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Improved Mechanical Properties of Clay Soil Modified by Activated Nano White Cement and Nano-Silica Mixture

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Abstract
In Egypt, the Kaolin soil is the most widespread dispersion. So, it has appeared to the necessary to investigate new techniques for improving the performance properties of these soils, especially for highway construction. This study aims to assess and compare the efficiency of nano-white cement in enhancing the mechanical properties of kaolin alone and kaolin mixed with nano-silica. The results of the compaction tests of the kaolin soil treated with different percentages of nano-white cement revealed a decrement in the maximum dry density, the plasticity index, and the workability. While they had elevated the optimum moisture content, plastic limit, Liquid limit, and unconfined compressive strength. The tested samples treated only with nano-silica reached their maximum strength properties with a concentration of 0.9% nano-silica then declined. The samples treated with the lowest percent of nano-silica and the different percentages of nano-white cement recorded higher readings in the unconfined compressive strength compared with the result of the sample treated with the highest percent of nano-white cement individually. Furthermore, the SEM images of treated samples represented the physical and chemical bonds between soil particles, nano-white cement, and nano-silica. In conclusion, the nano-white cement and nano-silica additive mixtures have a powerful improving effect on the mechanical properties of kaolin soil than the nano-white cement additive only. From the results, the nano-additive (nano-silica) in tested clay blended with nano-white cement had a significant positive effect on the behavior of clay soil. So, using additives and activators on a nanoscale has economic feedback with a positive ecological effect.

Keywords
Nano-white cement, Nano-silica, Kaolin soil, Unconfined shear strength, Soil stabilization

1. Introduction
Geotechnical properties of soils have a critical role in civil engineering construction like road work, foundations, embankments, and dams. Soil stabilization objectives are to ameliorate soil strength and raise resistance to softening by water bonding the soil particles together, waterproofing the particles, or integrating the two methods (Afrin, 2017; Ayininuola and Balogun, 2018).
The two main categories of the soil stabilization processes are mechanical stabilization and chemical stabilization. Mechanical Stabilization is the process in which the soil's properties can be improved by changing its gradation. The chemical stabilization process of expansive soil comprises changing the physical-synthetic around and within clay particles whereby the earth obliges less water to fulfill the static imbalance and making it troublesome for water that moves into and out of the framework to fulfill designing road ventures (Ikeagwuani and Nwonu, 2019).

The geographical nature of Egypt has an area of about one million square kilometers or 238 million feddans. The total agricultural land in Egypt amounts to nearly 8.4 million feddans which means kaolin soil is around 3.5% of the total area in Egypt (Negm, 2019; Abdalla et al., 2023). Cement is the most important component inside concrete, but also it is considered one of the most harmful substances to the environment and a dangerous source of pollution in the world (Kakavand and Dabiri, 2018). For this reason, scientific research aims to decrease cement use and substitute it with other materials or technology that could preserve the environment around us. Today, the world is more interested in eco-friendly construction units and using them in green buildings (Haeri et al., 2015; Garcia et al., 2017).

Nanotechnology is a technique used to discover some unconventional soil-strengthening stabilizers. The nature of this Nanomaterial is that it has a high specific surface area (SSA), and its particles are so fine, that it has fast binding to soil particles. Even a small amount of Nanomaterial can change the physical and chemical properties of the soil (Kulanthaivel et al., 2021). Once Nanomaterial is added to the soil, singly or accompanied by the activator, it reduces the spacing of the soil particles, making the bond stronger with the cement materials present in the soil (Aguib, 2021; Kulanthaivel et al., 2021). The Nano stabilizer additives have a constructive influence on the mechanical properties of the soil up to a specific limit while the extreme dosages of nanomaterials cause particle agglomeration which hurts the soil behavior (Thomas and Rangaswamya, 2020). Nanomaterials, such as nano-white cement (N-WCem) and nano-silica (N-Si), can be used in the production of eco-friendly construction units.

Converting white cement to nano size changes its behavior reaction with the buildings' structure components (either above or below the soil level). The N-WCem-treated construction materials, such as concrete, have fewer pores and less porosity so they are considered better quality. N-WCem produces a high percentage of calcium silicate hydrate (viscous gel) which fills the pores well. Also, N-WCem possesses an important advantage in that it can safely store longer time than regular cement (Khalafalla, 2019). For these reasons, it is highly recommended to encourage such vital research in the world to develop new scientific applications in the field of modern construction. Some previous studies investigated the effect of natural nanoparticles on the engineering properties of soil (Verma and Maheshwari UK 2017; Thomas and Rangaswamya, 2020). It was found that the presence of a small number of nanoparticles in the soil had a significant effect on the physical and chemical behaviors of the treated soil which overcame the major soil problems such as water absorption and cracks by losing it (Mostafa et al., 2016; Ochepo and Kanyi, 2020). The treated samples with nanoparticles contained very small voids in between the particles due to filling them with the nanoscale particles, which led to a significant improvement in liquid and plastic limits (Pashabavandpouri and Jahangiri, 2015).

In the current work, we exploit two advantages of nanotechnology applications on traditional geotechnical soil stabilizers "cement"; minimizing crowded or occupied storage areas in road projects and limiting harmful ecological effects of cement uses by converting cement's traditional particle-size form into nano-size (Changizi and Haddad, 2017; Karimiazar et al., 2022).

Besides all the above, the current research study aims to improve kaolin soil properties by adding nanomaterials and improve its Atterberg limits, unconfined compressive strength (UCS) by adding three different percents of nano white cement (N-WCem) only/and different percents of nano-silica (N-Si).

2. Materials and Method

2.1 Materials

The as-received kaolin ore is considered the main material used in the experimental work, which was obtained from Wadi Kalabsha, Aswan, Egypt. The used silica sample was obtained from Asfour company for mining and refractories, Cairo, Egypt. White cement (WCem) used in the present study was purchased from Sinai White Portland Cement Co. Cairo, Egypt, which conformed to the specifications of ASTM C150 (2022).

