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Investigation of the Effect of Nanoclay on Geotechnical Properties of Beach Sands and Its Comparison with Other Conventional Approaches

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ABSTRACT

Due to the expansion of industry and maritime transport, as well as the need for better use of coastal areas, in recent years, studies in this regard have been increased. Beach sandy soils (known also as blown sands), if exposed to the path of water flow, are washed away and do not show sufficient bearing capacity due to their uniform granulation and lack of adhesion. Soil improvement to increase its bearing capacity and enhance its geotechnical properties through new technologies such as nanomaterials has led to successful results in engineering. In this study, the effect of using nano clay on improving the geotechnical properties of beach sand has been evaluated and compared to other methods such as the use of cement and clay with high plasticity properties. For this purpose, geotechnical experiments were performed in different mixing designs. The mixture designs used in this study were selected for nano clay 1, 2 and 3% by weight, cement 5, 7 and 9%, and adhesive clay with a combined ratio of 1:9, 1:6 and 1:3. The results indicate the positive impact of nano clay, when used alone, on improving the plasticity and resistance parameters and particularly the proper performance of this material combined with other materials in improving soil properties, so that soil density increased by 1.89 g/cm3 using nano clay 1%. Besides, using nano clay 3%, soil compressive strength increased by about 119 kPa. In this work, the nano clay-cement combined performance was also examined, which indicated an increase in specific weight up to 1.91 g/cm3 in the compaction section. Results of the compressive strength showed an increase of 721 kPa relative to the base soil. In the shear test, with the mixture scheme involving nano clay 3%, soil adhesion and internal friction angle increased by 17 kPa and 1 degree, respectively. Besides, using the nano clay-cement combination, adhesion increased by 77 kPa while friction angle decreased by 6 degrees.

