Using Nanomaterials in Stabilization of Soil for Oil Infrastructures

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Abstract:

The design foundations of storage tanks for oil industry experiences significant problems due to the widespread occurrence of weak and compressible soil which resulted in foundation failure. In this study, soft soils were taken from two locations and mixed with three types of nanoparticles which were nano-alumina (nano Al_2O_3), nano-copper (nano CuO), and nano-magnesium (nano MgO). Nanomaterials were incorporated in small percentage (less than 1%) by dry weight of soil. The tested geotechnical characteristics included the water content, dry density, and the unconfined compressive strength. The results showed significant enhancements in the maximum dry density and unconfined compressive strength. The level of enhancement depended on the type of nanomaterials and the contents. Improved strength and hardening properties were shown with the utilization of nano CuO material in comparison to the soil samples with the other nanomaterials additions, with its optimum addition of 0.7% provided an increment rate of 662.7% while the optimum nano CuO which is about 1% showed a 532% increasing rate in the compressive strength of S1 soil. It was noted that the maximum dry density and unconfined compressive strength enhanced with the increase in the nanoparticles content until reaching a percentage in which the strength decreased. The optimum content of the nano MgO was 0.3% while the optimum nano Al_2O_3 content was about 0.3% for soil S1 and was about

0.1% for soil S2. The presence of nanomaterials in excessive contents caused agglomeration of particles which had negative influences on mechanical characteristics of the soils. Generally, the incorporation of finer particles like nanoparticles even with low amount would improve the geotechnical characteristics of soils with the consideration of the potential environmental benefits, these combined admixtures are intended to lower the cost and become a more sustainable and environmental alternative for soil stabilization.

Keywords: Soil stabilization, Nanomaterials, Maximum dry density, Soft soil, Unconfined compressive strength.

استخدام المواد النانوية في تثبيت التربة للبنية التحتية النفطية

الخلاصة:

يواجه تصميم أساسات خزانات التخزين لصناعة النفط مشاكل كبيرة بسبب كثرة الترب الضعيفة والقابلة للانضغاط مما أدى إلى فشل الأساس. في هذا البحث، تم أخذ التربة الناعمة من موقعين و خلطها مع ثلاثة أنواع من الجسيمات النانوية وهي نانو ألومينا (نانو Al_2O_3)، نانو نحاس (نانو CuO)، نانو مغنيسيوم (نانو MgO). أدرجت المواد النانوية في نسبة صغيرة (أقل من 1٪) بالوزن الجاف للتربة. وتضمنت الخصائص الجيوتكنيكية التي تم اختبارها محتوى الماء والكثافة الجافة وقوة الضغط غير المحصورة، ولقد أظهرت النتائج تحسينات ملحوظة في أقصى كثافة جافة وقوة ضغط غير محدودة، ويعتمد مستوى التحسين على نوع المواد النانوية والمحتويات.

تم تحسين خصائص التحمل والصلابة المحسنة باستخدام مادة نانو CuO مقارنة بعينات التربة مع إضافات المواد النانوية الأخرى، مع إضافتها المثلى بنسبة 0.7٪ التي قدمت معدل زيادة 662.7٪ بينما أظهر النانو CuO الأمثل حوالي 1٪ 532٪ معدل زيادة في قوة الضغط للتربة S1. ولوحظ أن أقصى كثافة جافة وقوة انضغاط غير محصورة تعززت بزيادة محتوى الجسيمات النانوية حتى تصل إلى نسبة تقل فيها القوة. كان المحتوى الأمثل للنانو MgO 0.3% بينما كان المحتوى الأمثل للنانو Al_2O_3 حوالي 0.3 ٪ للتربة S1 وكان حوالي 0.1 ٪ للتربة S2. تسبب وجود المواد النانوية في المحتويات المفرطة في تكتل الجسيمات التي لها تأثيرات سلبية على الخصائص الميكانيكية للتربة. بشكل عام، فإن دمج جزيئات دقيقة مثل الجسيمات النانوية حتى مع كمية منخفضة من شأنه تحسين الخصائص الجيوتكنيكية للتربة مع مراعاة الفوائد البيئية المحتملة ، وتهدف هذه الخلطات المشتركة إلى خفض التكلفة وتصبح بديلاً أكثر استدامة وبيئيًا لتثبيت التربة.

