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Effect of Nanobentonite Particles on Geotechnical Properties of Kerman Clay

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***Abstract*—**Improving the geotechnical properties of soil has always been one of the issues in geotechnical engineering. Traditional materials have been used to improve and stabilize soils to date, each with its own advantages and disadvantages. Although the soil stabilization by adding materials such as cement, lime, bitumen, etc. is one of the effective methods to improve the geotechnical properties of soil, but nanoparticles are one of the newest additives which can improve the loose soils. This research is intended to study the effect of adding nanobentonite on soil engineering properties, especially the unconfined compression strength and maximum dry unit weight, using clayey soil with low liquid limit (CL) from Kerman (Iran). Nanobentonite was mixed with soil in three different percentages (i.e. 3, 5, 7% by weight of the parent soil) with different curing time (1, 7 and 28 days). The unconfined compression strength, liquid and plastic limits and plasticity index of treated specimens were measured by unconfined compression and Atterberg limits test. It was found that increase in nanobentonite content resulted in increase in the unconfined compression strength, liquid and plastic limits of the clayey soil and reduce in plasticity index.

***Keywords*—**Nanobentonite particles, clayey soil, unconfined compression stress, soil improvement.

I. INTRODUCTION

SOIL stabilization is one of the issues that geotechnical engineers deal with, and as a primary solution, traditional stabilizers such as lime, cement, etc. have been used to stabilize the loose soils. Although these materials improve some soil properties, they are gradually replaced by new stabilizers due to some issues such as environmental issues and their destructive effects and sometimes high cost. One of these eco-friendly stabilizers is nanomaterials.

Nanomaterials have various types which can be used by reducing the size of materials to nanoscale. A nanoparticle is defined as a particle that has at least one dimension at nanometer scale [1]. The main characteristic of nanoparticles is their small size, low agglomeration and high dispersibility [2], [3]. Special characteristics of nanomaterials are useful and important in civil engineering, especially in geotechnical engineering and soil stabilization. Many nanomaterials, including nano-magnesium dioxide, nanoclays, etc. have been used in many scientific researches by researchers around the world [4]-[10]. The nanomaterials that are often used to alter the geotechnical properties of soils are clay nanoparticles that significantly increase the strength of the specimens. Therefore, the addition of nanoclay to the soil can also be considered as stabilizer, which has many effects on the consolidation properties, permeability index and resistance parameters [4].

Taha and Taha [5] investigated the effect of adding 0.5, 1, 1.5, 3, and 5% nanoclay with a particle size of 10-20 nm to the clayey soil. They reported that as the percentage of nanoclay increased, the plasticity index and linear shrinkage of the soil increased. Bahari et al. [6] performed direct shear test on two types of silt with different plasticity properties stabilized with 0, 0.5, 1, 1.5 and 2% nanoclay. According to the results presented by them, it can be seen that with increasing the percentage of nanoclay, the amount of liquid and plasticity limits in both soils increase. They also showed that with increasing normal stress in direct shear test and increasing the percentage of nanoclay, shear strength increased.

Nikoukar et al. [7] investigated the effect of stabilization of two types of silty soil, with high (MH) and low (ML) plasticity index, by nanoclay under unconfined compression and California Bearing Ratio (CBR) tests. To stabilize the soil, the contents of nanoclay were considered 0, 0.5, 1, 1.5 and 2%.. Based on the stress-strain curve of uniaxial test on stabilized ML samples with different percentages of nanoclay, it can be concluded that with increasing the content of nanoclay unconfined compression strength increases but the rate of improving strength decreases with increasing nanoclay percentage. They also reported that increasing the percentage of nanoclay improved the results of CBR samples.

Iranipour and Haddad [8] performed consolidation tests on 5 types of soil stabilized with nano-copper, nano-aluminum, nano-clay and nano-silica in different percentages of 0.1, 0.2, 0.4 and 0.6. The results of the consolidation test to evaluate the collapse potential of the stabilized soils with different percentages of various nanomaterials showed that at low percentages of nanomaterials, nano-clay has the lowest collapse potential and nano-copper has the highest collapse potential. At high percentages of nanomaterials, nanosilica has the lowest collapse potential and nano-copper and nano-aluminum have the highest collapse potential. Abbasi et al. [9] investigated the effect of nano-montmorillonite particles on clayey soil with low (CL) and high (CH) plasticity. In their study, 0.25%, 0.5%, 2% and 4% by weight of dry soil, nanoclay were used and curing time of samples was 1, 3 and days. To evaluate the dispersivity potential of clayey soil (CL and CH), the pin-hole test was performed. Tests results showed that adding different percentages of nanoclay to each of the two dispersive soils typically decreases the soils

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dispersivity potential.