1. Introduction

Due to the importance of soil application in all construction projects, including projects in coastal areas, it is essential to conduct in-depth studies in the field of marine geotechnical engineering and solve problems to gain optimality and further productivity. One of the important points in this field is the necessity of using durable soils with more stability, more density and better geotechnical properties in the project sites that are adjacent to aquatic and marine environments. In general, most of the soils used in the projects are not ideal and completely desirable, from an engineering point of view, for construction, and thus they need to be modified for construction activities. This is especially important for soils in the vicinity of aquatic environments due to the continuous interaction of water and bed, which, if unattended, might cause many problems in the construction and operation stages and even lead to the complete destruction of the structure and failure of the project. Land is of particular importance in projects in the vicinity of aquatic environments, and the project relocation approach is usually not a good option, so soil improvement seems to be a better option. Improvement is the controlled reconstruction of soil for reuse in a new geotechnical structure. The application of these methods improves soil geotechnical parameters, reduces costs, saves execution time, increases operating life and reduces unknown risks [31]. Various additives can be used to improve the soil. Additives used in the past include cement, bitumen, lime, calcium chloride, volcanic ash, etc. [26]. One of the best known additives that have been widely considered due to its effect on improving soil properties is cement. For example, Dupas and Pecker [19] studied the static and mechanical properties of sand-cement to improve sand and avoid the risk of liquefaction and showed that increasing the amount of cementitious material increases soil adhesion. Clough et al. [17] investigated the effect of soil improvement with cement in California and concluded that the final strength of the samples increases with cementation. Zhang [46] proved that the presence of iron oxide is a factor in reducing soil plastic property and plasticity index due to limiting the performance of soil microstructures. Sarkar et al. [42] stabilized the soil using cement in a 0 to 12.5% mixing design, the results of which showed incremental changes of the liquid limit between 46 and 53 and incremental changes of the plastic limit from 27 to 37 and decreasing changes of the plasticity index from 19 to 16. Namdar et al. [37] by studying the improvement of clay soil by mixing cement and synthetic fibers with soil, concluded that the addition of cement and fibers to the soil increases its strength and this increase in strength is affected by the processing time and percentage of fibers. Khosravi and Raisi [30] by studying the improvement of clay using cement and a type of chemical resin concluded that the addition of resin and cement increases soil strength. With the advancement of technology and access to new solutions and materials, researchers have always focused on using new and effective materials in this field. One of the new technologies that is highly considered today is the use of nanoparticles. In 1993, Yonekura & Miwa [45]conducted a study to increase the compressive strength of sand using silica nanoparticles. They increased soil strength by 3.5% using nano silica 32% by weight percentage after 1000 days. Persoff et al. [39] in a study of sandy soils concluded that increasing the percentage of nano silica increases soil compressive strength. They also found that the addition of silica nanoparticles would reduce the permeability coefficient. Gallagher & Mitchell [22] studied the effect of nano silica slurry on liquefaction potential and cyclic behavior of loose saturated sand. The results showed that the behavior of the soil with nano silica significantly increased the resistance of loose sandy soils to cyclic loading changes. Burton et al. [16] performed uniaxial and triaxial compressive strength tests on soils mixed with nanomaterials and found that the mixed soils were elastic in the initial stages and then elastoplastic. Taha and Ying [44] investigated the effect of carbon nanotubes on the geotechnical behavior of kaolinite soils, the results of which show an increase in liquid and plastic limits and range. Majed & Taha [32] investigated the effect of nanomaterial behavior on the geotechnical properties of soft soils. The results showed an increase in compressive strength of the samples. Arbani et al. [3] increased the bearing capacity by 84.66 to 156.61 by adding 0 to 5% nano clay to sandy soil mixed with 7% cement. Nikookar et al. [31] stabilized clay using nano clay at mixing percentages of 0 to 2%, indicating an increase in compressive strength from 0.6 to 1.45 kg / cm. Neethu et al. [36] examined soil stabilization using nano-clay, by adding 0.25 to 2% nanomaterials to kaolinite clay. Their Atterberg experiment results indicated an increase in the liquid limit from 40 to 50 and an increase in the plastic limit from 22 to 30, and hence an increase in the plasticity index due to the faster increase in the liquid limit than the plastic limit. Bahari et al. [13] conducted a study on the stabilization of silty soils using nanomaterials. By adding nano clay at 0 to 2% by weight to silty soil, they concluded that as the nano clay percentages increased, an increase occurred in soil adhesion and shear strength. Besides, internal friction angle had slight changes and even remained constant. Seyedi et al. [43] examined the stabilization of weak soils using nanomaterials, by adding 1 to 7% by weight of nanomaterials, and observed that by adding 1% by weight of nanomaterials, the maximum specific dry weight was 1.72 g/cm3 in the optimum moisture content of 20%, but in the case of adding 7% by weight of nanomaterials, the maximum specific dry weight was 1.62 g/cm3 in the optimum moisture content of 22%, indicating that the increased volume of nanomaterials in the soil is inversely related to the soil specific dry weight while it is directly related to the optimum moisture content of soil. Khalid et al. [29] studied the change of properties due to the combination of 3% nano kaolin and kaolin, the results of which showed an increase in the values of liquid limit, plastic limit, and specific dry weight and a decrease in plasticity, moisture content, and electrical conductivity to a certain extent. The results showed that a small amount of kaolin nanoparticles improves the geotechnical properties of kaolin. Majed et al. [33] modified soft soil using three types of nanomaterials: copper, clay, and magnesium. The results showed a significant improvement in maximum specific dry weight, plasticity index, shrinkage, and unconfined compressive strength of soil. Hareesh and Vinothkumar [27] investigated the effect of zeolite and silica nanomaterials on clay. The results showed incremental changes in liquid limit from 51 to 55 for nano-silica composition and decreasing changes in liquid limit from 51 to 44 for nano zeolite composition. The results also showed an increase in optimum humidity for nano-silica from 16 to 22 and for nano-zeolite from 16 to 23. The specific dry weight also reduced from 1.64 to 1.59 for nano silica and from 1.64 to 1.56 for nano zeolite. Babu and Joseph [14] investigated the effect of nanomaterials at 0 to 2% on soft soil properties. The results showed a decrease in the liquid and plastic limits and an increase in CBR in nanomaterials. Fakhri et al. [20] investigated the effect of nano clay on the basic geotechnical properties of clay using Atterberg and standard compaction tests and concluded that the addition of nano clay increases the plasticity of samples. With increasing plasticity, it can be expected that the permeability of the samples decreases. Fattahi and Ladrian [21] by examining the addition of nano silica and bentonite to the divergent clay sample, concluded that the separate addition of 10% bentonite and 1% nano silica to the divergent clay reduces the divergence potential and increases the shear strength of the divergent soil. Behbahani and Khalghifard [15] investigated the effect of nano silica 0.5%, 0.7%, and 1% on soil engineering properties. The results of direct shear experiments showed that the use of nano-sio2 leads to an increase in shear strength. Accordingly, the optimal amount of nano silica mixed in the soil to achieve maximum strength was 0.7%, which increased the shear strength by 41% compared to the natural soil sample. Besides, according to the compaction test results, the optimal moisture content and maximum specific dry unit weight of the soil increased. Hareesh and Vinothkumar [28] used nano-silica in percentages between 0.2 and 1 and nano zeolite from 0.4% to 2% in CH and CI soils. The results showed that Atterberg limits increased in the presence of nano-silica, whereas Atterberg limits decreased using nano zeolite. Abasi and Farjad and [1] used nanomaterials 0%, 0.25%, 0.5%, 1%, 2% and 4% at the processing ages of 1, 3 and 7 days and showed that soil plasticity does not play an important role in the effect of these nanoparticles on divergence potential. They also found that the processing time has a significant role in soil stabilization with clay nanoparticles and it takes about three days to perform the chemical interactions required for stabilization. Candan et al. [18] investigated the effect of magnesium nano oxide and aluminum nano oxide in ratios of 0.5 to 2% on swollen soils. The results showed that the swelling potential is reduced by adding these nanomaterials and as a result the soil is suitable for structural purposes. Ghaffarpour and Yazdi [23] investigated the physical, volumetric and mechanical properties of weak cement-stabilized soils containing nano silica using Atterberg limits, uniaxial compressive strength, California load-bearing capacity, and swelling tests. Based on their results, as the amount of nano silica increased, mechanical properties such as uniaxial compressive strength and California bearing capacity significantly increased in the short term, so that by modifying the cement by adding 10% nano silica (in terms of cement weight), uniaxial compressive strength increased by 25% and California bearing increased by 45% in 7 days. These results indicate a significant reduction in soil inflation potential. Ghaffari and Dabiri [24] investigated the effect of nano-silica on Anzali sand combined with cement, the results of which showed an increase in uniaxial compressive strength of cement sand with nano-silica. Rosales and Agrela [40] studied the use of commercial silicate-based nanomaterials to improve the technical properties and bearing capacity of swollen soils, which showed that the use of nanomaterials reduces the environmental effects associated with soil stabilization. Compressive strength and California load ratio index also increased significantly. Ghaffari and Dabiri [24] processed clay mixed with nano-clay and limestone powder in two separate and combined modes with 5 and 10 percent and in 7, 14 and 28 hours. In order to evaluate the effect of the mentioned materials on the geotechnical parameters of clay, Atterberg limits, compaction, uniaxial and direct shear tests were done. The results showed a reduction in clay plasticity index by 72% and improvement of granulation structure and reduction of voids and increase of shear strength by 33% in the simultaneous mixing of 5% nano-clay and 10% limestone powder in the processing time of 7 days at ambient temperature. Nanoparticles are typically between 1 and 100 nanometers in size. Due to their very small size, these materials have a very high specific surface area. Therefore, they react very actively with other soil particles. Due to this very high specific surface area and surface loads, even in the case of very low use of these materials in the soil environment, physico-chemical behavior and soil engineering properties are very specifically and significantly affected [25]. One of the objectives of this research is to investigate the improvement of geotechnical properties and bearing capacity of soil by adding some innovative materials such as nanomaterials. Moreover, the related effects are compared with other existing methods after mixing design, as described below.