1. Introduction

Storage tanks are widely spread where the oil industry represented by producing and refining crude oil . Nevertheless, large storage tanks with diameter larger than 76 m are rare and need soil with considerably high bearing capacity to lower settlement to sustain the rigid skid system. For such sensitive structures, careful investigations and design are required, most importantly where the underneath soils have seasonal variations in engineering characteristics [1, 2].

Ideally, sensitivity structures like large tanks are built on pile as foundation, particularly in sites consisted of thick compressible soils having problems of settlement and seasonal variations. Nevertheless, the utilization of pile can be uneconomic when the thickness of clay soil is large [3]. For example, the pile foundation in many sections of the mangrove swamp is considered uneconomic for large tanks because of the thick compressible clay layers. The issues associated with pre-loading is that consolidation of the subsurface layers is considerably low due to the unfavourable situations occurred in the site represented by clay sediments that have low permeability and thickness of compressible layers [1]. Figure (1) showed photographs of storage tank problems in petroleum sector.

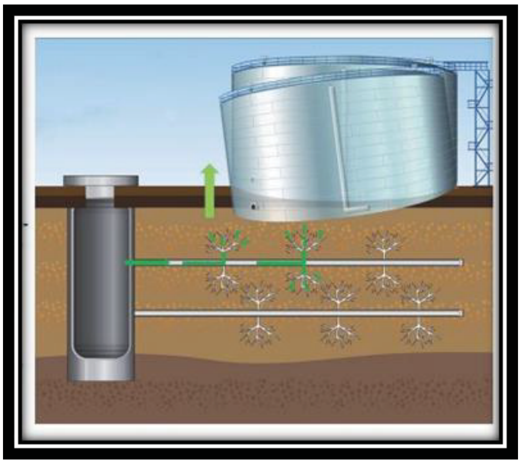


Fig. (1) Storage tanks problems in petroleum industry.

Soft soils presented conventionally in areas that have high moisture content. When the Moisture content reached liquid limits, the soils would exhibit low shear strength and high level of settlement [1]. Hence, the construction on these soils required selecting firm and strong foundations in order to meet the criteria of settlement and bearing capacity both before and after construction. Soil stabilization is the method utilized to improve soil properties in order to meet specifications of various projects [4, 5]. Many authors have studied the stabilization of various types of soft soils utilizing various materials. Lime, cement and by-product like silica fume, rice husk ash, and fly ash are the conventional materials utilized for enhancing soils [6, 7, 8, 9, 10].

Nanotechnology is the technology working on creating various types of nanomaterials (NM) and their applications in many sectors. This typically can be donated as NP i.e. nanoparticles. NM is referred to material with size of 100 nm or lower in term of the dimensions [11, 12]. In geotechnical engineering, the major nanotechnology strategy is the enhancement of soil poor characteristics with the addition of nanomaterials. The chemical and physical properties of soil can significantly be influenced with the presence of only a small quantity of nanomaterials in the soil because of the morphological characteristics as well as the high surface area and charges of such substances.

Recently, significant attentions have been paid to the utilization of nanoparticles due to the possibilities of using them in various applications and their low cost, high reactivity and eco-friendly green aspects [13, 14, 15]. Biosynthesized nanomaterials have beneficial features represented by using them in biomedical, agriculture and engineering industry [16, 17].

In soil stabilisation, various studies were conducted for investigation of effect of using nanomaterials on the properties of weak soils. [18] Investigated the strength and plasticity characteristics of a soft soul treated with a nanomaterial. Through unconfined compressive strength and Atterberg limits tests, they reposted that the mixture of Modified Montmorillonite Nano clay with the soil considerably enhanced the unconfined compressive strength and increase the plasticity index of the soil. [19] Studied the effect of four kinds of nanomaterials (nano-alumina, nano-silicanano-silica, nano-copper, and nano-clay) on the stabilisation of a collapsible soil. They found that the physical and chemical properties of soil could be enhanced by the use of appropriate amount of nanomaterials. [20] found that the use of recycled polyester fiber and nano-silicon dioxide increased the unconfined compressive strength, shear strength and modulus of elasticity of soft clay [21] indicated that the inclusion of nanoparticles in kaolin clay led to an increase in the shrinkage limit and a reduction in the total volume of the treated clay. [22] In their research indicated a considerable reduction in swelling and enhanced workability of an expansive soil stabilized with nano-alumina and nano-magnesium oxide. [23] Conducted a detailed study for evaluating the influence of using nano-copper, nano-clay, and nano-alumina on the shrinkage and expansion characteristics of clay. Their results indicated that the use of nano-alumina decreased the shrinkage and expansion strains though nano-clay had a small influence. While, the use of nano-copper had a more positive influence on the shrinkage and expansion strains in comparison with nano-alumina. The nano-copper density increased the specific gravity of the treated soil, increasing the soil maximum dry density and thereby reducing the expansion and shrinkage strains.