2. Method

2.1 Materials Preparation

The white cement powder was first thermally treated by burning in the oven at 400°C for two hours then it was crushed for two hours by ceramic balls to transfer it into Nano-size White Cement (N-WCem) (Alyasiry et al., 2022). This grinding process was carried out using the Planetary Mono Mill Pulverisette 6, Canada. The grinding process was done in dry condition using balls of 3-20 mm diameter. Nano-silica was treated by heating the silica powder in a Muffle furnace, Nabertherm GmbH, Lilienthal, Germany at 600ºC for 4 hr., then was grinding for 4 hr. using the Planetary Mono Mill Pulverisette 6, Canada. The particle size of the resulting powder was measured using a laser Microsizer 201C analyzer (InTechSA Ltd, China).

2.2 Mixture Preparation

Two main groups of mixtures were studied experimentally for different curing ages (7, 14, 21, and 28 days), beside one sample of untreated soil. Group A consists of 3 samples that contained different percentages of N-WCem (0.5, 1.0, and 1.5 dry wt. %) and different water percentages. Group B consists of 12 samples that were mixed with different percentages of N-Si (0.3, 0.6, 0.9, and 1.2 dry wt. %) and different water percentages with each percent of N-WCem as presented in Table 1. The nanomaterials were mixed with half the water volume for not less than 15 min. by using a Sonicator device (FALC instruments, Italy), to avoid nanomaterials particles agglomeration. Then, the remaining half of the water volume was added and mixed with the kaolin soil.

The optimum water amount was determined from the compaction test which provided the maximum dry density (MDD) and optimum moisture content (OMC). After complete mixing with water, the samples were kept in a closed container containing wet sawdust for the different ages of curing times (7, 14, 21, and 28 days). Then, the compressive strength tests was carried out. For each mixture, these tests were done three times, the average readings were recorded. The formulated samples were characterized using SEM-EDX to compare and investigate the changes in the internal structure when using the N-WCem only and samples contained a mixture of N-WCem and N-Si in the samples with high-strength readings.

Table 1 Investigated Modified Soil Mixes

NO.	Material Component		Mixture code
	%N-Wcem	%N-Si	
1	0	0	Control M0
2	0.5	0	M1,0
3	1	0	M2,0
4	1.5	0	M3,1
5	0.5	0.3	M1,1
6	0.5	0.6	M1,2
7	0.5	0.9	M1,3
8	0.5	1.2	M1,4
9	1	0.3	M2,1
10	1	0.6	M2,2
11	1	0.9	M2,3
12	1	1.2	M2,4
13	1.5	0.3	M3,1
14	1.5	0.6	M3,2
15	1.5	0.9	M3,3
16	1.5	1.2	M3,4

3. Results and Discussion

3.1 Physicochemical Composition of the Raw Materials

The chemical composition of the used kaolin sample is presented in Table 2[A]. The XRD of the as-received kaolin sample is presented in Figure 1[A] which indicates that it is composed mainly of kaolinite and quartz minerals. The physical characteristics of the unmodified kaolin soil sample are presented in Table 2[B] which shows that composed of 51.29% clay and 48.7% silt. Also, the liquid limit, plastic limit, and plasticity index of the kaolin soil sample are 29.72, 21.22%, and 18.5%, respectively. The soil was classified as stiff kaolin soil according to the unified soil classification system (USCS).

The particle size distribution of the kaolin ore sample is presented in Figure 1[B]. The average particle size of the kaolin ore sample is 1497.7 nm (D50). The SEM image of the kaolin ore sample is presented in Figure 1[C], which indicates that kaolin ore is presented on a micro-scale. The Specific Gravity of modified soils was performed using a pycnometer, which indicated that they are in the range (from 2.56 to 2.63) as shown in Figure 1[D].

Table 2[A]. Chemical Composition of Kaolin Ore Sample

Oxid	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	k_2O	P_2O_5	Cl	SO_3	L.O.I.
%	51.6	2.11	28.31	5.45	0.03	0.53	1.06	<0.01	0.15	0.08	0.01	0.98	9.68

Table 2[B]. Index Properties of Unmodified Kaolin Sample

Description	Notations	Soil Sample
Specific gravity	Gs	2.54
Ph	Ph	6.8
Gravel (%)	G	0
Sand (%)	S	0
Silt (%)	M	48.71
Clay (%)	C	51.29
Liquid Limit (%)	L.L	39.72
Plastic Limit (%)	P.L	21.22
Plastic Index (%)	P.I	18.5
Maximum dry density (g/cc)	MDD	1.85
Optimum Moisture Content (%)	OMC	14
Unconfined Compressive Strength (Kpa/m^2)	UCS	65.94
California Bearing Ratio	CBR	2.1