2- Materials and methods

In order to evaluate the effects of different mixtures of sand soil samples, after preparation and transfer to soil laboratory according to ASTM D 422-63 [4] standard and in order to determine soil classification, the granulation test was performed. Besides, a hydrometric test based on ASTM D 7928 [5] was performed to examine the fine-grained section (passing through sieve No. 200). In order to identify more soil characteristics, soil density test was performed according to ASTM D 854-14 [6] standard and also soil moisture content determination test was performed according to ASTM D 2216-90 [7] standard. Images of initial sandy soil identification experiments are shown in Figure (1).

Figure (1): Images of initial soil identification experiments

According to the results of sieving-based granulation experiments and hydrometry, the granulation curve was drawn on a semi-logarithmic scale for the soil sample. This curve is shown in Figure (2).

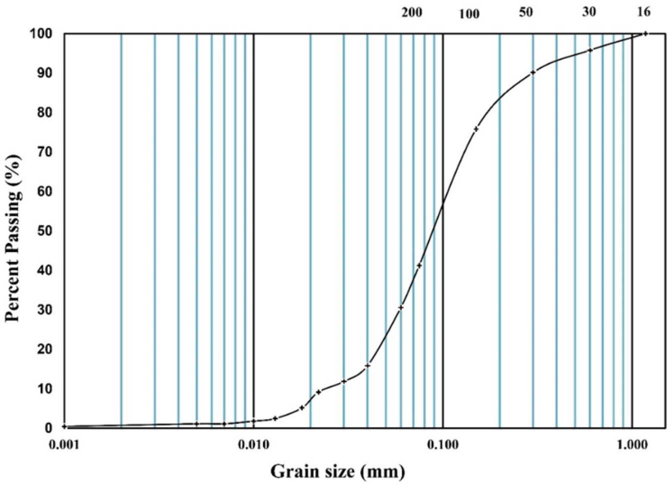

Figure (2): Grain curve of sandy soil sample

Based on the values obtained for the soil sample and based on the unified soil classification system, this soil was classified as silty sand (SM). Moisture and density percentages for this soil were calculated to be 11.06 and 2.6, respectively. The nano clay used in this project is montmorillonite nano clay. The specifications of this material are shown in Table (1).

Table (1): Specifications of the nanoclay used

Particle size	Specific surface area	Blank space between particles	Color	Moisture
1-2 nm	220-270 (m2/gr)	60′A	Light yellow	1-2%

Nanoclay was mixed with soil samples with a mixing percentage of 1 to 3%. In order to compare the effects of nanoclay with other methods, two materials, cement and sticky clay, were mixed and tested in specific percentages with beach sandy soils. The purpose of selecting this soil is to compare the effectiveness of clay and nano-clay. The test results for the initial identification of clay are shown in Table (2).

Table (2): Results of initial tests on clay

Soil name	Moisture percentage (ω)	Liquid limit (LL)	Plastic limit (PL)	Plasticity index (PI)	Specific dry weight of soil (γ_s)
CL	31%	44%	26%	18%	1.75

Clay soils in ratios of 1:3, 1:6, and 1:9 by weight percentage of the base soil were used in the mixing design. Besides, cement type II, due to its anti-chlorine and anti-sulfate properties, as well as its suitable performance in hot areas, was used as the option of choice in the mixing design at 5%, 7%, and 9%. In order to investigate the combined effect of materials in improving the sandy soil properties, a nano-cement composite mixing plan (with a ratio of 2% nano and 7% cement) and a nano-clay composite mixing plan (with a ratio of 2% nano and 1:6 sticky clay) were selected and tested. It should be noted that all selected ratios have been identified using the experimental data obtained from the initial experiments as well as the results of previous research. Due to its special nature, the use of cement and nano-clay also required processing time (for cement due to hydration and for nano-clay due to the complete absorption of surface water). Therefore, the period of 7 days after sample preparation for each experiment was selected for processing. After preparation, the samples were wrapped in plastic and stored for a specified period of time, and then they were tested. A very important issue in relation to the use of nanoparticles in soil mass is the proper dispersion of nanoparticles. Nanoparticles exhibit their excellent and potential properties when their compacted masses are broken down into separate units. In this study, in order to disperse the nanoparticles, the mechanical method of ball milling was used. In this method, for mixing, first sandy soil along with one of the composite materials (nano-clay or cement or sticky clay) is placed dry inside the chamber of the ball mill machine shown in Figure (3) and is allowed to mix for 2 hours. In this chamber, for better mixing of materials, 65 balls with an average diameter of 1.5 cm made of Teflon were used to finally obtain a homogeneous and uniform mixture from them.