This work aims to study the effects of incorporating nanomaterials in the soft soils in petroleum industry. Different soils have presented in such areas including soft soils which are characterized by variation in the lateral and vertical strength and compressibility in addition to influence of seasonal changes in moisture contents. Thus, these soils need enhancement which determined by soil peculiarity and sensitivity of the structure to the ground placed on. Three types of nanoparticles were used for the stabilization which were nano-alumina (nano Al_2O_3), nano-copper (nano CuO), and nano-magnesium (nano MgO). The unconfined compressive strength was used to indicate the mechanical characteristics of the soil samples while the physical properties were treated using the standard proctor test.

2. Materials And Methodology:

2.1 Soils:

Two locations in Malaysia were selected to extract two types of soft soils used in this study. Soil (S1) was taken from Transkrian, in the State of Penang while soil (S2) was extracted from Banting, in Selangor, Malaysia. The depth of excavation ranged from 0.5 to 1.0 m and all the soil samples were distributed. They were excavated by hand shovels and taken from bottom of the borrow pit. Table (1) gives the index characteristics represented by plasticity index (PI), Unified soil classification (USCS), and grain size fraction of the selected soils. Soil S1 had a relatively low specific gravity (Gs) because of incorporating high amount of organic substances in compared to soil S2. Hence, soil S1 was indicated to be organic (OL). Also, the soils were kind of acidic which is the conventional type of soil presented in tropical areas.

Table (1) The characteristics of the soft soils both physical and chemical one.

Characteristic	Standard	Value and description	
		S1	S2
Gs	ASTM D 854	2.42	2.75
pH	ASTM D4972	3.24	4.25
Organic content (%)	ASTM D 2974	12.17	1.31
Clay fraction (%)	ASTM D 422	29.8	36.2
Silt fraction (%)	ASTM D 422	31.3	31.3
Sand fraction (%)	ASTM D 422	38.9	32.5
Liquid limit index (%)	BS 1377 part 2 1990	46	51
Linear shrinkage (%)	BS 1377 part 2 1990	11	8
PI index (%)	BS 1377 part 2 1990	18	26
OMC (%)	ASTM D 698	21.60	24.80
MDD (kN/m^3)	ASTM D 698	14.44	15.68
USCS	ASTM D 2488	OL	CH

2.2 Nanomaterials:

The main characteristics of the utilized nanomaterials were illustrated in the Table 2 . It was indicated that the nano MgO, the nano Al_2O_3, and the nano CuO had 99.99 % purity and were all obtained from the Inframat Advanced Materials, Manchester, CT, USA. In addition, the largest specific gravity was for the nano CuO powder with 100 nm average particles diameter. Whereas, the nano MgO and the nano Al_2O_3 had a specific gravity of 3.6, with (20-50) nm range of particles diameter.

Table (2) The main characteristics of the utilized nanomaterials

Property	Nano MgO	Nano CuO	Nano Al_2O_3
Formula	MgO	CuO	Al_2O_3
Average particle size (nm)	25-30	100	20-50
Specific gravity	3.60	6.40	3.60
Purity (%)	99.90	99.99	99.99
Surface area (m^2/g)	N/A	>150	>50
Appearance	White	Black powder	White

2.3 Methods:

Soil samples were subjected to compaction at their maximum dry density (MDD) and optimum moisture content (OMC) utilizing standard compaction test. The soil samples subjected to compaction were both the untreated and treated ones (soils treated with nanoparticles (i.e., nano CuO, nano Al_2O_3, and nano MgO). The moisture content-dry density relationship was calculated depending on the standard proctor test and according to ASTM D 698 specifications.