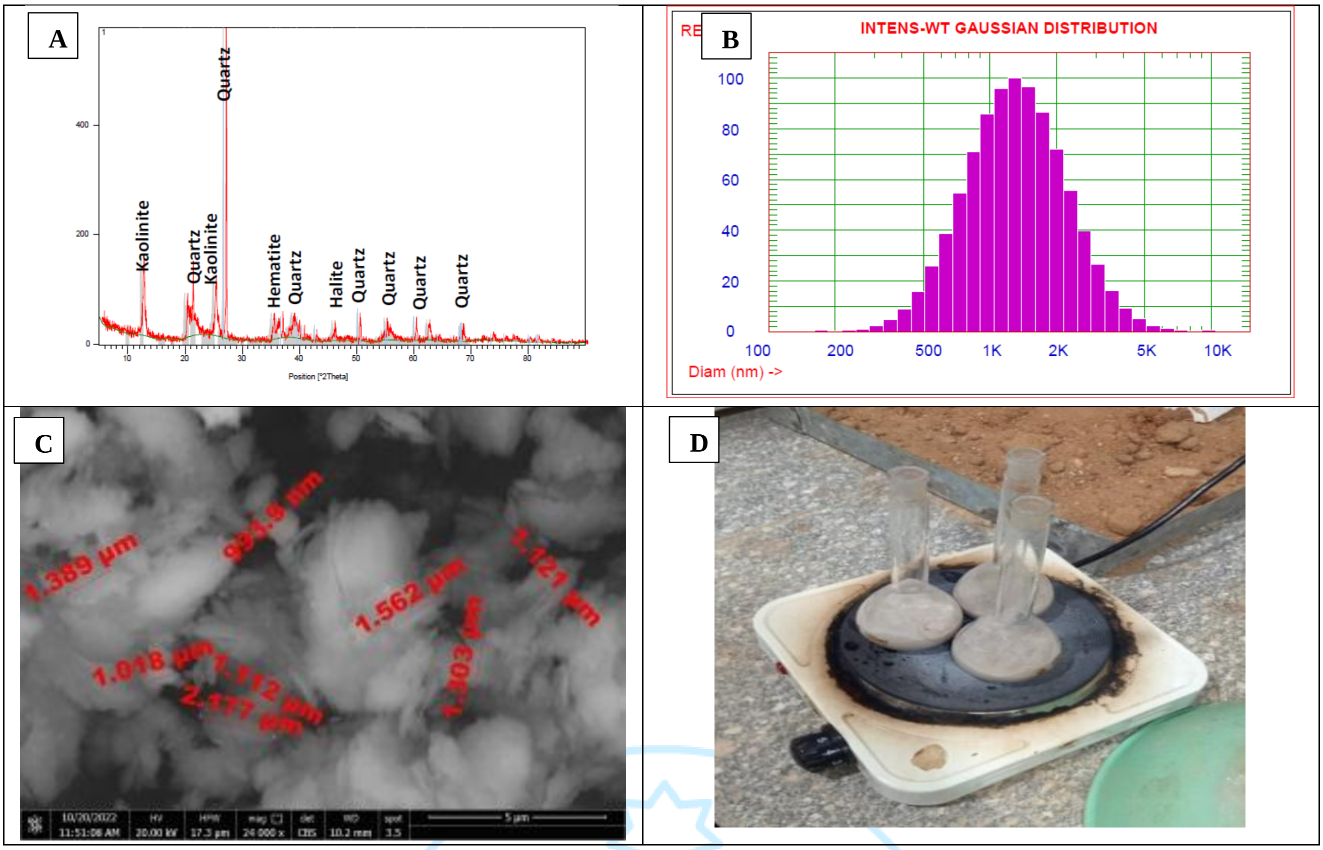


Fig. 1[A]. XRD Diffraction Analysis of the Kaolin Ore Sample, **[B]**.Particle Size Distribution of Kaolin Ore Sample, **[C]**. SEM Image of Kaolin Particle, **[D]**. Pycnometer Equipment for Specific Gravity Characterization

The chemical composition of the prepared N-Si sample is presented in Table 3. The XRD of the prepared N-Si sample is presented in Figure 2[A], which indicates that the sample is composed mainly of quartz minerals. The particle size distribution of the prepared N-Si sample is presented in Figure 2[B] which indicates that the average particle size of N-Si is 582.2 nm. The SEM image of the prepared N-Si sample is presented in Figure 2[C].

Table 3 Chemical composition of N-Si Sample

Oxid	SiO_2	Fe_2O_3	AL_2O_3	MgO	CaO	Na_2O	P_2O_5	LOI
%	97.63	0.06	0.13	0.11	0.14	0.21	0.01	1.71

