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Investigation of various nano-additives impact on the physical and mechanical behavior of expansive soil

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Abstract:
The current study aims to investigate the effect of adding Nano-silica (NS), Nano metakaolin (NMK), and Nano cement (NC) with various ratios into the expansive soil. The effect of adding nanomaterials on soil physical properties was measured. Then, Energy-dispersive X-ray (EDX) and Scanning Electron Microscopy (SEM) were performed to study the microstructure of the swelling soil. Finally, the effect of adding the previous three nanomaterials on the swelling indices of swelling soil was obtained. According to the results, NMK and NS improve soil swelling at a 2% addition ratio, while NC performs better at a ratio of 3%. SEM and EDX analysis showed that the small particle size for the NS and NMK represents the main factor that improves the swelling soil behavior, as they act as a filler for the interface spaces among soil grains. While the positive effect of adding NC results from the chemical hydration reaction effect.

Keywords: *Nano-silica, Nano metakaolin, Nano cement, Expansive soil, Free swell, Swell pressure test.*

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I. Introduction

Expansive soil has harmful effects on lightly loaded structures such as pavements and residential buildings as they are very sensitive to volumetric increase or decrease due to water content variations. This increase in volume produces uplift pressure under the foundations of structures resting on such soil [1,2]. As little as a 3% volume expansion might cause harm to a structure [3]. The amount of water in the near-surface (active) zone determines how much the earth can shrink or swell; considerable activity often occurs up to a depth of around three meters.[4–6].

Mainly, expansive soil consists of clay minerals that cause swelling by absorbing water such as smectite and montmorillonite, which exhibit high swelling with the increase of water content [2]. Montmorillonite mineral is a part of the smectite family that can absorb very large quantities of water molecules among its sheets, and subsequently have a large shrink-swell potential [7]. The shrink-swell ability of expansive soil is determined by its initial water content, internal structure, void ratio, and vertical stresses, as well as the type and quantity of clay minerals in the soil [5].

Many alternatives have been proposed to relieve the effects of swelling soil on civil infrastructures such as mechanical treatments, and chemical stabilization [8,9].In addition, the hydraulic barriers method is used where the compound effect of vertical and horizontal moisture-loss barriers is very successful when applied correctly [10].

Compaction is one of the popular methods to increase the bearing capacity as well as the improvement of subgrade soil and reduces swelling potential, S.P. Interparticle repulsive force can be minimized under compaction at less than optimum moisture content [11]. Mechanical treatment has been effectively used to reduce the swelling potential in expansive soils. Common inclusion materials are fibers and geosynthetics such as expanded polystyrene, EPS, geogrid, geonet, geomembrane, geocell, geocomposite, and other related inclusion products. Briefly, the three types of treatments described as mechanical are surcharge stresses, fiber reinforcement, and geosynthetics. [12,13]. In another study, the feasibility of depending on only sodium silicate in stabilizing swelling soil was investigated [14]. Results showed that the addition ratio of 10% of sodium silicate was able to control the swelling behavior of the investigated expansive chlorite soil sample. Earlier, the suitability of cement was studied as a stabilization material for expansive clay. Both cement and lime were used to treat swelling soils, and both showed a significant improvement in swelling indices. The swell percent and swell pressure were both minimized to zero with the addition of 6% lime.[15]

On the other hand, nanotechnology has become one of the most important and modern sciences and is considered a promising research field in recent years due to its availability of innovative materials that have contributed to solving many engineering problems[16]. In addition, it is a technology that allows us to develop materials with improved or new properties [17] .Nanotechnology refers to the use of very small pieces of material by themselves or their manipulation to create new large-scale materials. The size of the particles is the critical factor. At the nanoscale (anything from one hundred or more down to a few nanometers, or 10^{-9} meters) material properties are altered from that of larger scales, while the exact point at which this alert occurs depends on material nature.

In an experimental study by (Changizi & Haddad, 2017) [18], they investigated the use of glass fibers in combination with nano-clay to improve soil engineering qualities. Using clay soil with a low liquid limit, they plan to investigate the effects of applying nano-clay and glass fiber on soil mechanical characteristics, particularly shear parameters. The glass fiber and nano-clay ratios applied to the soil range between 0.5% and 1.5% addition ratio. This study's findings indicated that a considerable shear strength increase of up to 84% could be achieved depending on both the ratios of glass fiber and nano-clay that are used to improve the soil. In addition, the experimental results showed that binary usage of fiber and nano clay can increase the unconfined compression strength of the soil.

Later in a study by (Kulanthaivel et al., 2021) [19], the authors illustrated that adding Nano-particles, particularly Nano-silica and white cement as admixtures, improves the strength of clay soil. According to the findings of the tests, the best dosage of nano-silica and white cement was determined to be 2 % nano-silica and 3 % white cement by weight of soil. Furthermore, when the soil was treated with 2 % nano-silica and 3 % white cement, the permeability was reduced by 45 %.

(Ahmed, et al., 2021) [20] studied the effect of adding three percentages of Nano Cement-Waste (1, 2, and 3% by weight) to soft clay soil on mechanical and physical characteristics is shown by using the Oedometer and consistency tests. Prestressed kaolin clay was created as soft soil with an undrained shear strength of 0.35 kg/cm^2. The results for mechanical characteristics indicated that raising the NCW ratio increased shear strength and lowered settlement. For physical properties, the results showed a slight increase in the liquid limit (LL), and plastic limit (PL) by increasing the ratio of the NCW. While the plasticity index (PI) decreased by increasing the ratio of the NCW. Increasing the ratio of the NCW does not affect specific gravity (Gs). Generally, NCW improves the geotechnical properties of soft clay.

And then, in an attempt to improve the swelling soil behavior by using nanotechnology advantage the current study aims to investigate experimentally the effect of adding different nanomaterials. The experimental study was divided into three main stages that aim to obtain the physical properties, microstructural composition, and the basic swell indices of expansive soils. In the first stage, The effect of adding nanomaterials on Atterberg limits was measured for physical properties. In the second stage, Energy-dispersive X-ray (EDX) and Scanning Electron Microscopy (SEM) were carried out to study the microstructure of the swelling soil structure before and after adding nanomaterials at different percentages, as well as clarify the distribution of nanoparticles inside them. The third phase of the practical program studied the effect of adding the previous three nanomaterials on the free swell, swell pressure, and swelling potential of expansive soil.