Compacted samples were taken by placing tubes with 38 mm in diameter in the soil utilizing a compression machine. Samples were extruded from the tube using an extruder, after that they were cut into 89 mm long samples. Immediately then, all samples were tested utilizing a test carried out in accordance with the ASTM (D2166-65).

3. Results and Discussion:

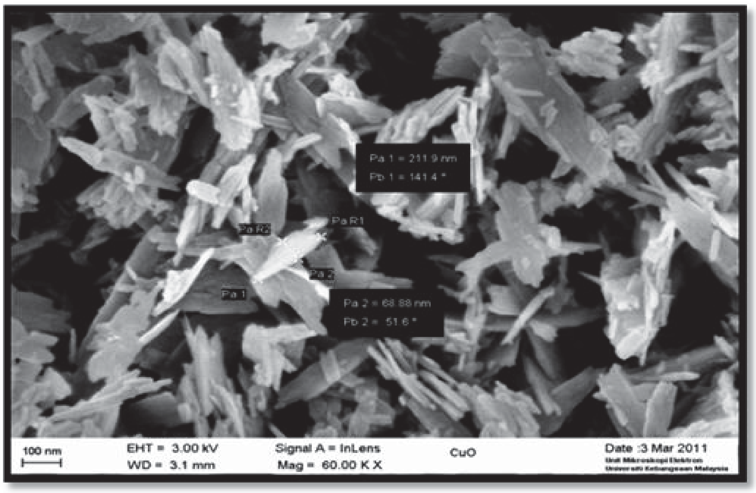
Figures 3 and 4 showed the relationships between the optimum water content and the maximum dry density of the utilized nanomaterials. The effects across the different types of nanomaterials used indicated almost similar maximum dry densities were with nano CuO provided the highest results. On the other hand, noticeable fluctuations were indicated from the effect of the different nanomaterials used on the optimum water content. From those figures, it was also indicated that for soil S1, the addition of all types of nanomaterials increased both the maximum dry density and the optimum water content. In general, a maximum dry density increase indicates strength improvement of the soil. This result was in agreement with those of the [24] who stated that compaction is influenced by some factors including specific gravity and the particle size of the stabilizer and the soil. The optimum moisture increase was related to the excess absorbed water that held in the flocculent structure of the soil due to its porous nature. This additional water in the soil can be justified by its content of organic materials.

However, for soil S2, the use of all types of nanomaterials reduced the optimum water content and increased the maximum dry density. The optimum water content reduction was attributed to the nanomaterials tendency of absorbing the moisture from the soil as previously explained. Also, the high surface area of the nanomaterials can reduce the optimum water content [25] which in turn can result in a decrease in the soil voids' number [26]. The dry density increase can be related to the high density of the nanomaterials in comparison with that of the soil. Moreover, the nanoparticles filled the pores between the soil particles and thereby reducing the porosity and bonding the particles together.

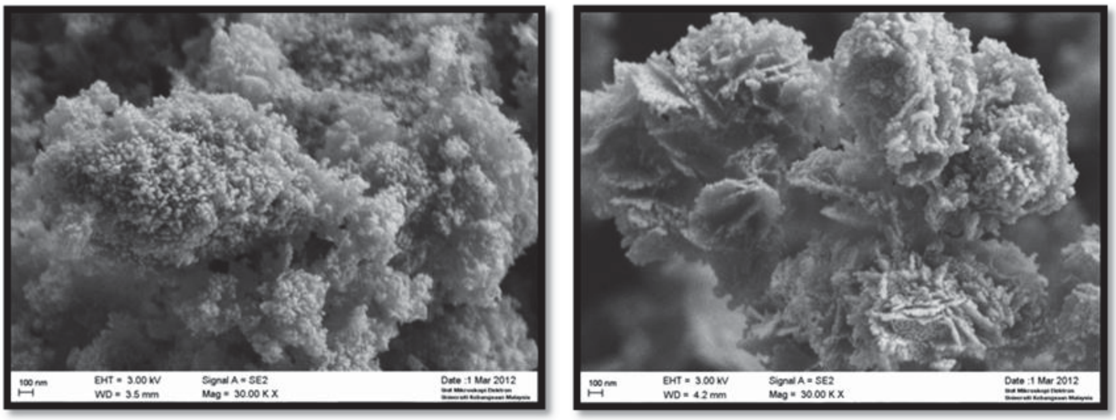
For soil samples with various nanomaterials contents, the unconfined compressive strengths were indicated in Figure (5). It can be observed that the unconfined compressive strength increased with the increment in the nanomaterials contents, and with a general increasing trend throughout the increment of the nanomaterials contents. The results indicated that soil with nano CuO addition had the maximum shear strength. Also, improved strength and hardening properties were shown with the utilization of nano CuO material in comparison to the soil samples with the other nanomaterials addition. That can be attributed to the nano CuO having a high specific gravity in comparison with the other nano additives.