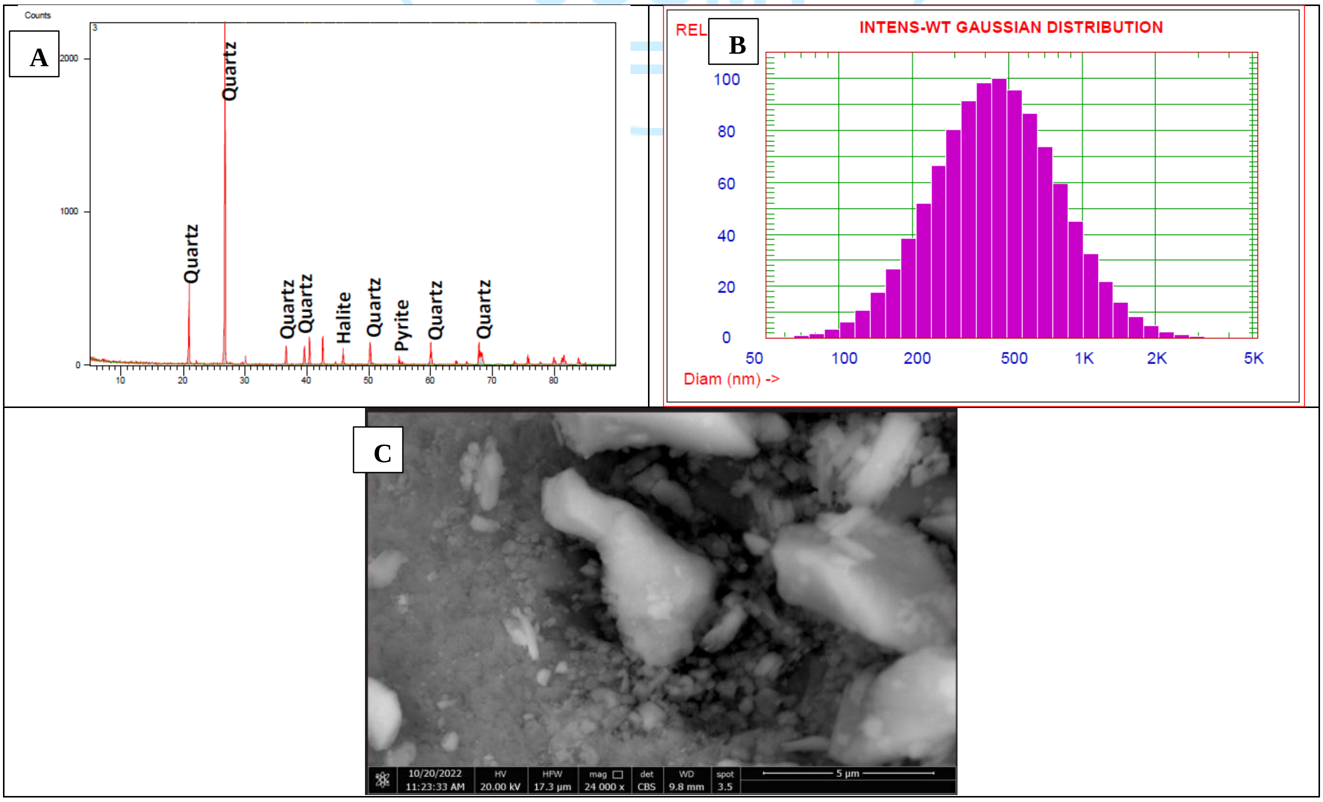


Fig. 2[A]. XRD Diffraction Analysis of the N-Si Sample, **[B]**. Particle Size Distribution of the Used N-Si, **[C]**. SEM Image of N-Si Particles.

The declaration of performance and the chemical composition of the white cement provided by Sinai White Portland Cement Company, Egypt is presented in Table 4 [A&B]. The XRD analysis of the prepared N-WCem is presented in Figure 3[A]. The particle size distribution of the prepared N-WCem sample is presented in Figure 3[B] which indicates that the average particle size of N-WCem is 794.9 nm. The SEM image of the prepared N-WCem sample is presented in Figure 3[C].

Table 4 [A]. Declaration of Performance of White Cement (No.2092/02-Dop)

Essential characteristic	Performance
Initial setting time	≥60min
Soundness/Explanation	≤10.0mm
SO_3 content	≤3.5%
Cl content	≤0.10%
Portland Cement Clinker	65-79%
Limestone	21-35%
Minor additional constituents	0.5%
2days compressive strength	≥10.0 MPa
28days compressive strength	≥42.5MPa≤62.5MPa

Table 4 [B]. Chemical composition of N-WCem Sample

Oxid	SiO_2	Ins R	Fe_2O_3	AL_2O_3	MgO	CaO	SO_3	LOI
%	21.66	0.17	0.24	3.40	0.28	67.09	3.34	2.80

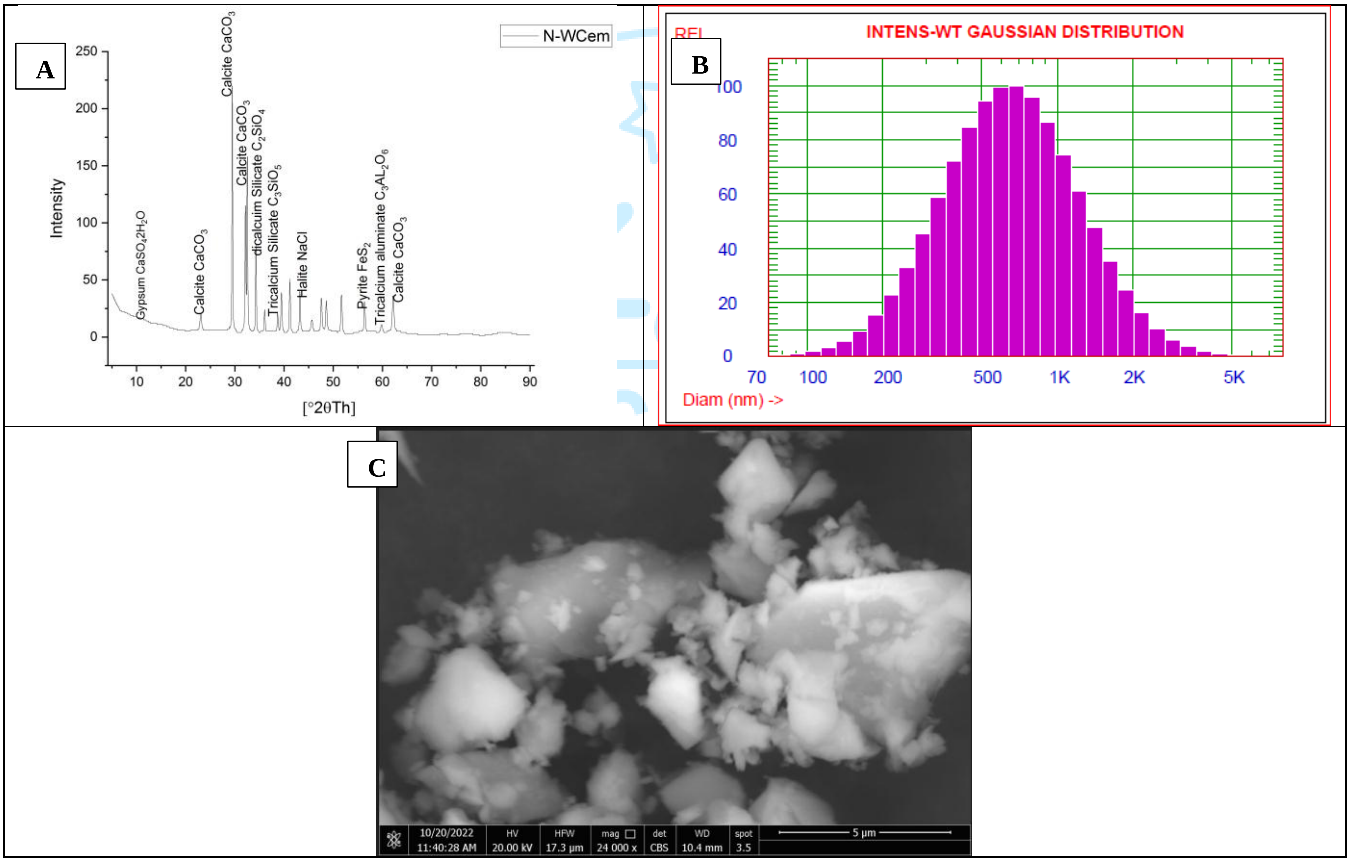


Fig. 3[A]. XRD Analysis of the Prepared N-Wcem Ore, **[B]**. Particle Size Distribution of the Used N-Wcem, **[C]**.SEM Image of N-Wcem.