Tabresa et al. [10] conducted a series test such as Atterberg limits, consolidation, unconfined compression, and consolidated-undrained (CU) triaxial tests on soft clayey soil stabilized with 0, 0.5, 1, 1.5, 2, 2.5 and 3% of montmorillonite nanoparticles to investigate the effect of nanoclay on the behavior of stabilized specimens. According to the Atterberg limit result of the samples stabilized with various nanoclay content, the liquid and plastic limits increase with increasing nanoclay content. As the content of nanoclay increases, the unconfined compression strength and the cohesion increased and the internal friction angle decreased. They also stated that as the percentage of nanoclay increased, the sample settlement under the consolidation test also decreased.

In the present study, the effect of nanobentonite on the engineering properties of Kerman fine-grained soil was investigated. In this research, nanobentonite was added to the soil at three different contents by soil dry weight with three different days for curing time. Atterberg limits and unconfined compression tests were performed and the results of tests were analyzed.

II. MATERIALS

A. Fine-Grained Soil

The soil used in this study was from a region of Kerman province with fine-grained soil. The grain size distribution curve obtained from the sieve and hydrometric tests on this soil are shown in Fig. 1. Base soil properties are also presented in Table I. This soil is considered CL in the unified classification.

TABLE I
PROPERTIES OF KERMAN'S CLAYEY SOIL

Property	Value
Specific gravity, G_s	2.75
Liqiud limit, LL (%)	32
Plastic limit, PL (%)	15
Plasticity index, PI (%)	17
Maximum dry unit weight, $(\gamma_d)_{max}$, (kN/m^3)	18
Optimum moisture content (%)	16
USCS classification	CL

TABLE II
PROPERTIES OF NANOBENTONITE

Property	Value
Predominant clay mineral	Montmorillonite
Average particle size (nm)	1-2
Specific surface area (m^2/g)	250-280
Density (g/cm^3)	0.35

B. Nanobentonite

For soil stabilization, nanobentonite-water colloidal suspension was used with a concentration of 33% by weight (1:3 nanobentonite: water), having an average diameter of 1-2 nm. In the nanobentonite suspension, the nanobentonite particles are dispersed in an environment such as water that has a certain concentration. The properties of nanobentonite suspension are shown in Table II. The desired nanobentonite was obtained from Sigma-Aldrich Company.

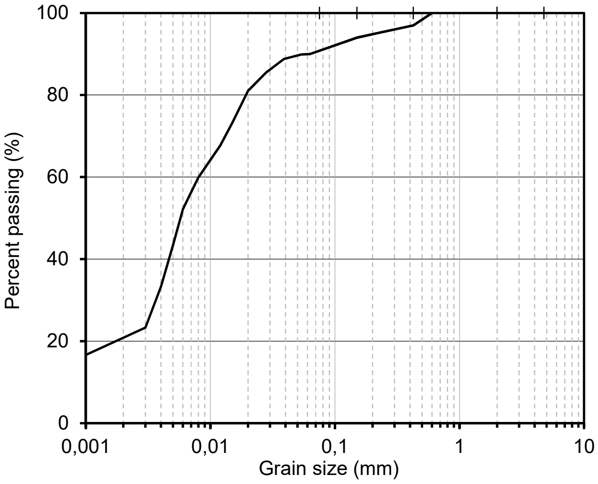

Fig. 1 Grain-size distribution curve of the clayey soil

The compounds of nanobentonite are also noticeable in Table III and the presence of SiO_2 and Al_2O_3 is recognized as its main composition.

TABLE III
CHEMICAL PROPERTIES OF NANOBENTONITE

Compound	Value (%)
SiO_2	52.24
Al_2O_3	25.68
Fe_2O_3	6.72
CaO	1.97
K_2O	0.96
Na_2O	0.85
MgO	0.6
TiO_2	0.78
LOI	10.2