Nevertheless, the unconfined compressive strength only increased slightly with the increment beyond the optimal content of the nanomaterials. For an instance of soil S2 sample, the optimum addition of 0.7% of nano CuO provided an increase from 43 kPa of the control soil to 328 kPa which equalled an increment rate of 662.7% while the optimum nano CuO of about 1% showed a 532% increasing rate in the compressive strength of soil S1. [27] also found a considerable increment in the unconfined compressive strength of highly clay soil of about 343% upon treatment with 1.5% nano CuO. That considerable soil compressive strength improvement at less than 1% content of nano addition were also obtained with the utilization of the other nano additives in this research (i.e. nano MgO and nano Al_2O_3). The optimum content of the nano MgO was 0.3% providing a small compressive strength improvement of about 5.6% for soil S1 and a considerable strength improvement of about 341.8% for S2. Whereas, the optimum nano- Al_2O_3 content was about 0.3% for soil S1 with compressive strength improvement of 111% and was about 0.1% for so S2 with compressive strength improvement of 400%. The results were in a good agreement with those of the [28, 23].

It was noted from below figures that for all types of nanomaterials used, the improvements in compressive strength of the treated soil S2 were considerably higher than those of the soil S1. This could be as a result of the organic content of the soil S1. [29] Reported that the presence of high organic content can reduce the formation of stabilisation products since it influences the chemical reactions of the nanomaterials with soil. However, in general, the strength of soil depends on its type and the numerology of clay.



(a) Nano-Copper Oxide (CuO)



(b) Nano-Alumina (Al2O3) **(c) Nano-Magnesium (MgO)**

Fig. (2) The SEM of the nanomaterials utilized in this study

The SEM images of the nanomaterials utilized in this study were shown in Figure (2). As previously mentioned that the responsible for the compressive strength increase is the chemical reaction between the fine grained soil and the nanomaterials. The S2 soil sample micrograph which contained the optimal nano Al_2O_3 content of 0.1% was demonstrated in Figure (5-a). The micrograph showed the rod-like crystals, i.e. ettringite, formation which filled the voids and attached the soil and nanoparticles together thereby possibly causing the overall strength increase. Whilst, Figure (5-b) demonstrated a micrograph of S2 soil sample containing 0.3% nano MgO. This illustrated the growth of the ettringite crystals on the clay-relics surfaces in addition to the nucleation of the crystals with the nano MgO particles.

As illustrated in the two parts (a and b) of Figure (6), the micrographs of the mixtures of the nanomaterials and the soil indicated the formation of crystals with a needle like shape nanostructure representing a new phase of an interlocking network. Then, between adjacent particles of the soil, bridges were formed. The crystals grew in the interstices, forming a continuous network that was later prescribed on terms of the soil strength improvement.

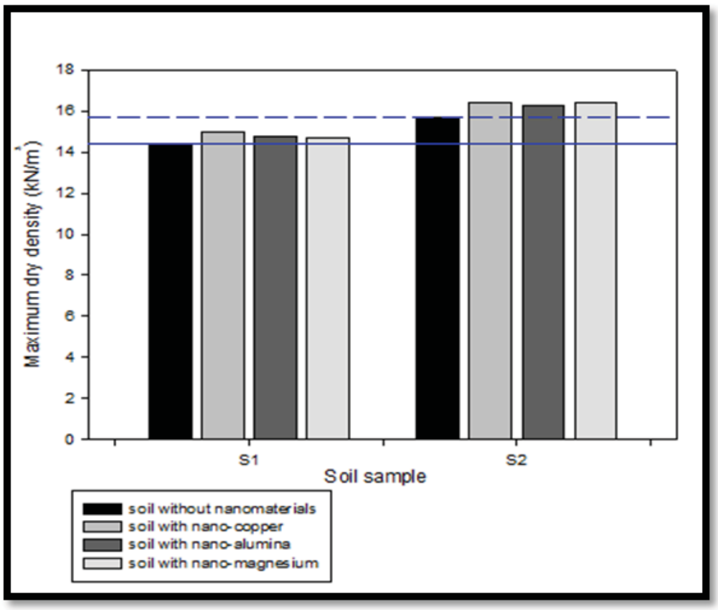


Fig. (3) The impact of the nanomaterials on the maximum dry density, $\rho_{d(max)}$