II. Experimental work

Preparation method of swelling soil sample

To ensure the stability of the results. the decision was taken to use artificial (not natural) soil samples in the current experimental program. The control swelling soil sample is an admixture of kaolinite and bentonite according to a certain mixing ratio. Kaolinite has a very low swelling nature, but bentonite has an extremely high swelling nature. Therefore, the ratio of bentonite to kaolinite was chosen to achieve a high swelling, while keeping the overall swelling value at the realistic zone. The reason for choosing a sample with a high swelling is to capture the improving ratios in the swelling values. For the admixture of kaolinite and bentonite soil, the dry weight ratio was selected at (40%-60%) based on the results of the free swell (F.S), liquid limit (L.L), and plastic limit (P.L)

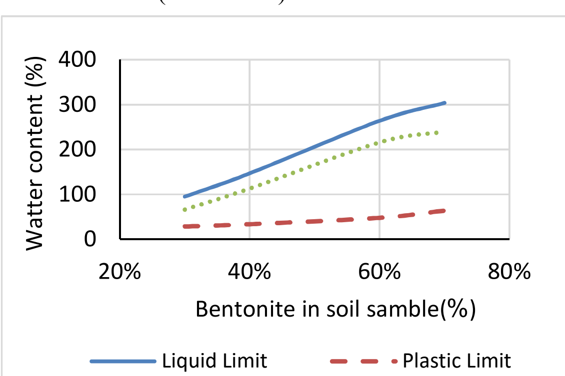

Fig. 2 Changes in the liquid limit, plastic limit, and plasticity index with (% bentonite) increase

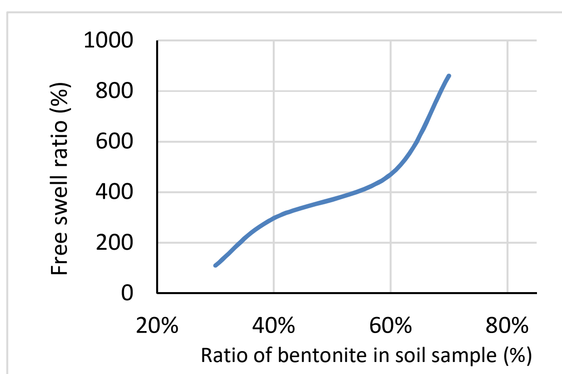

Fig. 1 Change in the free swell ratio with (% bentonite) incensement

tests as shown in **Fig. 1&Fig. 2**. At 60% bentonite, the accompanied free swell ratio was reported at 470%, which is high and suitable to represent swelling soil behavior.

Compaction test

Expansive soil and improved soil samples were compacted to achieve maximum dry density(MDD) and optimum moisture content(OMC) values. The objective of the compaction test is to determine the maximum density of the soil and the water percentage associated with it to standardize this percentage when conducting all tests. This action aims to maintain a stable behavior of the soil that is stable with the change in the percentage of water. Hence, the improvement rates can be determined for the soil after adding nanomaterials, making sure that the improvement is due to the addition of nanomaterials and not the change in compaction rates. The MDD and OMC were found to be 1.51 t/m3 and 25.75% respectively as shown in **Fig.3**.

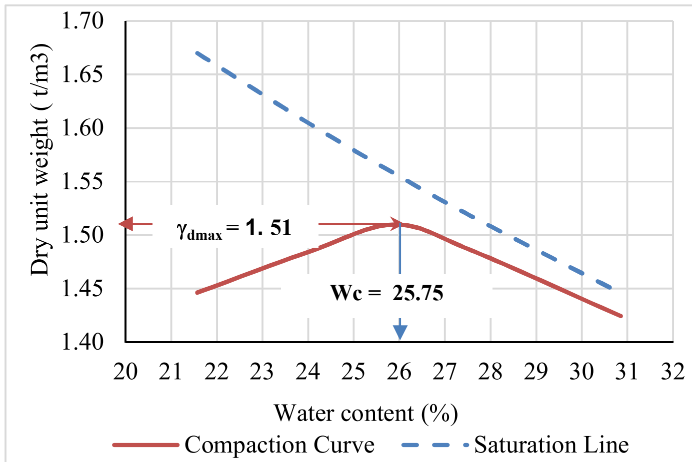

Fig.3 Optimum Moisture Content, O.M.C (%), and Max-Dry Density, MDD, (t/m^3)

Properties of the expansive soil

Several experiments were conducted to determine the properties of the artificial soil before adding nanomaterials, such as the atterberg limits, physical properties, swelling index, etc as illustrated in **Table 1**.

Table 1 Swelling soil properties

Property	Value
Specific Gravity, Gs	2.56
Silt Content (%)	31
Clay Content (%)	69
Liquid Limit, L.L, (%)	270
Plastic Limit, P.L, (%)	45
Plasticity Index, P.I, (%)	228
Shrinkage Limit, Sh. L (%)	27
Optimum Moisture Content, O.M.C, (%)	25.75
Max-Dry Density, MDD, (t/m^3)	1.51
Activity	3.29
Free Swell, F.S, (%)	430
Swelling Pressure, (kg/cm^2)	3.03

Energy dispersive X-ray (EDX) analysis was carried out on the soil sample to specify the mineral and oxide composition as illustrated in **Table 2** and **Fig.4**. Samples of about five grams for each sample were prepared and dried for 24 hours, then imaged using Carl ZEISS Sigma 500 VP that is available in the physics lab attached to the faculty of sciences, Fayoum University.

Table 2 Swelling soil EDX analysis for Chemical compositions

Oxide Composition	Mass %
Silicon dioxide (SiO_2)	61.5
Aluminum oxide (Al_2O_3)	24.55
Ferric oxide (Fe_2O_3)	6.78
Magnesium oxide (MgO)	2.37
Calcium oxide (CaO)	1.25
Sodium oxide (Na_2O)	2.25
Potassium oxide (K_2O)	0.51
Titanium dioxide (TiO_2)	2.04

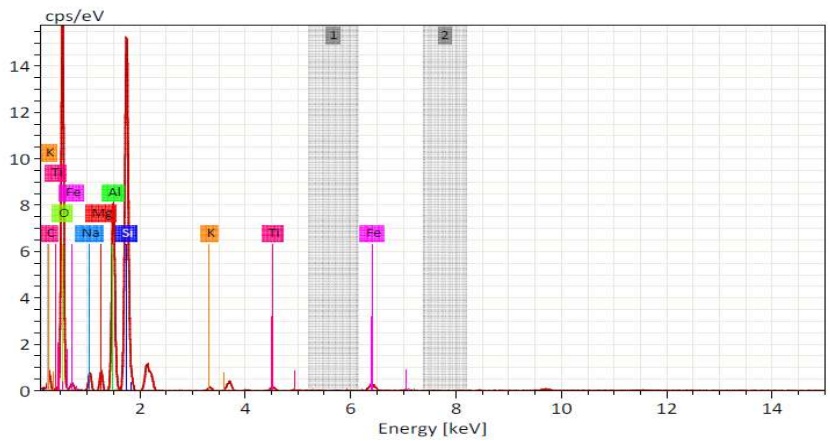

Fig.4 Types of minerals in the artifitial of expansive soil without nano-materials

Properties of nanomaterials

Three types of Nano-materials were used in this study, i.e., Nano-meta kaolin, Nano-silica, and Nano-cement. Properties of the Nano-materials are discussed in the following section.

