano-ZnO and nano-SiO_2, on lime-stabilized high-plasticity clay soils. For this purpose, a series of UCS and CBR tests were performed on samples, and later, based on SEM images, soil microstructure changes before and after treatment were investigated. Nanospheres have a much higher surface area because of their very small size, and they therefore participate in the reactions and accelerate the formation of cementitious products. Moreover, these materials are placed between lime and soil particles and fill voids, which increases the mechanical strength of the samples. Based on the tests performed on various compounds, the following results were obtained:

(i) The addition of nano-ZnO and lime to soil increased UCS in such a way that the optimum nano-ZnO value in a mixture with 6% lime was reported to be 1.5%, which led to a 5-fold increment after 28 days of curing compared to that of untreated soil.

(ii) The addition of nano-SiO_2 to lime-stabilized soil resulted in an increased mechanical strength, meaning that a UCS value of about 1000 kPa was measured in the sample containing 6% lime + 2% nano-SiO_2 after 28 days of curing, which is equivalent to about 5.3 times that of the untreated soil.

(iii) In all the samples, an increased curing time resulted in an increased UCS, which can be attributed to the completion of long-term pozzolanic reactions and the formation of calcium silicate hydrate and calcium hydrate aluminate gels.

(iv) Based on the results obtained from the CBR test, it was found that the performance of nano-SiO_2 was slightly better than that of nano-ZnO. The CBR value was reported to be about 81.1% for the sample containing nano-SiO2, while the highest CBR value for the nano-ZnO samples was about 72.6%. This increased performance was significant compared to untreated soil (4.9%).

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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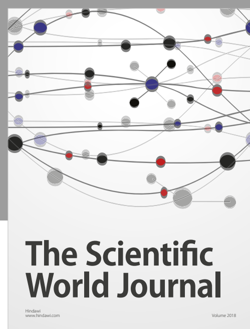
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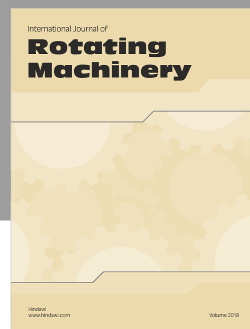
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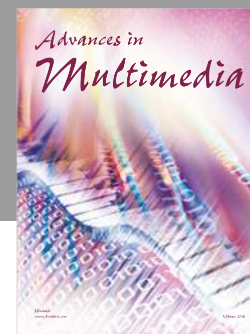
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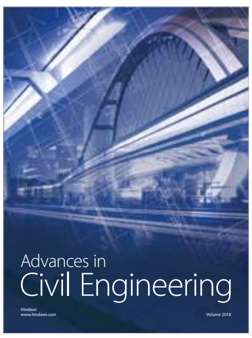
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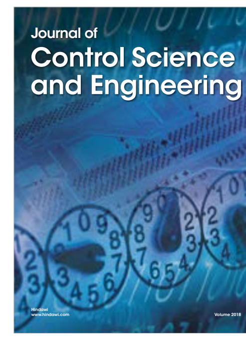
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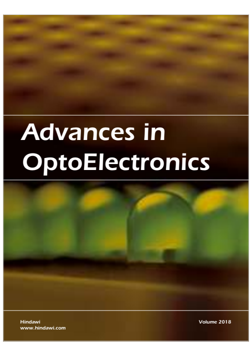
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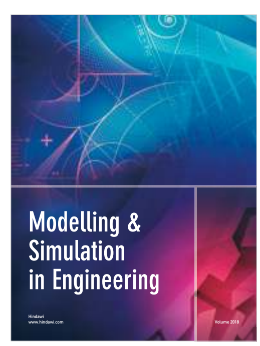
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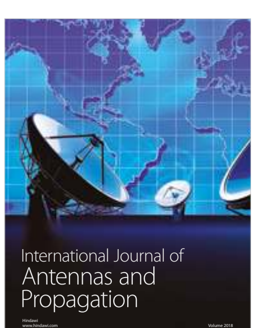
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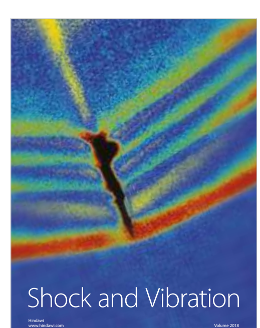
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