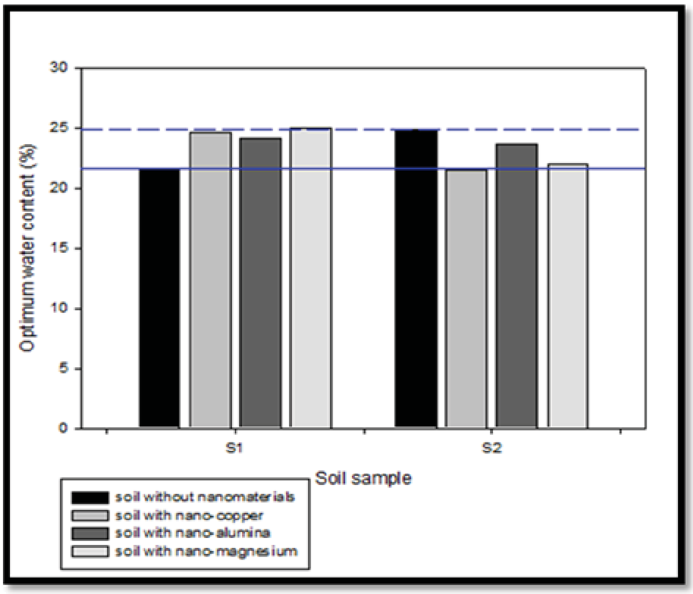


Fig. (4) The impact of the nanomaterials on the optimum water content, w_{opt}

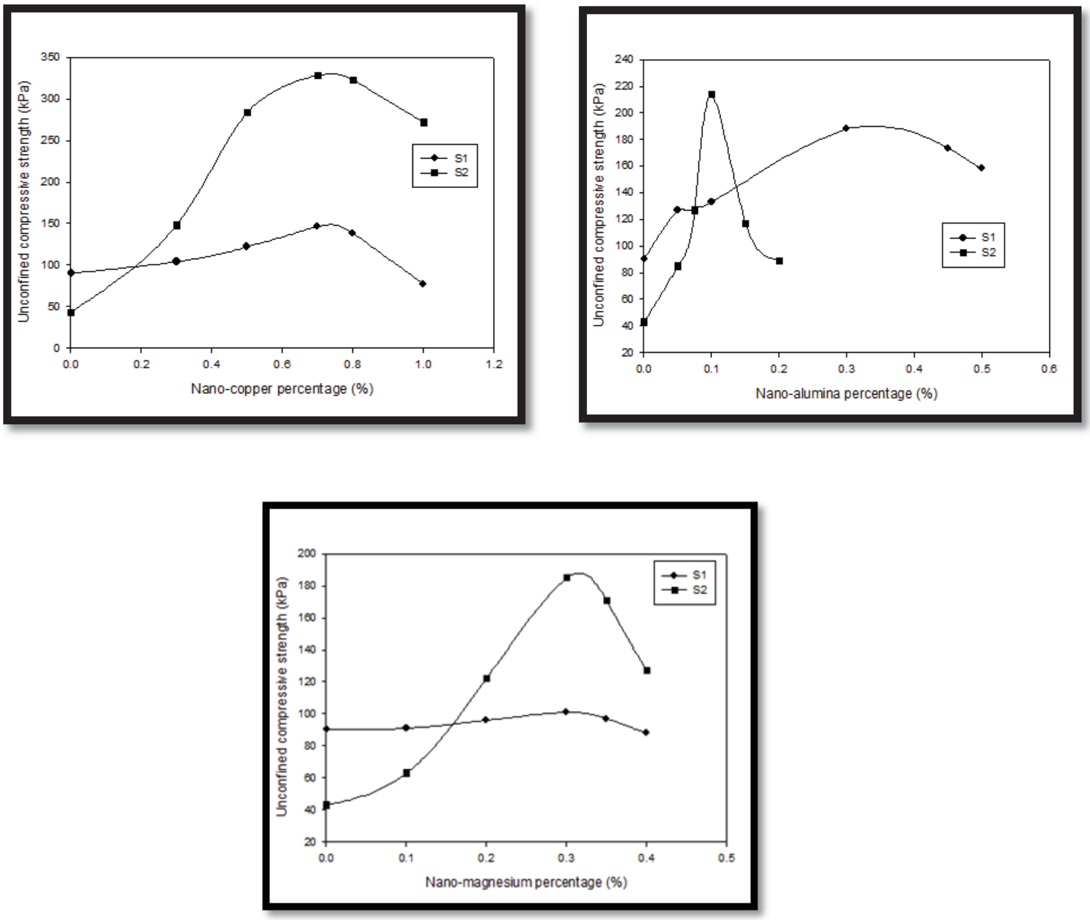
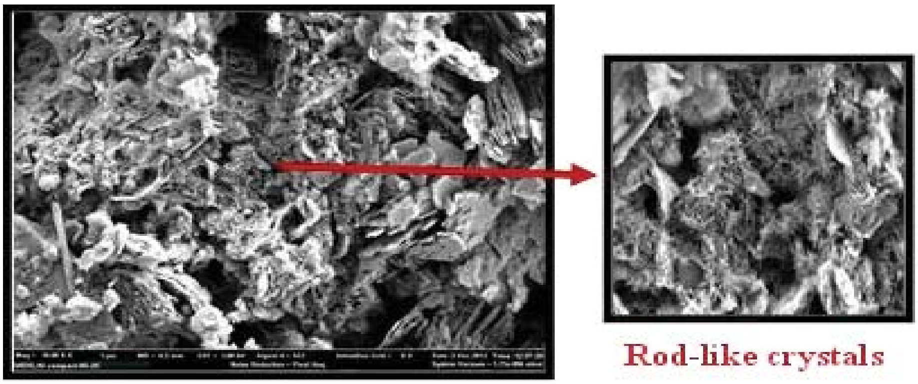