III. TEST METHODS

A. Sample Preparation

In order to prepare the mixture of fine-grained soil and nanobentonite suspension for tests, the percentages of nanobentonite for stabilization of fine-grained soil 3, 5 and 7% by dry weight were selected. The procedure and time of mixing is important, however, the way of laboratory tests is related to the condition of the large scale projects. In untreated samples, the optimum moisture content of the clayey soil, which was determined from modified proctor compaction test, is added to it. Then, the stabilized samples were prepared according to the procedure described above. In order to prepare specimens stabilized with nanobentonite, initially premix or hand mixed, the quantity of soil was divided into five layers and each layer was sprayed with the required content of nanobentonite suspension. The content of nanobentonite particles and the concentration of nanobentonite suspension is also one of the effective parameters in this study. The content of optimum moisture that is exposed to the soil is the amount of water available in the nanobentonite suspension (with concentration 1:3 nanobentonite to water) and, if needed, the pure water is added and the water spreads all over the soil. Mixing of the suspension and the soil continues until the sample reaches homogeneity, which requires about 30 minutes. For this purpose, a low speed electric mixer was used to prevent separation of the additive or manual mixer [11]. After the initial mixing, a homogenizer was used to create integration between particles, as can be seen in Fig. 2. This procedure was the best method to obtain homogeneous samples. The density of the specimens was equal to 95% of the optimum parameters obtained from the modified proctor compaction test was considered. For unconfined compression test, the mixture was filled in 38 mm diameter and 88 mm high cylindrical stainless steel mould. After preparation of the specimens, they were placed in plastic bags and the air was completely discharged with a suction apparatus for curing. Also, the curing time of samples is considered 1, 7 and 28 days.

Fig. 2 Image of homogenizer apparatus

IV. Results and Discussions

A. Atterberg Limit Tests

In samples preparation for testing, the soil was mixed with different percentages of nanobentonite suspension. In order to obtain a homogeneous mixture, turbomixer was used. Then the specimens were kept in an isolated environment for 24 hours.

Liquid and plastic limit tests were performed on samples with different percentages of nanobentonite according to ASTM D12: 4318-87 [12] and the results were reported in Fig. 3. With regard to Fig. 3, with increasing bentonite nanoparticles' content in the soil, there is an increase in the amount of liquid and plastic limit of specimens due to the high ratio of surface to volume of nanobentonite particle size, high water absorption in the nanomaterial, and increased water capacity in the soil. The results showed that the rate of increase of plastic limit was more than the liquid limit. Also, the plasticity index was obtained by the difference between the liquid limit and plastic limit (PI = LL-PL). With the addition of nanobentonite, plasticity index decreases.

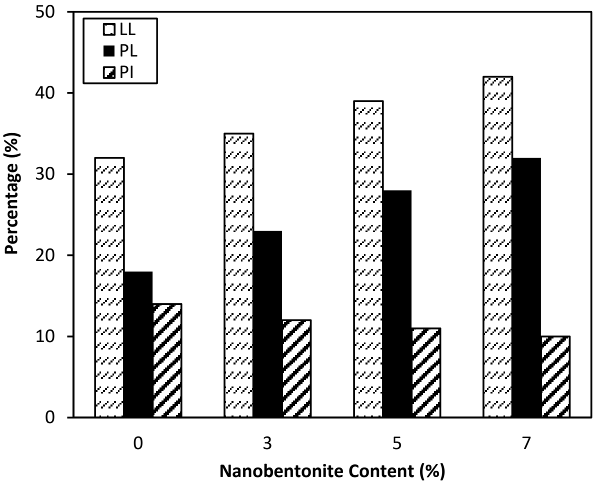

Fig. 3 Effect of various content of nanobentonite on Atterberg limits

B. Unconfined Compressive Test

Unconfined compressive test has been widely used to evaluate the strength and properties of fine-grained soils. The specimens were prepared according to the sample preparation section and the specimens were made in a cylindrical steel mould with a diameter of 38 mm and a height of 88 mm. Unconfined compressive strength of Kerman clay (untreated sample) (according to ASTM D16: 2166 [13]) was also obtained 375.9 kPa (Fig. 4). For comparison of the untreated and stabilized specimens, the results of the uniaxial test on stabilized soil with 3% nanobentonite with 1, 7, and 28 curing day in Fig. 5 are visible. According to this figure, the results showed that the unconfined compression strength increases in the nano-stabilized specimens relative to the natural soil. It can be also stated that by adding bentonite nanoparticles to the soil, strain at failure moment increases due to increasing sample flexibility and high specific area of nanoclay. This issue has been observed in recent studies [14], [15].