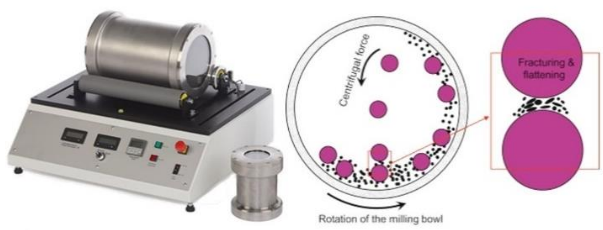

Figure 3. Ball milling

Another important point is soil regeneration for experiments that require intact specimens. In this method, according to the soil characteristics, the required moisture is added to the sample and according to the volume of the mold and the density of the soil, the required amount of weight is calculated and weighed using the specific weight ratio. The sample weighed in several layers (usually three layers) was pounded and compacted by a mandrel on a two-scale mold to reach the mold volume. After soil regeneration and processing, samples were prepared for experiments in different mixing designs. The first test performed in this study was the standard Compaction test based on ASTM D 698-12. [8] The purpose of this test was to obtain the optimum humidity at which the maximum specific weight is achieved. The experiment was performed by a modified method with a small mold. The standard density test method is shown in Figure (4).

Figure (4): How to test Compaction in different mixtures of materials

In order to find the plastic and liquid limits, the Atterberg limits test was performed according to ASTM D4318-17 [9] standard. The purpose of this experiment is to find the amount of moisture in which the soil changes from the semi-solid to the plastic mode. How to test the Atterberg limits is shown in Figure (5).

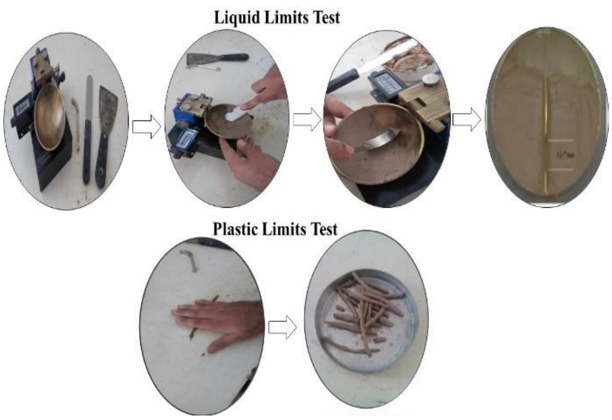

Figure (5): How to test Atterberg in the design of different mixtures of materials

Moreover, in order to determine the approximate and rapid compressive strength of the soil, uniaxial compressive strength test was performed according to ASTM D2166-87 [10] standard. In this experiment, soil sample was placed under the reconstruction mold and the jack machine. Stress readings were performed every 0.25 mm of strain, and the amount of stress was recorded. How to test the compressive strength is shown in Figure (6).

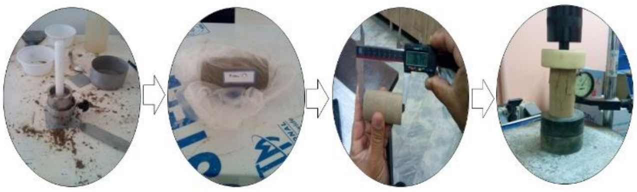

Figure (6): How to test the compressive strength in the design of different mixtures of materials

In order to determine the parameters of soil shear strength, direct shear test was performed according to ASTM D3080-90 [11] standard. This experiment was performed under three overheads of 0.5, 1, and 1.5. The loading speed in the direct shear test was 0.5 mm / min. The shear test method is represented in Figure (7).

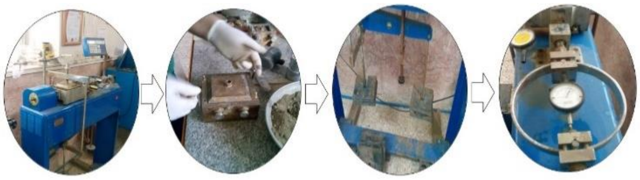

Figure (7): How to test direct shear in the design of different mixtures of materials

In order to determine the tensile strength of mixed soil, Brazilian tensile strength test was performed according to ASTM C496-96 [12] standard. The purpose of this experiment was to determine the tensile strength of soil. The tensile mode is shown in Figure (8).

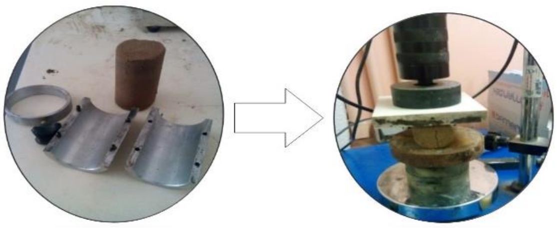

Figure (8): Brazilian tensile strength test for soil in different mixing designs

3. Results and discussion

In what follows, tests results are discussed. The compaction test results are shown in Figure (9).