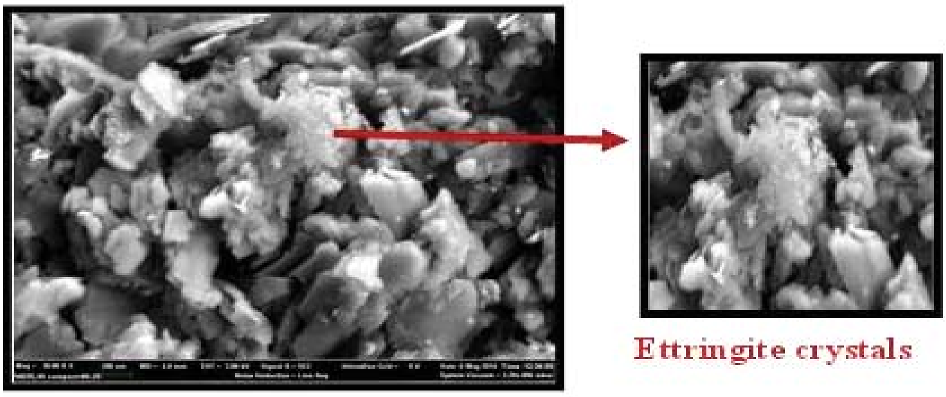
Fig. (5) The impact of the nanomaterials on the unconfined compressive strength, UCS

The increment in the amount of nanomaterials beyond their optimum might led to the agglomeration of nanoparticles which caused a void ratio increase, density reduction, and water content increase. The agglomeration of the nanoparticles was evident as adversely impacted the soils mechanical characteristics. The agglomeration represents a natural phenomenon involving particles sticking to solid surfaces and to each other which causes a size enlargement. According to [30] for nano-scaled particles, the agglomeration phenomena increase the necks amount between particles and thereby reducing the soil density.

The phenomena were illustrated in Figure (7) in which the images of the SEM showed that the S1 soil sample of 0.8 nano CuO (part a) and the S2 soil sample of 1.0% nano CuO (part b). The agglomeration of the nano particles occurred when the content of the nano CuO increased beyond its optimal limit of 0.7%. It should be noted that the same magnification of 25000 KX were used for taking all of the SEM photos.