3.2 The Mechanical Properties of the Modified Soil

3.2.1 Effect of the N-Wcem & N-Si on Compaction and Strength Characteristics of Clay Soil

OMC and MDD were measured for the studied clay samples according to (ASTM D-698-07). The effect of different N-WCem percentages on the OMC and MDD is presented in Figure 4[A] and Figure 4[B]. With increasing N-WCem percentage, the OMC elevated, and the MDD diminished. The range of the OMC is from 14.16% to 16.10% and MDD is from 1.85% to 1.81%. Increasing the added N-Si has a visible effect in enhancing the OMC values of the samples more than the enhancing percentage in the case of adding a mixture of N-WCem and N-Si. Further depletion was observed in the MDD readings, even with an elevation in the proportion of N-Si % to the tested soil mixture with different proportions of N-WCem. This effect can be attributed to that the nano-scaled particles coat the micro-scaled particles of clay soil, thereby magnifying the wettable surface area of the matrix, which in turn diminishes the moisture content in the soil beside that the nano-scaled particles increase the number of necks (bridges) between clay particles that lead to increase in the void ratio of the soil matrix and hence the reduction in the dry unit weight of the soil and this mechanism is in agree with that presented by Thomas and Rangaswamya (2020). The elevation in OMC values might be attributed to the high-rise water absorption capacity of cement particles and water consumed during the hydration process of the cement. Hydration reactions would happen after the mixing of N-WCem with water which produced an excess calcium hydroxide and the cementitious compounds of calcium silicate hydrate (C-S-H). The formation of calcium hydroxide was started within 12 min. of water and N-WCem contact which made use of cation exchange, agglomeration, and flocculation for the stabilization of clay soil. On the other hand, the C-S-H promoted cementitious bond with the soil, which outcome in the progress of the strength and matrix of treated soil. Calcium hydroxide remained dispersed in the treated sample in the form of very fine and highly reactive crystals. At the same time, CSH was composed of crystallization which started by mixing with water and this mechanism agrees with that of Marik et al. (2022).

In addition, with adding N-Si and N-WCem to the tested clay samples, the OMC increases due to N-Si hydrophilic properties which caused more absorbing of the excess water of the clay particles surfaces. Therefore, nano-additives were preventing the accumulation of water between clay particles and hence the results recorded more increase in the OMC with more diminishing in the MDD of the tested samples. This improvement is due to the very small particles in size which have a high specific surface area that can fit into pores of kaolin soil and react with other particles. Nano-scaled particles improve the micro and macrostructure, compaction efficiency, and bearing capacity of tested soils and this agrees with the mechanism explained before by Dewi et al. (2018); Karimiazar et al. (2022); and Marik et al. (2022).

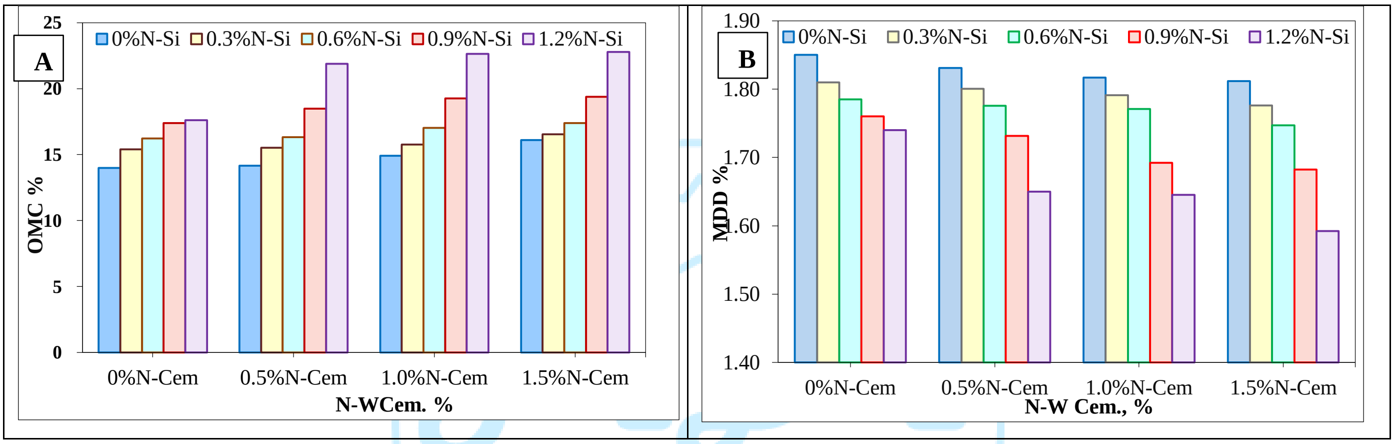
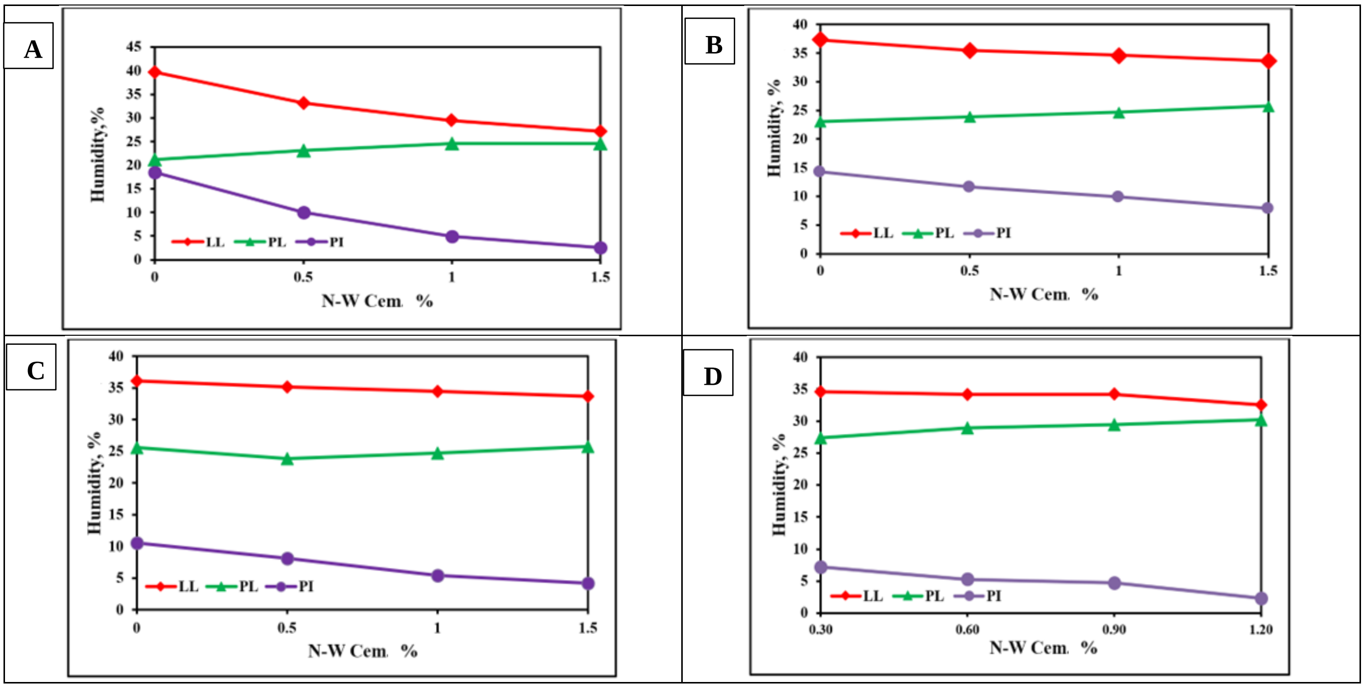