Properties of Nano-silica NS

Amorphous Nano silica (SiO_2) with particle sizes ranging from 12-80 nm was used in the preparation of the Nano silica blended soil specimens. The Nano silica used is powder type, Colourless (White), and with an average density of 2.2 – 2.6 g/ml at 25 °C. The chemical properties of Nano silica used in this study are shown in **Table 3**. These Chemical compositions were obtained by analyzing EDX, Faculty of Science, Fayoum University.

Table 3 Chemical compositions of Nano silica

Oxide Composition	Mass %
Silicon dioxide (SiO_2)	99.20
Aluminum oxide (Al_2O_3)	0.40
Ferric oxide (Fe_2O_3)	0.10
Magnesium oxide (MgO)	0.07
Calcium oxide (CaO)	0.08
Sodium oxide (Na_2O)	0.05
Potassium oxide (K_2O)	0.06
Titanium dioxide (TiO_2)	0.04

Properties of Nano metakaolin NMK

The Nano Metakaolin is created from the heat treatment of kaolin. At around 900°C[21], this treatment breaks down the choline structure so that the alumina and silica layers wrinkle and lose their long-term arrangement, resulting in nano-metakaolin NMK used is a powder with an (off-white) color, with an average density of 0.5 – 0.9 gm/cm^3 at 25 °C. The chemical properties of the utilized NMK are listed in**Table 4**.

Table 4 chemical composition of Nano Metakaolin

Oxide Composition	Mass %
Silicon dioxide (SiO_2)	50.00
Aluminum oxide (Al_2O_3)	41.00
Ferric oxide (Fe_2O_3)	1.40
Calcium oxide (CaO)	2.20
Magnesium oxide (Mgo)	0.30
Potassium oxide (K_2O)	0.60
Titanium dioxide (TiO_2)	2.40
Sodium oxide (Na_2O)	0.10
Loss on Ignition	2.00

Properties of Nano cement

Nano cement was produced by grinding ordinary Portland cement of 42 grade in a high-intensity ball grinder for 18 hours. In a high-energy ball grinding milling machine, high-impact collisions were used to reduce microcrystalline materials down to Nanocrystalline structures without chemical change. Care was taken to avoid balling effect and agglomeration. The particle size of the NC is ranging from 40-100 nm, powder type, light grey color, and with an average density of 2.4 – 2.8 g/ml at 25 °C as. The chemical properties of Nano silica used in this study are shown in**Table 5**.

Table 5 chemical composition of Nano cement

Oxide Composition	Mass %
Silicon dioxide (SiO_2)	14.01
Aluminum oxide (Al_2O_3)	3.85
Ferric oxide (Fe_2O_3)	2.77
Calcium oxide (CaO)	58.90
Magnesium oxide (MgO)	1.47
Sulfur trioxide (SO3)	4.69
Potassium oxide (K2O)	2.6
LSF	8.22
SM	2.10
AM	1.39

Experimental program

The experimental protocol of this study was divided into three main phases. The first phase's scope was the specimen preparation criteria in addition to investigating the physical properties of the control and nano-supported

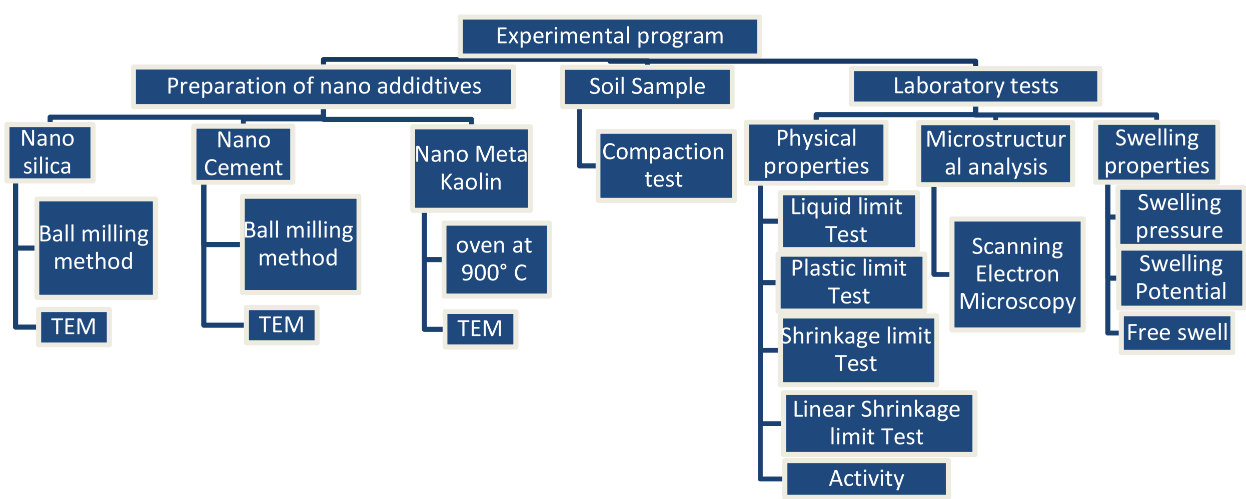

Fig. 5 Lay out of experimental program

soils by conducting various experiments such as Atterberg limits, shrinkage limit, and linear shrinkage limit. All these experiments were carried out on both control and nanomaterials-supported soils at different addition ratios (1, 2, and 3% of sample weight). The second stage was the study of the microstructure of either soil samples or nanomaterial additions used to improve their expansive behavior. In this phase, the EDX and SEM analysis were conducted order to provide a better understanding of the microstructure of the soil, as well as clarify the distribution of nanoparticles inside it. The third phase dealt with determining the swell values of control and nano-supported soils, either through the free swell test or mechanically through the swelling pressure and swelling index tests. In the current section, a detailed description of the used materials and control soil sample properties is previewed, in addition to clarifying all the experiments implemented through the practical program of this study, whether related to experiments to determine indicators of soil swelling, or the devices used to study the microstructural composition of different soil samples. ***Fig. 5*** shows the general layout of the experimental tests through the three phases of the current study.

III. Test setup

Preparation of nanomaterials

Mechanical milling is faster than the chemical method for producing materials at the nanoscale level from bulk materials. Nano Cement has been obtained upon doing chemical analysis and has been modified via mechanical activation (Ball Milling). The mechanical activation is applied to obtain a small Nano homogeneous particle size. The right selection of duration and speed of milling is very important for producing nanomaterials, and it can be obtained by trial and error.