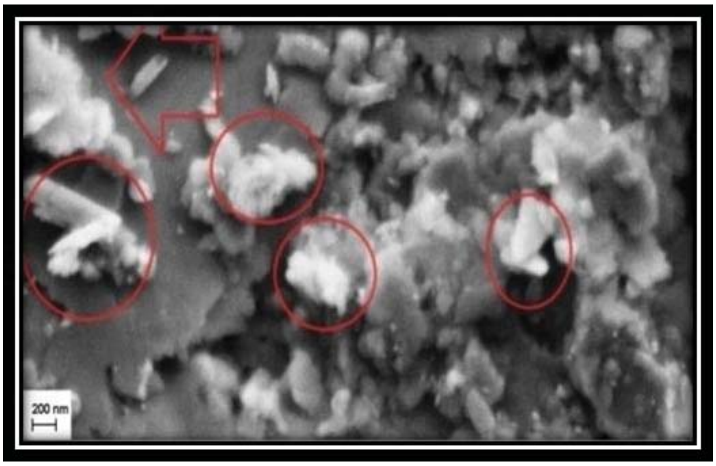


(a) S2 with 0.1% nano

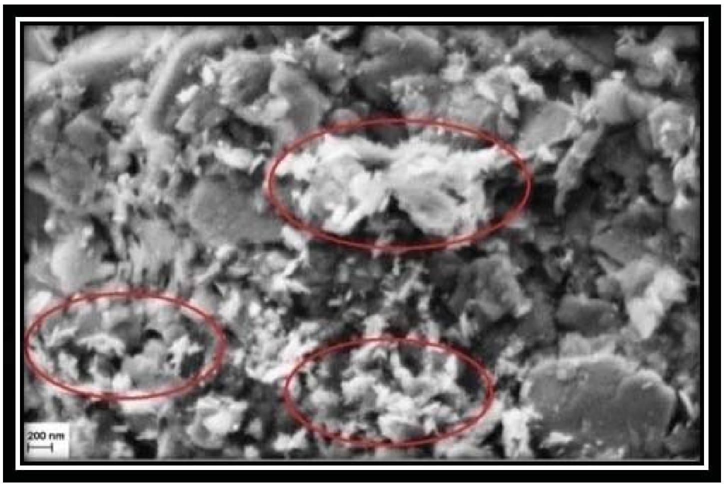


(b) S2 with 0.3% nano MgO

Fig. (6) The nanomaterials chemical action under the SEM-micrograph



(a) S1 with 0.8 % nano CuO



(b) S2with 1% nano CuO

Fig. (7) Nano-copper agglomeration beyond its optimal content

4. Conclusions:

This study was carried out for investigating the impact of using three types of nanomaterials (nano CuO, nano MgO, and nano Al_2O_3) on some of the geotechnical characteristics of soft soil. The tested geotechnical characteristics included the water content, dry density, and the unconfined compressive strength. The results indicated that the increment in the nanomaterials content increased both the dry density and the compressive strength and decreased the moisture content of the soil mixtures. The effects across the different types of nano materials used indicated almost similar maximum dry densities was with nano CuO provided the highest results. On the other hand, noticeable fluctuations were indicated from the effect of the different nanomaterials used on the optimum water content. Also, improved strength and hardening properties were shown with the utilization of nano CuO material in comparison to the soil samples with the other nanomaterials additions, with its optimum addition of 0.7% provided an increment rate of 662.7% while the optimum nano CuO of about 1% showed a 532% increasing rate in the compressive strength of soil S1. That considerable soil compressive strength improvement at less than 1% content of nano addition were also obtained with the utilization of the other nano additives in this research (i.e. nano MgO and nano Al_2O_3). The results also indicated that for all types of nanomaterials used, the improvements in compressive strength of the treated soil S2 were considerably higher than those of the soil S1. This could be as a result of the organic content of the soil S1. Moreover, there was evidence of particles agglomeration when the amount of the nanomaterials increased more than their optimal content, affecting negatively on the mechanical characteristics of the soils. Generally, the utilization of nanomaterials in small quantities of no more than 1% improved the geotechnical characteristics of the soil by enhancing the durability and strength of all soils that were tested in this study. Such results indicated the possibility of utilising the nanomaterials to enhance the strength and other properties of soils, though further research should be carried out for examining the cost effectiveness of their utilization in soil improvement.

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