Fig. 4. A) OMC The effect of adding N-W Cem. on, **B) MDD** of the tested clay soil in the presence of different percentages of N-Si.

3.2.2 Effect of the N-Wcem & N-Si Addition on the Index Properties of the Clay Soil

Treatment with N-WCem as well as with a mixture of N-WCem and N-Si have changed the consistency limits of the tested clay sample. The Atterberg limit test (liquid limit (LL), plastic limit (PL), and plasticity index (PI)) were piloted on untreated and treated soil samples. The Atterberg limit test was carried out by (ASTM D 4318 standard). **Figure 5** summarizes the values of LL, PL, and PI of untreated and treated soil samples by varying dosages of additives with different curing periods.



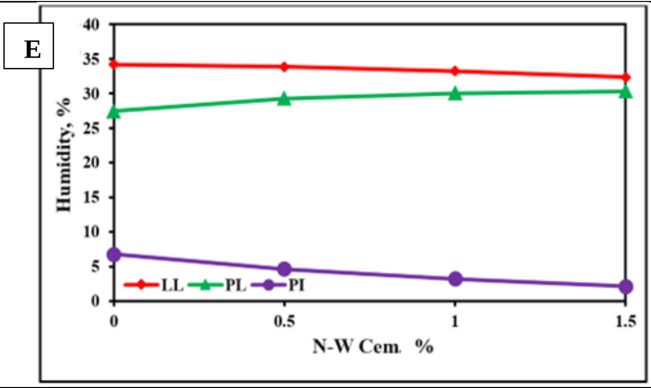


Fig. 5. The Effect of N-W Cem., Addition on PI of Modified Soils in the Presence of Different Percentages of N-Si Where; **A**) 0% N-Si, **B**) 0.3% N-Si, **C**) 0.6%N-Si, **D**) 0.9%N-Si And **E**) 1.20%N-Si.

A radical reduction in LL was observed with the addition of N-W Cem. individually, as well as with the addition of the mixtures of N-W Cem. and N-Si together to the soil. When the liquid inside the samples decreases, this decreases results from the initial formation of the blocks and the bonds between the soil particles. The PL values appeared to be raised with the addition of N-W Cem. individually, as well as with the addition of the mixtures of N-W Cem. and N-Si together even though the untreated tested soil showed the lowest PL value in the absence of nanomaterials. This is a good indicator of the improvement in the UCS. The decrease in LL and the positive change in PL are shown for treated soils compared to untreated soils which agrees with the mechanism explained by Mostafa et al. (2016), Changizi and Haddad (2017), and Eissa et al. (2021). Noticeably, the samples' workability was increased due to the presence of N-Si due to the increased surface area of the nano-silica. Besides that, the silica particles have a high tendency for water absorption (Hert and Hair, 1969; Pichot et al., 2012) which was highly increased in the presence of nano-silica particles due to the interaction between the particles. The absorption of water on silica takes place on the H-bonded hydroxyls. The adsorbed water is diagramed in Figure 6. This hexagonal structure is composed of six water molecules in three layers: the first layer; a single water molecule adsorbing on each pair of surface hydroxyl groups, the second layer; two water molecules adsorbing on the hydrogen atoms of the first water molecule, and finally; completion of the ring by the adsorption of a further three molecules. If such a structure were to be released from the surface, it could produce a polymeric species that would elevate to the high viscosity associated with anomalous water. This explains the OMC increase in the mixture containing different percentages of N-Si (Figure 4). Besides that, the N-W Cem. absorb more water due to the hydration reaction (Phanikumar and Raju, 2020).