Nano metakaolin is produced as a result of the process of heat treatment of kaolin at a very high temperature. At about 900˚ C, the extreme energy which is generated by thermal treatment breaks down the microstructure of kaolin such that the alumina and silica layers become puckered and lose their long-term order, producing Nano metakaolin NMK.

Microstructure test

SEM can offer clear, high-resolution images of the size and surface texture of particles, allowing researchers to discriminate the interfering particles. In addition, SEM or environmental SEM equipped with EDX can determine the main atomic composition of putative plastic particles, which is useful for identifying carbon-dominant plastics from inorganic particles[21–25]. Inorganic plastic additives, such as titanium dioxide nanoparticles, barium, sulfur, and zinc, were identified by SEM/EDX [27].

Swelling pressure test.

The swelling pressure test aims to measure the swell coefficients according to [28] when exposed to water. The coefficients include swelling pressure (SP) and swelling potential (S%). An odometer apparatus was used for carrying out the swelling pressure tests having a diameter and height of 750 and 20 mm respectively. The sample was completely immersed in water and left for one day until it reaches the state of equilibrium. Reading of the odometer is recorded before and after the immersion. For most soils, the test continues for 14 days. Then, the test ended when there is no volume change recorded in the specimen for 24h. In this study, the swelling potential was defined as the maximum recorded swell at the end of the test. The system has been loaded with (0.23,0.68,1.81,4.08,6.34 and 8.61 kg/cm^2) and the reading is recorded at every loading stage. Then, the pressure was estimated corresponding to the point of intersection of the stress-strain curve with the horizontal line for a swell ratio equal to zero.

IV. Result and Discussion

Effect of Nano- additives on physical properties.

Effect of Nano- additives on Liquid Limit.

It is clear from **Fig. 6** that the expansive soil takes a different approach when adding Nano-cement, which will be confirmed successively by the rest of the laboratory experiments. The liquid limit is significantly lower than the control sample by 36 %, which in turn indicates a change in the soil's ability to absorb water. On the other hand, the expansive soil showed no change in the liquid limit when adding nano-silica and a slight change when adding nano-metal-kaolin.

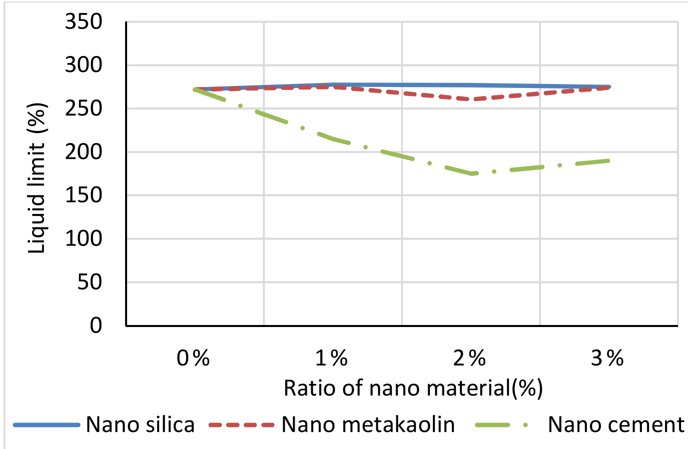

Fig. 6 Effect of Nano- additives on Liquid limit

Effect of Nano- additives on plastic Limit.

Fig. 7 indicates that the Plastic limit of swelling soils when adding nano-meta-kaolin behaves moderately and changes slightly when compared to nano-cement or nano-silica. In addition, it shows that the Plastic limit of the swelling soil supported with nano-cement has higher values than the other samples. This indicates the ability of the sample to form is low compared to the rest of the samples. This can be explained that nano cement needs a portion of the water content to complete the hydration process. however, the differences are not as large as the differences in liquid limit value. The plasticity index depends on the liquid limit more than the plasticity limit .In other words, since the plasticity index depends on the liquid limit, which means that the change in the plastic limit value is considered secondary and does not significantly affect the value of the plasticity index. Is known that the plasticity index depends on the liquid limit and the plasticity. Where the PI is defined as to be the difference between the LL and the PL.

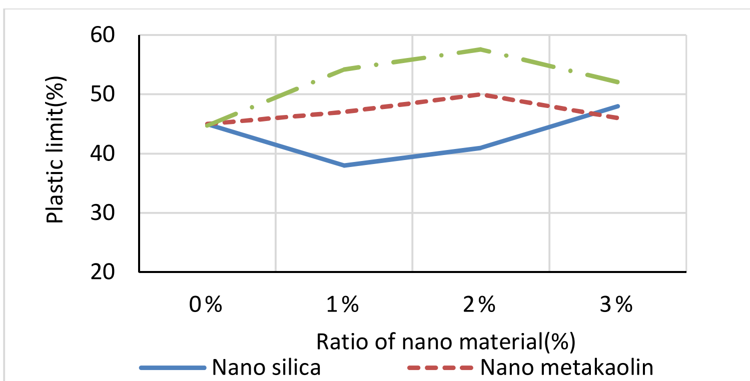

Fig. 7 Effect of nano- additives on Plastic limit

Effect of Nano- additives on linear shrinkage limit.

Fig. 8 shows the values of shrinkage limits at the various types and addition ratios of nano additives. Nano cement is the best resistant to decreasing size change and the most resistant to cracking. On the other hand, the difference in the improvement ratios and the behavior of nano-meta-kaolin appears, as it shows less behavior in the resistance compared to nano-silica.

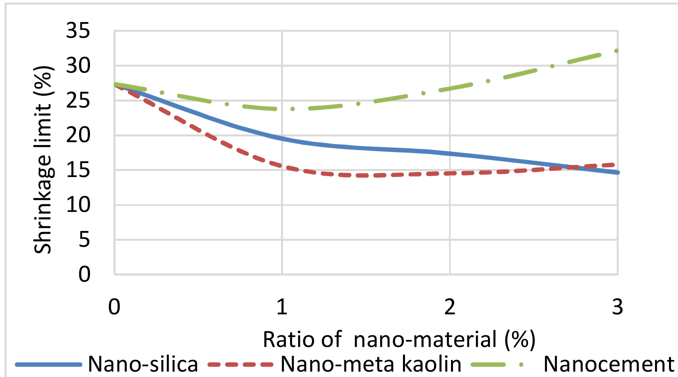

Fig. 8 Effect of Nano -additives on shrinkage limit

Accordingly, the behavior of the samples for the three nanomaterials in the Atterberg limits tests can be explained, where the nano-cement sample needed less water to reach the liquid limit, as the nano cement grains (due to the size of their ultra-fine particles) coated the soil sample. After hardening occurred as a result of the cement hydration reactions, the hardened cement nanoparticles formed a barrier around the charged clay soil particles, preventing more water from being drawn into them. In the same context, it is possible to understand the need for soil samples treated with nano-cement for a greater amount of water compared to the rest of the samples to reach the plasticity limit. As the initial hardening of the sample prevents the sample from forming. Consequently, it needs larger quantities of water compared to the NS and NMK, which do not have a hydration process due to the arrival of water.