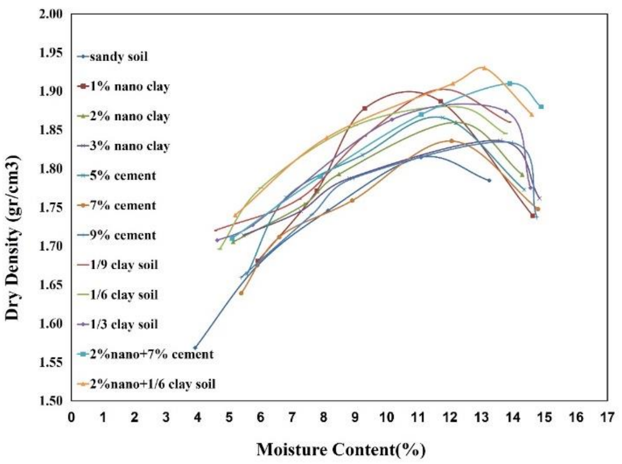

Figure (9): soil compaction in different mixing designs

According to the figure, the maximum specific weight for the base sandy soil without a mixing design was 1.82 g/cm3 at an optimum moisture content of 11.1%. With the addition of nano-clay, the specific dry weight of the soil increased to a certain extent, so that in the design of mixing 1% of nano-clay with sandy soil, the specific dry weight of soil increased by 1.89 g/cm3. Then by increasing the percentage of nano-clay in the mixing design, the specific dry weight decreased, so that in the mixing design of 3% nano clay, the specific dry weight was of soil obtained to be 1.84 g/cm3. Furthermore, the trend of changes in the two materials is the same as nano clay, and initially the density increased with the addition of the mixing material to the base soil and decreases with further increasing the mixing material. Another noteworthy point is the ever-increasing trend of the optimum moisture percentage with increasing the mixing percentage in all sandy soil mixing designs.

Poorly grained sandy soils have high porosity. By adding materials, these pores are first occupied by these fine materials themselves, thus increasing the soil density to some extent. On the other hand, the presence of moisture creates a layer of water on the surface of the grains and makes it easier for the grains to roll on top of each other (so-called lubrication stage), which increases the density and specific dry weight of soil. In the presence of fine grains, when exceeding a limit in the mixing design, the surface water absorption increases due to its softness and higher specific surface area than larger grains, which in turn reduces the specific weight, and finally with the presence of a weight percentage of more than a certain amount, the specific weight will be less than the specific weight of soil without mixing plan. Besides, due to this higher specific surface area, more water is absorbed and as a result, the optimum humidity increases. This theory was also tested with higher percentages of nanomaterials, cement and clay, so that the specific dry weight was reduced to 1.78 g/cm3 in a 12% cement mixing design. In the 8% nano clay mixing design, the specific dry weight was reduced by 1.8. Humidity also increased by 1 to 2%. According to the diagrams in Figure (9), the maximum range of specific dry weight changes is for sticky clay and nano-clay, followed by cement. The results show that nano-clay and sticky clay are in approximately equal range in terms of moisture and changes. However, there is a significant difference in the amount of mixing design, which indicates that nano clay, with its small dimensions at low percentages (about 1%), can exert the same effects as the mixing designs with over 30% clay. A mixing design containing 1.6 sticky clay and 2% nano-clay and another mixing design with 7% cement and 2% nano-clay were also tested. These two mixing designs, respectively, showed a maximum specific dry weight of 13.1 and 1.91 with an optimum moisture content of 13.9. The results of the Atterberg limits test are shown in Figure (10).