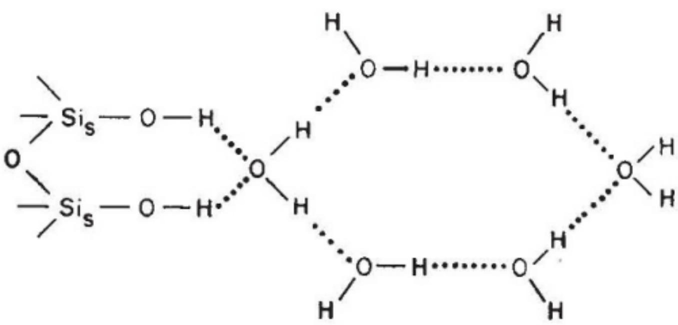


Fig. 6. Proposed structure of water absorbed on H·-bonded surface of silica hydroxide (Si–O–H) (Hert and Hair, 1969).

3.2.3 The Effect of N-W Cem. & N-Si Addition on the UCS of the Clay Soil

The unconfined compressive strength (UCS) was determined using an unsaturated soil testing system (GDS Instruments). The UCS test was carried out in accordance (with the ASTM D2166 standard). Figure 7 and Figure 8 demonstrate the effect of various mixtures of N-W Cem. only as well as the mixtures of N-W Cem. and N-Si on the tested clay soil, which was obtained from the UCS test at curing ages of 1, 7, 14, 21, and 28 curing days. The combination of kaolin clay soil and low percent of nanoparticles provided a plausible performance in the UCS, by elevation nanoparticle percent UCS increased gradually (Gupta, 2011; Baioumy and Ismael, 2014; Fadzil et al., 2017; Verma and Maheshwari, 2017; Blayi et al., 2020; Thomas and Rangaswamya, 2020).

The obtained results presented in Figure 7 and Figure 8 indicate that the addition of (0.5, 1.0, and 1.5 % dry weight) N-WCem could improve strength (116.95, 174.29, and 184.12 KPa, respectively) after 28 curing days. Secondly, the UCS of 0.5% N-WCem mixture with addition (0.3, 0.6, 0.9, and 1.2N-Si) increased by (16%, 29%, 36%, and 41%, respectively) after 28 curing days in comparison to the UCS reading with addition 0.5% N-WCem only. Thirdly, the UCS of 1.0% N-WCem mixture with addition (0.3, 0.6, 0.9, and 1.2N-Si) elevated by (30 %, 40 %, 59 %, and 61 %, respectively) after 28 curing days in comparing to the UCS reading with addition 1.0 % N-WCem only. Finally, UCS of the maximum percentage of N-WCem mixture with addition (0.3, 0.6, 0.9, and 1.2N-Si) enhanced by (41%, 63%, 70%, and 73%, respectively) after 28 curing days in comparison to the UCS reading with addition 1.5 % N-WCem only. These results agreed with Salem et al. (2016), Khalafalla (2019), and Karimiazar et al. (2022). UCS improved due to the Nanoparticles acting as ‘‘nuclei’ of hydration, which possessed pozzolanic behavior and could fill the voids in the cement matrix. Also, the addition of silica in the Nano-state acted as cohesion materials which produced more soil strength and accelerated soil stabilization.

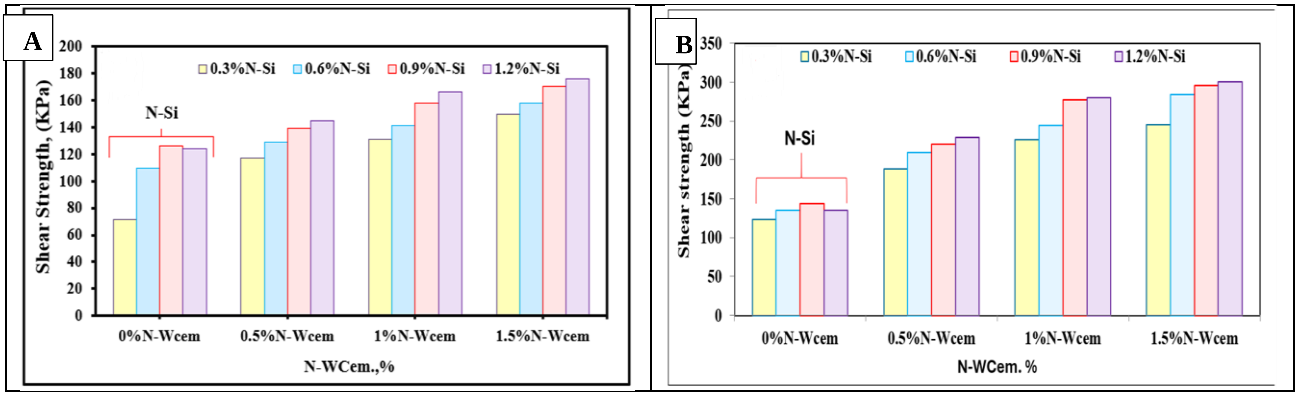


Fig. 7. The effect of N-Cem addition on the Shear strength of modified soil mixtures in the presence of different percentages of N-Si **A**) UCS after one day of curing ages, and **B**) UCS after 28 days of curing ages.