Effect of Nano- additives on shrinkage limit

Fig. 9 shows the results obtained from the linear shrinkage limit test for the three types of nano-supported soils under study. The shown curves indicate that there is no large difference in the value of linear shrinkage between the three types of nano-treated soils. The results show that the difference between the highest value of the aforementioned coefficient (at nano cement) and the lowest value (at nano metakaolin) does not exceed 8%, where the higher value of this coefficient means a greater ability of the soil to resist volume shrinkage changes when water is withdrawn from it. The advantage of nano cement over the other two types of nanomaterials can also be explained by the occurrence of a degree of hydration as a result of the chemical reaction with water and the occurrence of hardening of the sample combined with the soil.

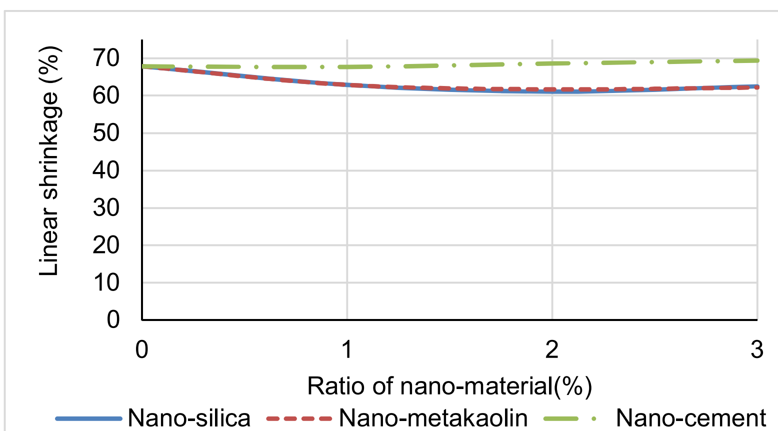

Fig. 9 Effect of nano- additives on Linear shrinkage

Effect of Nano- additives on Activity

Fig. 10. shows a similarity in the behavior of the three Nanomaterials with each of the following properties that are liquid limit, plastic limit, and shrinkage. In addition, the significant change in the activity value when adding Nano-cement confirms the superiority of Nano-cement over the rest of the used nanomaterials. As the chemical changes resulting from the hydration reactions led to a change in the physical properties. Which in turn supported the concept of improving swelling soil.

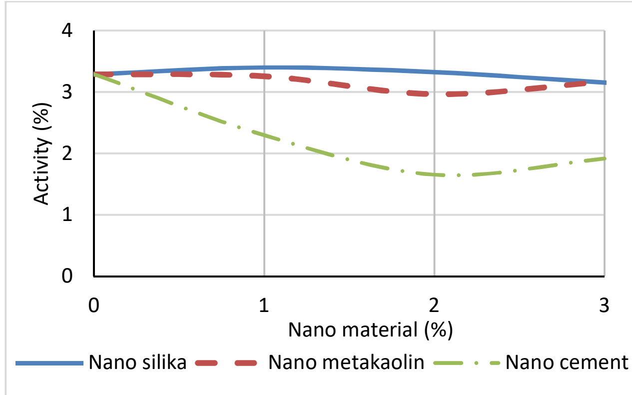

Fig. 10 Effect of Nano -additives on Activity

Effect of Nano- additives on mechanical properties.

Effect of Nano additives on free swell ratio.

Fig. 11 shows the free swell ratios and improvement rates obtained from the free swell test for the soil samples with various nano additives at addition ratios of 1, 2, and 3% of the sample weight. For the NMK and NS samples at the first addition zone (0-1)%, it is noticed that the rates of improvement in each of them are equal and they behave with the same behavior. On the contrary, NC shows lower rates of improvement. As a general observation, it's possible to say that the point of 2 % nano addition is the critical one on the swell behavior of the three samples. At the intermediate addition zone (1-2%, there is no enhancement was recorded for the NMK samples has an improvement rate compared to nano-silica.It's worth mentioning that the three curves intersect at the added value of 2.6 % of the sample weight. Consequently, it could be concluded that the three nano additives have the same positive effect on the swell behavior of expansive soil at the addition rate of 2.6 % with an improving ratio of 32.5 % (as obtained from the free swell test). At the third addition zone (2-3% of sample weight), the NS sample continued at the stable improving rates (with a lower slope of improving curve) that reached approximately 34%. On the contrary, the NC sample showed a sharp increasing slope of the improvement curve. Results indicated that at a 3% addition ratio, the NC additives have the best-improving effect among the three nanomaterial additives with a ratio of 47%.

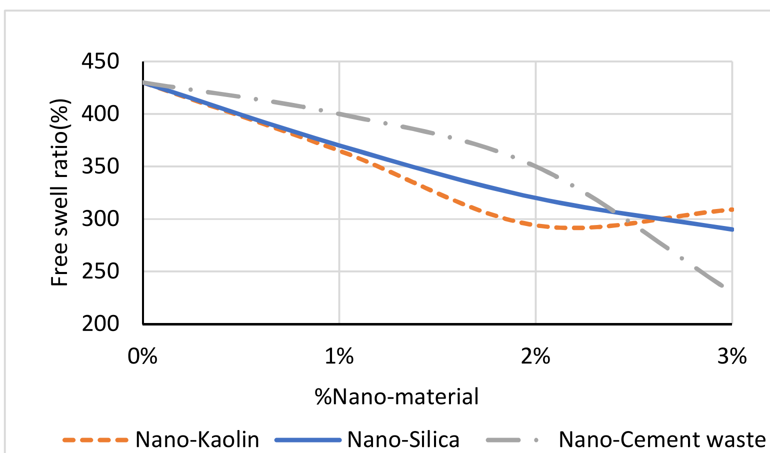

Fig. 11 Effect Nano additives on free swell test

Effect of Nano additives on swelling potential index.