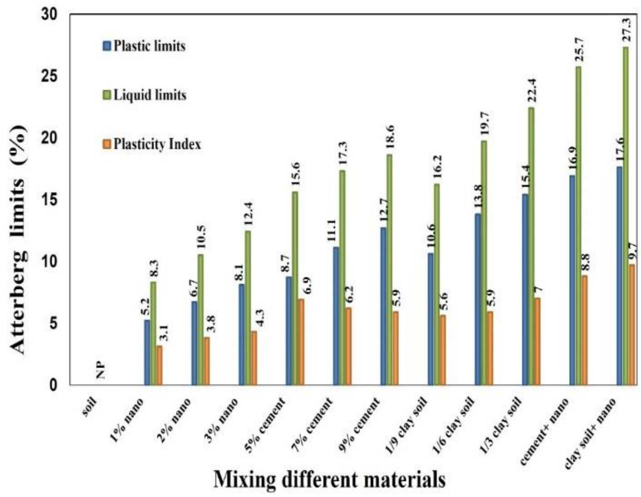

Figure 10. Atterberg test diagram in mixing different materials

By adding nano clay, due to the increase in moisture adsorption, the liquid limit increased as the maximum liquid limit for 3% nano clay was calculated to be 12.4. For cement and sticky clay mixing designs, the trend was also ascending. The increasing trend of the liquid limit for the two mixing designs of cement and sticky clay in the present study is higher than the mixing percentages of nano clay. However, this is not necessarily the case with higher percentages, and rather it needs investigation. The maximum liquid limit value was calculated to be 22.4 for 1.3 of the sticky clay. Likewise, the changes of the plastic limit in the three mixing designs was incremental; however, the increase in the plastic limit was slower than the liquid limit. Moreover, the highest amount of plastic limit changes was observed for the adhesive clay mixing design. The maximum amount of plastic limit was related to the mixing design with nano clay 3%, which was equal to 8.1, while it was equal to 12.6 and 15.4 in the mixing designs of cement 9% and adhesive clay 1.9, respectively. The trend of plasticity index changes in nano-clay and adhesive clay mixtures was also increasing. In soil, the free water between the soil mineral plates causes the liquid behavior and the slip of the grains on each other and water adsorption is a factor for the plastic behavior of the soil. As the percentage of clay particles in the soil increases, the amount of water adsorbed by these particles increases and the soil mass must gain more moisture as free water to reach the liquid level, and consequently the liquid and plastic limits increase. The increasing trend of plastic and liquid limits depends on the minerals that make up the soil. On the other hand, nanomaterials due to their very small dimensions have a high specific surface area and high electrical charge on their surface, which increases soil plasticity and reduces permeability; therefore, the water surrounding the mixed particles is increased and this factor will increase the plastic parameters of the mixed soil [38]. The presence of iron oxide is a factor to reduce the plastic limit and plasticity index of soil due to limiting the performance of soil microstructures [46]. Therefore, due to the fact that iron oxide is one of the main constituents in the cement structure, the trend of the plasticity index in this mixing design is decreasing. Besides, the mixing design of 1.6 sticky clay with 2% nano-clay and the mixing design of 7% cement and 2% nano clay were tested. The liquid limit, plastic limit, and plasticity index for the first mixing design were 27.3, 17.6 and 9.7, respectively. In the second mixing design, the values were 25.7, 16.9, and 8.8, respectively. The results of uniaxial compressive strength are shown in Figure (11).

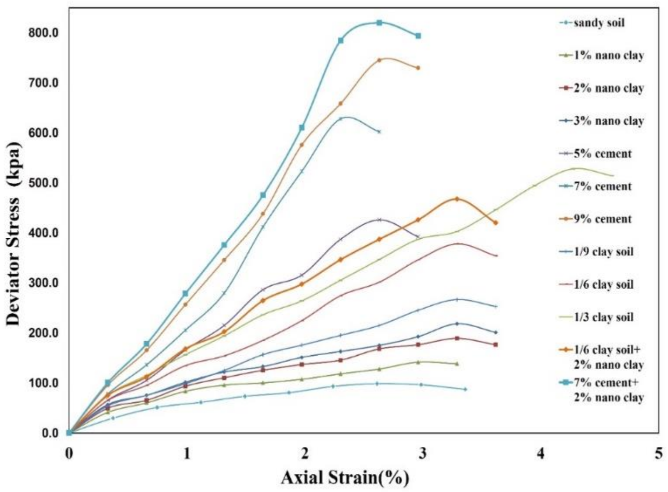

Figure 11. Compressive strength test diagram

According to the diagram of Figure (11), with increasing the percentage of mixing material, the compressive strength has increased in all three mixing designs of nano clay, cement and sticky clay. Figure (12) shows the trend of changes in maximum compressive strength in uniaxial experiments in mixing different materials.

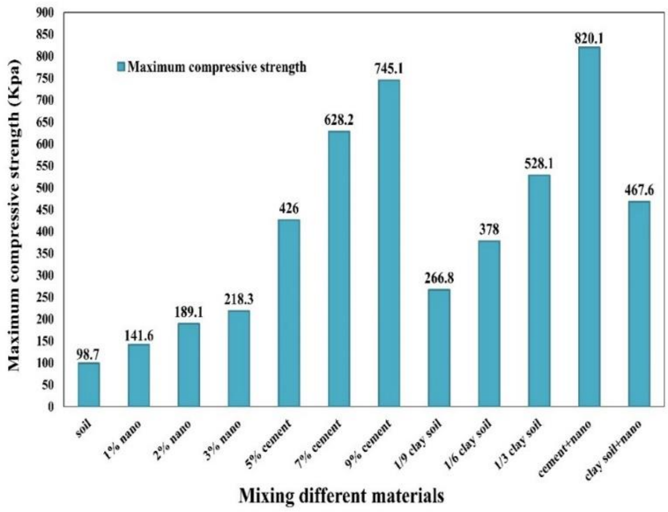

Figure 12. Diagram of maximum uniaxial compressive strength in different mixing designs

As can be seen, the highest strength trend is related to the cement mixing design, which has the highest compressive strength in the 9% cement. In addition, the lowest strength trend was related to the nano clay mixing design, the minimum value of which was calculated for the 1% nano clay mixing design and equal to 141.16 kPa. As we know, the presence of clay in the soil causes more compaction and adhesion. With the addition of nanoparticles, the porous structure of the soil is filled and uniform, and this uniform and dense structure has a major and important effect on increasing the compressive strength. Due to this, the resistance to deformation is increased and this issue is directly related to the adhesion due to the presence of nano clay in the soil, but this effect is limited compared to other methods. Increasing the compressive strength of cement-stabilized soils due to hydration of cement leads to the separation of calcium ions, which eventually react with alumina and silica in the soil, leading to the formation of pozzolanic products. These pozzolanic bonds, together with soil particles, form new bonds that are stronger than the main soil matrix [41]. It should be noted that the mixing design of 1.6 sticky clay with 2% nano-clay and the mixing design of 7% cement with 2% nano-clay were tested. For the first mixing design, the maximum compressive strength was 467.6 kPa and for the second mixing design, the maximum compressive strength was 820.1 kPa. The results of the direct shear test are shown in Figure (13).