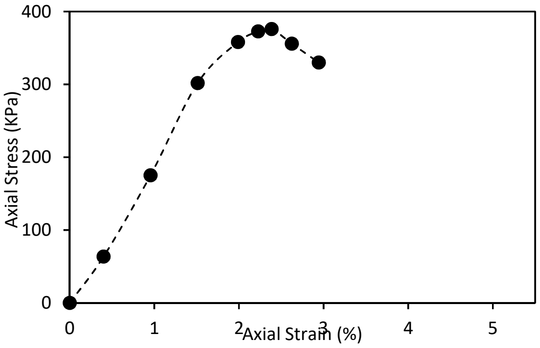

Fig. 4 Stress-strain curve for untreated soil

Fig. 6 shows the uniaxial strength changes for different percentages of nanobentonite during different curing times. Uniaxial strength also increases with increasing weight percent of nanobentonite at constant curing time. For example, by adding nanobentonite to Kerman fine-grained soil and increasing its content from 3% to 5 and 7% with 7-day curing time, the uniaxial strength at failure moment was 1.7, 2.13 and 3.34 times the uniaxial strength of unstabilized specimens, respectively (Fig. 6).

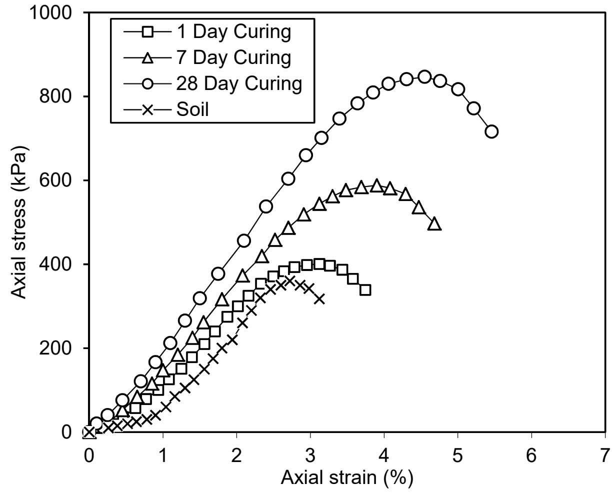

Fig. 5 Stress-strain curve for stabilized specimens with 3% nanobentonite

As can be seen in Fig. 6, the time of curing also has a large effect on the compressive strength of the stabilized specimens and, over time, an increase in resistance is achieved by completing the bonds formation between the specimen particles.

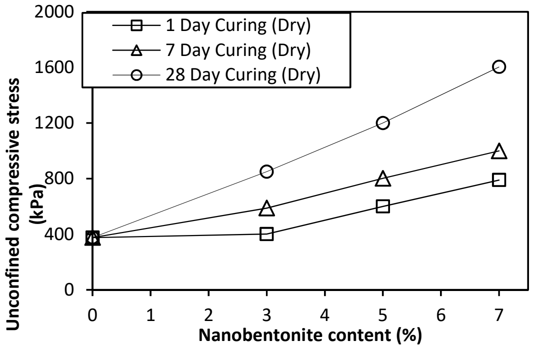

Fig. 6 Effect of different content of nanobentonite on UCS of stabilized specimens

In Fig. 7, the compressive strength ratio of nanobentonite-stabilized specimens to untreated soil $[(q_u)_s/(q_u)_0]$ for a 28-day curing time is presented. According to Fig. 7, this ratio increased with increasing nanobentonite content, such that the compressive strength in stabilized specimens with 3% nanobentonite and 28-day curing time would be 2.26 times higher than the untreated soil.

As shown in Fig. 8, the compressive strength also increases with the increase of the curing time, which can be due to the completion of the cation exchange process over time, as well as the increase in particle specific area due to the higher crystal fragmentation and dispersion. This process increases the cation exchange capacity, decreases the thickness of the diffuse double layer, creates the flocculant structure and increases the compressive strength. In some percentages of nanobentonite (for example, a curve corresponding to 5% nanobentonite), the slope trend had a higher slope during the first seven days of curing (compressive strength increased with more slope) and until the 28 day curing time, the trend slope decreases, indicating that more bonds between particles of stabilized specimen are formed (Fig. 8).