Fig. 12 illustrates the results of the swelling potential test for the three nano additives at the same studied addition ratios. The previous curve shows propinquity in the behavior when adding nanomaterials with the results of the free swelling test in terms of the optimal nano additives and percentages of additions, but with some differences in the improvement percentages and curve slopes. For example, when adding 1% of NMK, the improvement percentage remains the best compared to the other two nano additives, but it is noticed that the differences in the improvement rates are closer when compared to the free swelling test results. In addition, nano-silica additive showed stability in the improvement rate when the addition rates changed from 2 to 3 percent, in contrast to the result of the free swelling test, where the improvement continued at the same two percentages. It is also noted that the improvement rates in the swelling potential test are relatively less than the improvement results in the free swell test. These results are logically acceptable due to the difference in the test mechanism in terms of the presence of an external load during the swelling potential test, and the low water content compared to the free swell test. Despite this change in the improvement rates, the addition of nano-cement still gives the best improvement in terms of resistance to soil swell, followed by nano-silica and nano-meta kaolin, respectively. for the NMK sample, it is obvious that there is a negative effect of using it at dosages over 1% of the sample weight as a continuous decrease of the curve slope is recorded.

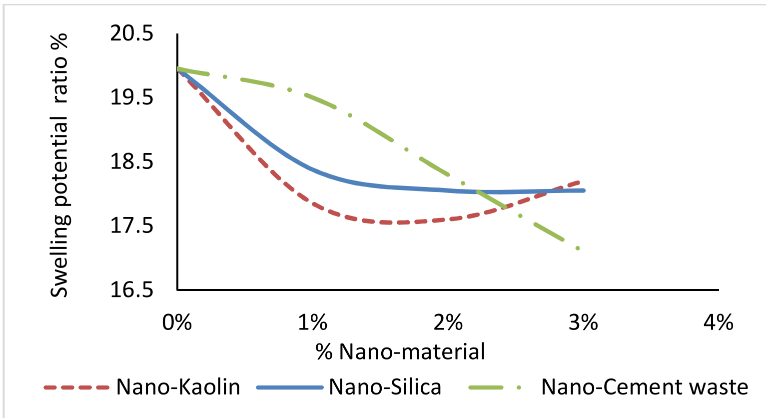

Fig. 12 Effect Nano additives on swelling potential indicator

Effect of Nano additives on swelling pressure.

The swelling pressure test is one of the most important tests adopted in the evaluation of soil swelling. While experiments such as free swell and swelling potential are strong indicators of the extent of the soil's susceptibility to swell, the swelling pressure test is the main and most reliable test in simulating the extent of soil swelling under the influence of the loads on it. The swelling pressure test is used in determining the swelling pressure resulting from the soil, which in turn is an indicator of the extent of expected damage to the structure as a result of soil swelling. The following curves summarize the results of the swelling pressure test which is the main test in the experimental work of the current study for the various types and ratios of Nano additives.

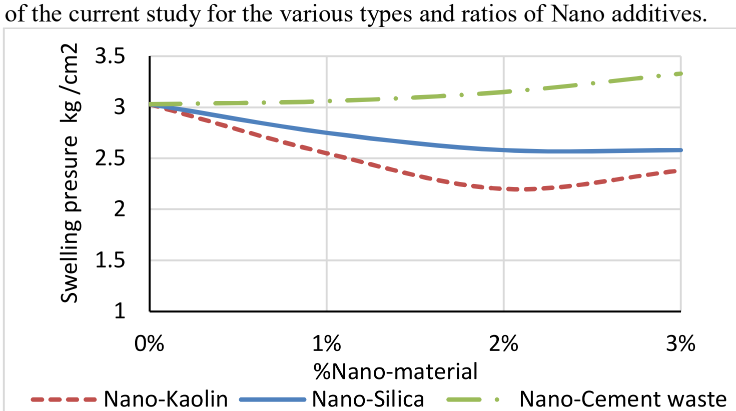

Fig. 13 Effect Nano additives on swelling pressure

The curves shown in **Fig. 13** can be commented on in two stages. First, concerning Nano-silica and Nano metakaolin, the addition of Nano metakaolin shows the best improvement rate for soil swell at 2% addition compared to the rest of the nanomaterials. Also in the total percentages of addition, Nano metakaolin can be considered the best material for different percentages of addition, where the optimum improvement percentage reached 27% at a 2% addition rate, and these results converge with the results of the free swell test. It can also be noted that increasing the percentage of adding nanomaterials to more than 2% of the sample weight is of no great benefit in improving its ability to swell. Secondly, concerning the mechanism of action of Nano-cement to improve soil swelling, the results of the swelling pressure test may lead to a kind of confusion in the interpretation of the behavior of this addition, especially compared to the results of the experiments of free swell and swelling potential.

Results of adding Nano-cement in the swelling pressure test show a significant increase in the value of the swell load needed to return the samples to their initial position, and therefore a decrease in the value of the improvement even when compared to the control sample. These results can be explained by comparing the mineral and chemical composition of Nano-cement and soil used in practical experiments. The chemical composition of the soil under study shows the presence of high percentages of the two substances of silicon dioxide (SiO_2), which is an important material in the cement process and helps to increase hydration rates and calcium silica hydrate (C-S-H) gel composition which is the major hydration product of Portland cement that works to give cement materials their strength[29]. Moreover, Al_2O_3 nanoparticles act as a nucleation site to generate the needed energy of the hydration process that contributes to the strengthening gain for the cement compositions[30].

Based on the foregoing, the soil sample under study was exposed to a degree of hydration that contributed to the hardening of the sample and gave it a high ability to resist the loads involved, which are considered pressure loads in the current experiment. Consequently, the swelling pressure test results are not evidence of the inability of Nano-cement to improve soil resistance to swelling, as the results of Nano-cement are the best if the behavior of the sample related to its exposure to the hydration process associated with cement compounds is explained.

Optical observations

It was observed that the samples with Nano-silica and Nano metakaolin and Nano cement soil have a denser soil surface structure than the untreated expansive soil. In addition to that, it was observed during the laboratory experiments related to the linear shrinkage and shrinkage limit that crack width and quantity in the Nano-modified samples were better than the control one. As shown in following **Fig. 14 & Figure *15***This can be explained as follows:

The sample with 3% Nano-cement has the least percentage of cracks in terms of quantity and crack width. This is observed through sample No. 4 in **Fig. 14 & Figure *15***. On the other hand, control sample No. 1 shows the worst behavior of crack resistance. Moreover, samples No. 2 and 3 of the swelling soils supplemented with 1% Nano Meta Kaolin and 2% Nano Silica, respectively, show moderate behavior in improving the control. But the sample to which Nano-silica is added, its behavior is better than the one to which metakaolin is added.