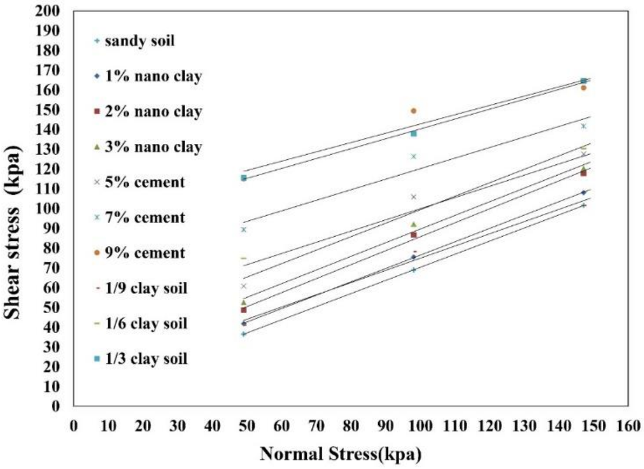

Figure 13. Direct shear test diagram

According to the diagram, the shear strength increases with a limited increase in the percentage of nano clay. Moreover, the y-intercept, which represents soil adhesion, has a limited increase with the addition of nano clay. Based on the results, nanomaterials have a slight effect on soil shear strength. The results also show an increase in shear strength by increasing the percentage of cement and adhesive clay mixing design. Adhesion is increased as in the nano clay mixing scheme, but the internal friction angle decreases as the percentage of cement increases. In general, the test results from different mixing designs show an increase in soil shear strength. Besides, soil strength parameters such as adhesion and internal friction angle are subject to changes under these different mixing percentages. The results show that the trend of change for cement and sticky clay is more than nano-clay. The greatest effect is observed in the 9% cement and 1.3% sticky clay. In the design of nano clay mixtures, the adhesion increases with increasing the percentage of nanomaterials. Also, the internal friction angle changes to a few degrees and is very limited, which indicates the low effect of nanomaterials on changes in internal friction angle. Another point is that with increasing the percentage of nano in the soil, the angle of internal friction decreases and has a similar function to the two composites of cement and adhesive clay. That is, initially with low percentages, the internal friction angle increases or remains somewhat constant, then with the increase of the composite material, this parameter has a downward path. This was investigated on the 5% and 7% nano clay mixing designs, which showed an increase in adhesion and a decrease in the internal friction angle of the soil.

Table (3): Different values of adhesion and friction angle for different mixing designs

mixing design	Adhesion (C) (Kpa)	Internal Friction Angle (Ø)
Sandy soil	٣/٩	٣٣/٥
1% nano-clay	٨/٨	٣٤/١
2% nano-clay	١٥/١	٣٥/٢
3% nano-clay	٢٠/٦	٣٤/٦
5% cement	٣١/٣	٣٤/٢
7% cement	٦٦/٨	٢٨/١
9% cement	٩٥/٨	٢٥/١
1/9 Sticky clay	١٣/٢	٣١/٦
1/6 sticky clay	٤٣/٣	٢٩/٥
1/3 sticky clay	٩٠/٤	٢٦/٥

Mohr Coulomb rupture cap is defined by two parameters: friction and adhesion. Nanoparticle-enriched soils generally have larger friction and adhesion angles due to increased bonding between nanoparticles and other soil particles, which ultimately results in relatively stronger, larger, and more dense masses in the soil. In other words, soil nanoparticles increase the shear strength of soil due to their locking effect in soil mass [34]yyyy. As mentioned before, with increasing nanomaterials, the adhesion and the angle of internal friction of the soil increase. However, the parameter of the angle of internal friction increases up to a certain percentage of mixing and then has a decreasing behavior. By increasing the amount of added adhesive, due to the increase in the fine-grained part of the soil and hence the increase in the plasticity index, the adhesion of the mixture increases. The higher the percentage of adhesive used, the higher the adhesion. Some reasons for decreasing the internal friction angle with increasing the adhesive are as follows.

-By adding the adhesive, due to the increase of the fine-grained part of the soil and its dominance over the coarser part, the mechanical behavior of the soil is more controlled by the fine part. By decreasing the grain efficiency, the internal friction angle parameter, which is a characteristic of coarser soils, is reduced. The composite substance in the mixture during contact with water, due to its gelling or thixotropic properties, plays the role of oily substances between soil particles and ultimately increases the ease of movement of soil particles on each other and reduces the internal friction angle.

-In mixtures containing higher percentages of the adhesive, due to the reduction of the maximum dry density, the soil compaction is reduced, and resultantly the contact of the particles with each other and their interlocking are reduced, hence decreasing internal friction angle.