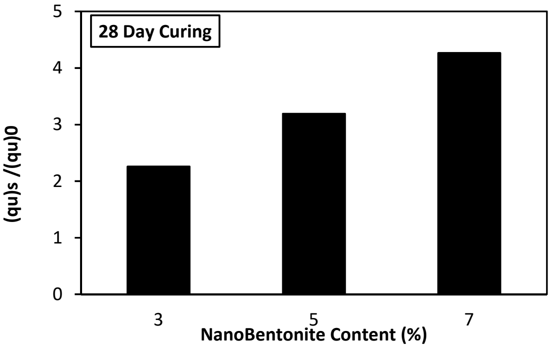

Fig. 7 Ratio of UCS of stabilized specimens with various content of nanobentonite (28-day curing time) to natural soil

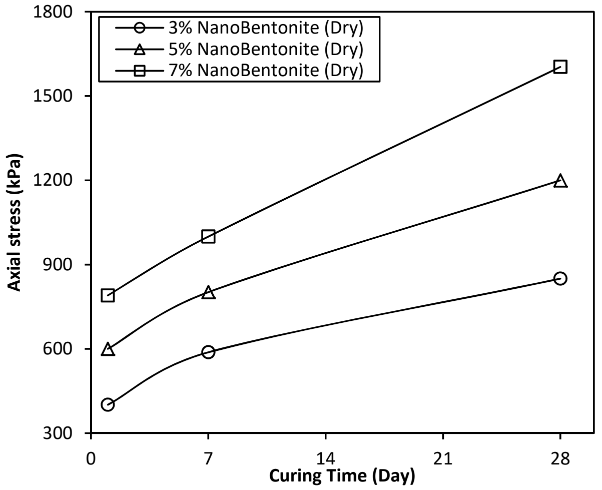

Fig. 8 Effect of curing time on UCS of stabilized specimens

The increase in ductility due to the increased percentage of nanobentonite is one of the factors that lead to an increase in failure strain (strain at failure moment in stress-strain curve) in the natural soil and the trend of changes is visible in Fig. 9. The ratio of failure strain in the stabilized samples with 3, 5 and 7% nanobentonite (28-day curing time) to the failure strain in the unstabilized soil $[(\varepsilon_p)_s/(\varepsilon_p)_0]$, were 1.22, 1.52 and 1.92, respectively, as shown in Fig. 10. According to this figure, it is observed that the failure strain ratio of nanobentonite-stabilized specimens (with 28-day curing time) to the untreated soil is more than 1, indicating that the failure strain of stabilized specimens also has higher values in comparison with untreated specimens, which may be due to increase the ductility of samples containing nanobentonite.

The effect of different percentages of nanobentonite particles on the elastic modulus E_{50} of the stabilized samples is shown in Fig. 11. In the samples stabilized with different percentages of nanobentonite, with increasing the nano content, the elastic modulus is increased compared to the untreated soil, which may be due to the increase of the floccule structure (with increasing specific area, specific and cation exchange capacity and reduction of the thickness of the diffuse double layer) between the sample particles due to the addition of nanobentonite. The changes of the elastic modulus is such that in the samples stabilized with 3, 5 and 7% nanobentonite with a 28-day curing time, the E_{50} values would be 54.6, 67.9, and 85.5 MPa, respectively.

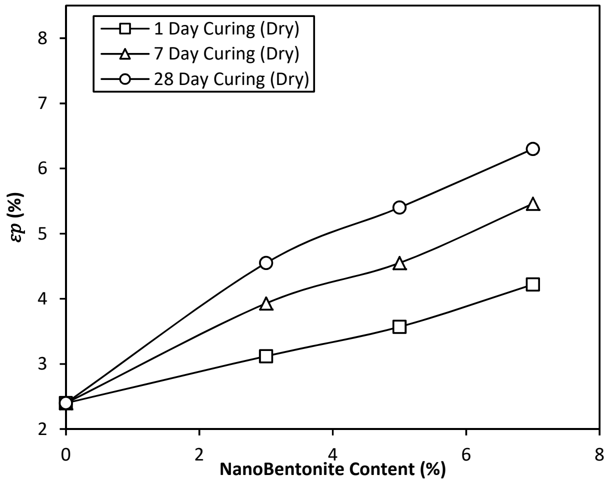

Fig. 9 Failure strain values of stabilized specimens with nanobentonite and natural soil

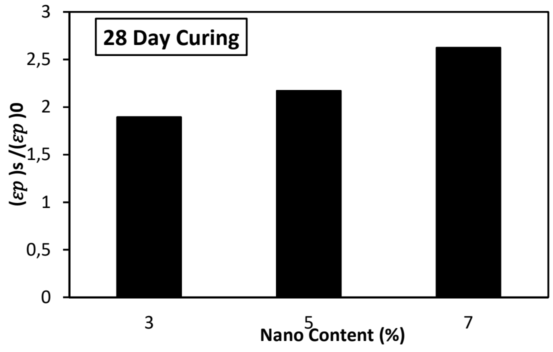

Fig. 10 Ratio of failure strain of stabilized specimens with various content of nanobentonite (28-day curing time) to natural soil