Fig. 14 Shows the shape of the cracks by shrinkage limit test

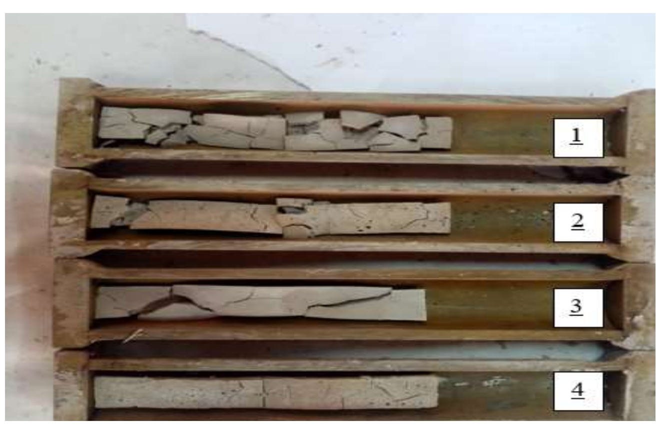

Figure 15 shows the shape of the cracks by a linear shrinkage test.

Scanning Electron Microscopy (SEM) analysis

SEM analysis shows several changes to samples that were treated with nanomaterials, which vary according to the type of nanomaterial used. This can be explained by the optical analysis of the samples at the micro and nanoscale. Microscopic images show the microstructure of four samples. In the first image of the control swelling soil under study, the second sample of the soil was enhanced by adding 2% of nano-silica, the third sample was enhanced by adding 2% of nano-meta kaolin, and finally, which was enhanced by adding 3% of nano-cement. The ratios in which the images were taken are attributed to the optimal ratios of each nanomaterial

Optical analysis of Micro-scale

Fig. 16. A shows the control expansive soil sample at the vision scale of 100 micro-meters. There are many voids and cracks in the sample structure. The lack of cohesion between the soil particles can be attributed to the loss of moisture from the sample as a result of drying it before carrying out the SEM test. While the subsequent figures will show a remarkable improvement in the microstructure of the soil after being reinforced with additions of nanomaterials.The other three parts of Fig. 16**. (B,C,D)** show the microstructure composition at the 100 µm scale of nano-supported soils at the optimum addition ratios. For the 2% nano-silica, **Fig. 16 (B)** shows a significant improvement in terms of reducing the size of the total voids and reducing the number and size of cracks in the sample. A similar improvement also appeared in the case of adding 2% NMK, where the cracks almost completely disappeared from the sample with the presence of some voids and pits in separate and unconnected places in the sample as shown in **Fig. 16 (C**). Concerning the sample reinforced with nano-cement, it should be noted that the sample prepared for testing was of a large degree of hardness, and to be able to perform the test, part of the sample was broken. **Fig. 16 (D)**shows the microstructure of the nano-cement sample, which appears almost free of cracks, and with a large degree of occlusion. Concerning the little voids in the sample, most of them are the result of the sample's instability when it is broken to prepare it for testing. The figure shows the effect of the cement hydration reaction, which caused a large coverage and coating of the surface of the soil sample.

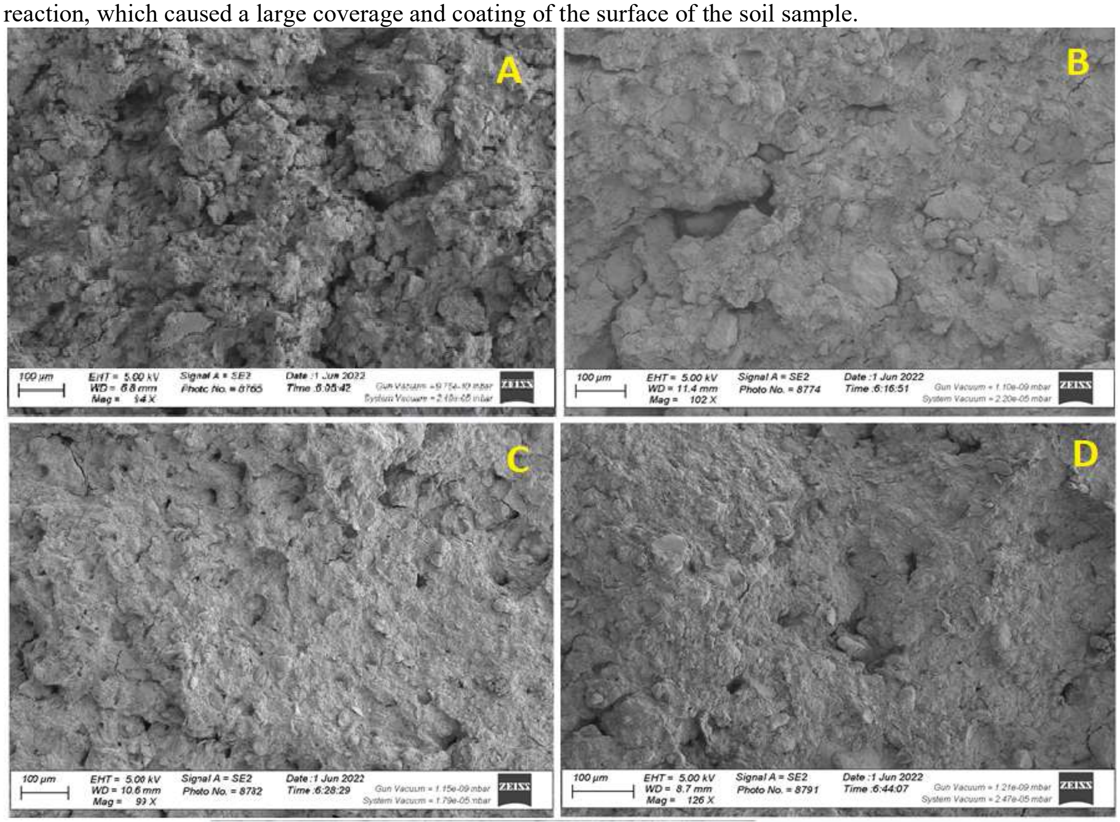

Fig. 16 SEM Image of expansive soil at 100 µm of (A) control,(B) control treated with 2 % Nano silica,(C) control treated with 2 % Nano metakaolin (D) control treated with 3% Nano cement

Optical analysis of nanoscale

Fig. 17 was detected using the maximum reduction degree in the device used to conduct the SEM test. ***Fig. 17***(A) clearly shows the sample of the swelling control soil, and it consists of overlapping slices punctuated by many large cracks and voids. This vision is consistent with what was mentioned in the literature review chapter of this thesis, where it is known that the clay soil consists of a group of overlapping ***Fig. 17***(B)& ***Fig. 17*** (C) show the mechanism of action of nano-silica and nano-mica kaolin materials, as they act as filling materials for voids and cracks inside the soil, and the better the degree of dispersion and distribution within the soil, the better results can be obtained for improving the physical and mechanical properties and resistance to swelling. Finally, ***Fig. 17*** (D) clearly shows the mechanism of action of nano-cement entering the soil, where large contiguous blocks appear free of voids, as a result of the effect of the hydration reaction of the cement and the formation of the cement paste that works to cover the entire surface of the soil.