In addition, the mixing design of 1.6 sticky clay with 2% nano-clay and the mixing design of 7% cement with 2% nano-clay were tested. For the first mixing design,

the adhesion parameter and the friction angle were calculated to be 50.33 and 28.76, respectively, and for the second mixing design, the adhesion and the friction angle were calculated to be 81.09 and 27.3, respectively.
Regarding the mixing of nanoparticles and cement, it should be noted that when a small amount of nanoparticles are evenly dispersed in cement, hydrated cement products sit on nanoparticles during hydration due to their high surface energy and turn into nanoparticle-containing masses. Nanoparticles in cement samples direct and affect the hydration process of cement due to their high activity. In other words, nanoclay acts as the filler of interatomic spaces inside the hardened skeleton of the cementitious microstructure, hence increasing the strength of the sample as well as its density. The results of the Brazilian tensile test are shown in Figure (14).

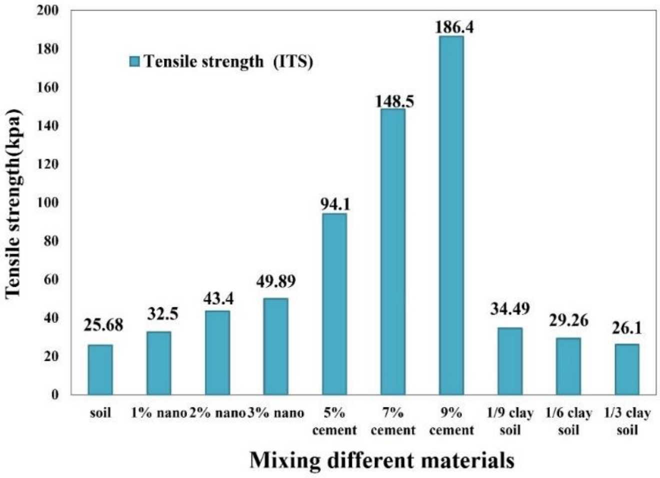

Figure 14. Tensile strength test in different mixing designs

The results show an increase in tensile strength with increasing the percentage of material in the cement and nano-clay mixture designs. However, the trend of increasing tensile strength was observed for cement mixing design more than nanoclay. Besides, the trend of changes for the adhesive clay mixing design decreases with increasing mixing percentage. The highest tensile strength was obtained for 9% cement mixing design. After adding cement to the soil, different reactions take place between the soil and the cement. The most important of these reactions are the positive ion substitution reaction and the aggregation-density reaction. In this reaction, the soil texture changes with the accumulation of soil particles (or its granulation) and thus its strength (compressive, tensile or shear) increases. The finer the cement particles, the greater the hydration, which might last for a long time, even many years. This leads to an increase in the strength of the cementitious composite over time.

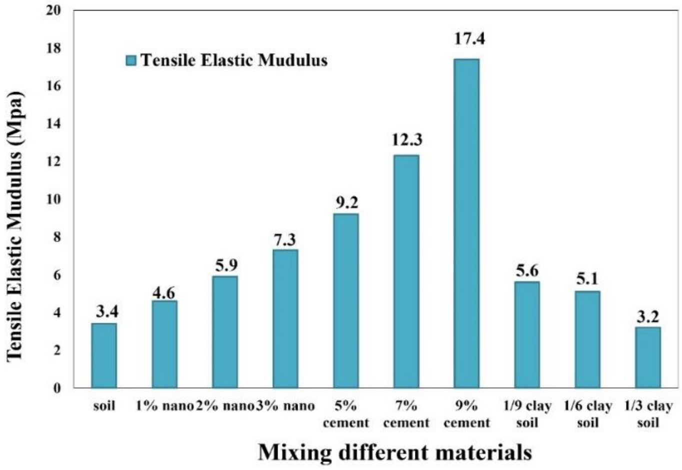

Figure 15. Tensile elastic modulus in different mixing designs

The results of changes in tensile elastic modulus in Figure (15) show the compliance of the trend of changes in tensile elastic modulus and the trend of changes in maximum tensile strength. Accordingly, with increasing the percentage of material, the elastic modulus for the cement-nano clay mixing design increases, whereas it decreases for the adhesive clay mixing design.

4.Conclusion

In soil compaction tests, nano-clay, cement, and clay all increase the maximum specific dry weight to a certain extent and then decrease it. On the other hand, they increase the optimum humidity. In this context, the best performance is related to the 1% nano-clay and 1.9% sticky clay.
In the Atterberg limits test, nano clay and sticky clay soils increase the plasticity index and cement decreases the plasticity index. In this regard, the best performance is related to 1.3 sticky clay.
In the compressive strength test, all the three materials increase the compressive strength of the soil, among which the 9% cement causes the highest compressive strength.
In the shear test, all the three considered materials increase adhesion. The highest adhesion is related to the 9% cement. On the other hand, the internal friction angle for nano clay is slightly changed and is reduced by the combination of cement and sticky clay.
In the combination of nano clay with cement, better performance was calculated in most experiments, so that with low percentages of cement and nano clay mixing design, we see better results than the separate mixing design of each of these materials. We can use this method instead of designing single-material mixtures. In the bearing capacity test, the combination of cement and nano-clay increases the bearing capacity and sticky clay reduces the bearing capacity. In the tensile test, nano clay and cement compounds increase the tensile strength and the sticky clay decreases this

strength. In this experiment, the highest strength is related to the 9% cement.

It should be noted that the nanoparticles used in this study are not toxic and the use of these nanoparticles in applied projects will not have a negative impact on the environment.

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