Increasing the curing time in samples containing 7% nanobentonite increased the elastic modulus of E_{50} and reached its maximum value in 28 days of curing (similar to the above procedure for samples containing 3 and 5% nanobentonite can be seen). For example, for samples stabilized with 7% nanobentonite particles with 1, 7, and 28 day curing times, the E_{50} values of stabilized specimens were 1.47, 2.52, and 4.88 times the natural soil $[(E_{50})_s/(E_{50})_0]$, which is visible in Fig. 12. Also, the rate of increase of E_{50} for samples stabilized with nanobentonite with 28-day curing time was more than other curing times (e.g., curing time of 7 days). Asakereh and Avazeh [16] investigated the effect of nanobentonite on clayey soil and the results showed that the addition of nanobentonite resulted in increased unconfined compression strength, elastic modulus and failure strain.

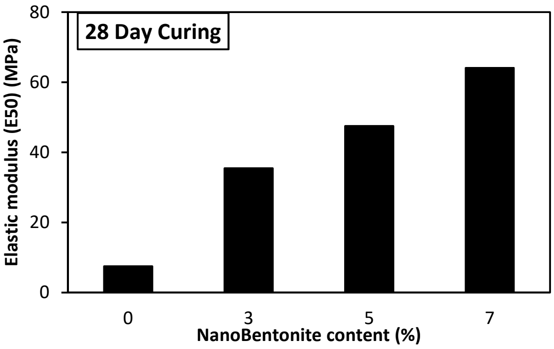

Fig. 11 Effect of various content of nanobentonite on elastic modulus (E_{50})

V. CONCLUSION

In this study, bentonite nanoparticles were used to stabilize Kerman clay (Iran). Stabilized specimens were tested in three different percentages (3, 5 and 7%) with various curing times (1, 7 and 28 days) under Atterberg limits and unconfined compressive strength tests and the following results were obtained:

1. Liquid and plastic limits and plasticity index in untreated clay (CL) were 32%, 18% and 14%, respectively. With the addition of nanoparticles to the natural soil due to the increase in specific surface area and the presence of nanoparticles in the stabilized samples, the liquid and plastic limits increased but the plasticity index decreased. For example, by adding 3% nanoparticles, the parameters of liquid and plasticity limits and plasticity index were obtained 35, 23 and 12, respectively, indicating an increase in liquid and plastic limit and decreasing in plasticity index.
2. Unconfined compressive strength was obtained for the natural soil at 375.9 kPa, using nanobentonite to increase compressive strength. By adding different contents of nanobentonite (3, 5 and 7%), the compressive strength of the stabilized samples to the natural soil increases, so that with the addition of 3, 5, and 7% nanobentonite at the curing time of 28 days, the compressive was 2.83, 3.72 and 5.53 times the natural soil, respectively.
3. Addition of different percentages of nanobentonite results in an increase in strain at the moment of failure of the stabilized specimens due to the high ability of adsorption and retention the water in the presence of nanobentonite (due to the increased specific area of the specimens) and there is also an increase in the ductility of nanobentonite

in the soil. This increase is such that by adding 3, 5, and 7% nanoparticles at 28 days of curing, the strain failure under dry conditions will be 1.74, 2.06 and 2.33 times the natural soil, respectively.

4. Decreasing the thickness of the diffuse double layer leads to the closure of the soil and nanobentonite-soil particles and by creating floccule structure, the compressive strength and also the elastic modulus of the nanobentonite-stabilized specimens increases relative to the natural soil. The elastic modulus of untreated soil was 17.5 MPa, indicating that the soil has a relatively low elastic modulus. The elastic modulus in the samples stabilized with 3, 5 and 7% nanobentonite at the 28-day curing time was 3.74, 4.62 and 5.27 times the untreated soil, respectively.
5. The curing time also has a great effect on the compressive strength and elastic modulus, so that by increasing the specimen specific area during curing time and increasing the cation exchange capacity, the compressive strength and elastic modulus will increase. The compressive strength in the samples stabilized with 3% nanobentonite and 1, 7 and 28 days curing times were 1.27, 1.81 and 2.81 times the untreated soil, respectively, indicating that curing time has a significant influence on the strength of the stabilized samples.

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