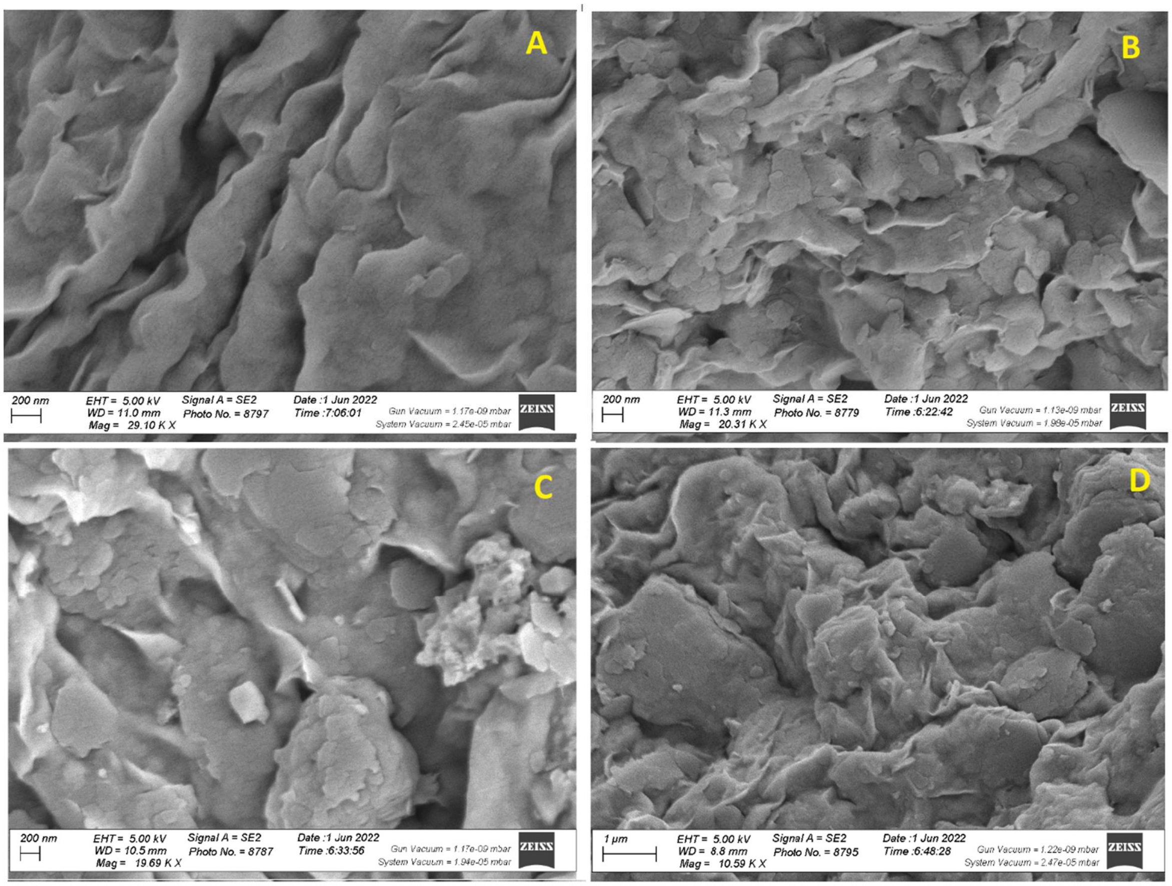

Fig. 17 SEM Image of expansive soil at 200 nm of (A) control,(B) control treated with 2 % Nano silica,(C) control treated with 2 % Nano metakaolin (D) control treated with 3% Nano cement

Conclusion

The main objective of the current study is to investigate the effect of adding several nanomaterials to expansive soils to improve their swelling behavior. The chosen nanomaterials used in this study (Nano-silica, Nano metakaolin, and Nano-cement) lead to remarkable enhancement in the swelling behavior. Based on the results of the current experimental study, the following conclusion can be made:

1- The liquid limit of the sample treated with nano cement is significantly lower than the untreated sample by 36 %, which in turn indicates a change in the soil's ability to absorb water. the Plastic limit of the swelling soil supported with Nano-cement has higher values than the other samples. This indicates the ability of the sample to form is low compared to the rest of the samples. On the other hand, there is no significant change when adding Nano-silica and Nano-metakaolin compared to adding Nano-cement.

2- Shrinkage and linear shrinkage limit curves showed an increase in Nano cement samples starting from 1%, and this increase means a greater ability to resist volume changes and shrinkage.

3- The activity value increased by 49% when adding Nano-cement. On the other hand, the value did not change significantly when adding Nano-silica and Nano-metakaolin.

4- The hydration process occurs due to the presence of 58.9% Cao in the nano-cement with other oxides of swelling soil samples such as SiO_2 at 61.5% and Al_2O_3 at 24.55 %. This was determined from an EDX test.

5- For the free swell test, which is an indicator of soil susceptibility to swelling, the optimal addition ratios of the investigated nanomaterials (nano-silica, nano meta kaolin, and nano cement) were (1, 2, and 3%), where the improvements ratios are (32.5, 28.13, and 46.5%) respectively.

6- Results of the swelling potential test showed a similarity in the optimal percentages of additions with the free swelling test, but the optimal improvement percentages varied, as it was recorded at (9.52,11.77, and 14.28%) for the (nano-silica, nano metakaolin, and nano cement), respectively.
7- For the swelling pressure test, adding 2 % of nano-silica and nano-metakaolin reduces swelling pressure by 14.85% and 27.4, respectively.
8- Nano-cement showed a different and confusing behavior from the other two nanomaterials, as its addition to the soil led to a noticeable increase in the value of the swelling pressure by 9.9% when adding 3% of nano-cement. It makes the soil harder as a result of the interaction of hydration with water particles.
9- SEM, XRD, linear shrinkage limit, shrinkage, liquid limit…..etc, shows that both nano-silica and nano-metakaolin act as fillers that occupy the interspaces in the soil, which prevents more water from entering the soil, and thus reduces its swelling rates. On the other hand, the mechanism of improving nano-cement for the behavior of expansive soil depends on making the soil harder as a result of the interaction of hydration with water particles coming to the soil, which gives the sample great resistance to pressure loads and a greater ability to resist formation and volume changes.
10- Nano cement shows the best Nano material used to improve the swelling soil when 3% is added, despite the confusion about the swelling pressure values.

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