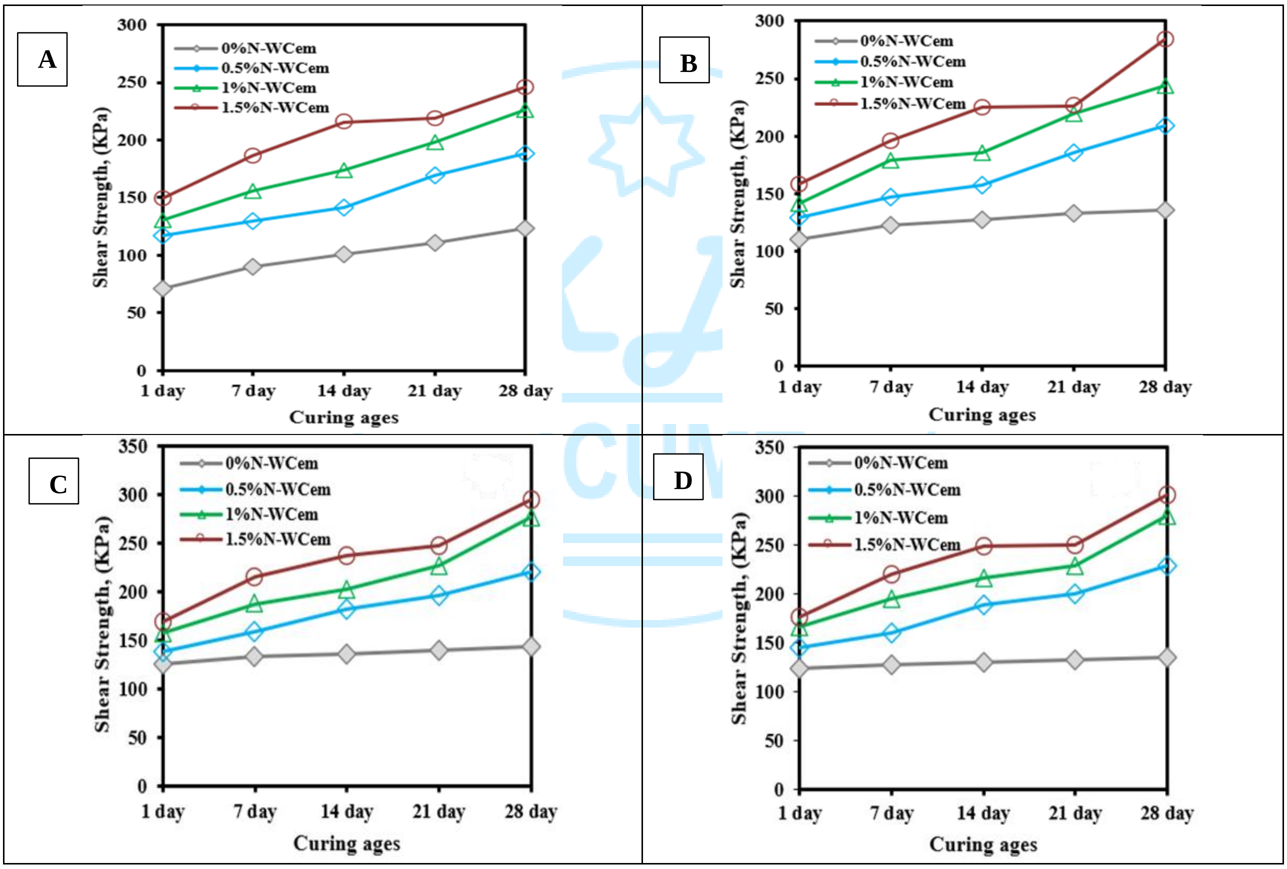


Fig. 8. Effect of curing ages on (UCS) Shear strength of modified soil mixtures in the presence of different percentages of N-WCem and N-Si where; **A**) 0.3 N-Si, **B**) 0.6 N-Si, **C**) 0.9%N-Si, and **D**) 1.20%N-Si.

The clinker is the main constituent of white cement with 65-79% of the total content. A clinker is a pyro-processed hydraulic material that is made from raw materials in a cement kiln with calcium sulfate (gypsum rock at approximately 5% by weight). Clinker is a mixture of four major oxide phases: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetra calcium alumino-ferrite (C_4AF). According to the standard notation used in cement chemistry, ($C = CaO$; $S = SiO_2$; $A = Al_2O_3$; and $F = Fe_2O_3$). The clinker is ground to a sufficiently fine powder to elevate the rate of hydration. At room temperature, the soil stabilization mechanism is a pozzolanic reaction “which is a cation exchange and flocculation-agglomeration steps”, which need calcium supply, mainly the two calcium silicate phases (C_3S and C_2S) according to the following equations.

$$2C_3S + 6H \rightarrow C\text{-}S\text{-}H + 3Ca\,(OH)_2 \quad \text{……………………………….(1)}$$

$$2C_2S + 4H \rightarrow C\text{-}S\text{-}H + Ca\,(OH)_2 \quad \text{………………………………..(2)}$$

where, $H = H_2O$ and C-S-H = calcium silicate hydrate ($C_3S_2H_3$).

Calcium may also react with alumina and produce C-A-H which is cementitious in nature. The reactions are as follows:

$$Ca(OH)_2 + SiO_2 \rightarrow C\text{-}S\text{-}H \quad \ldots\ldots(3)$$
$$Ca(OH)_2 + Al_2O_3 \rightarrow C\text{-}A\text{-}H \quad \ldots\ldots(4)$$

The formation of these additional cementing materials (C-S-H and C-A-H) may require the solubilization of silica and alumina from the soil components Sasanian and Newson (2014). In this study, the tested soil contains the following percentages: silica (51.6%), alumina (28.31%), and other minor constituents.

The C-S-H gel (Calcium Silicate Hydrate) is produced from the hydration process filling the clay porous, so it reduces the porosity and rises in the strength of the soil.

The strength of clay soil was enhanced using N-Si along with the minimum dosage of N-WCem as possible which can be beneficial both economically and ecologically. The pozzolanic reaction occurred in the soil by the presence of the activator (N-WCem) in which its calcium hydroxide reacted with the silica and alumina in the soil. N-WCem possesses the ability to produce a higher percentage of calcium silicate hydrate and fill the pores well than the WCem in molecular size (Khalafalla, 2019; Karimiazar et al., 2022). These pozzolanic reactions took place slowly over a period which further enhanced the tested clay soil engineering properties (Thomas and Rangaswamya, 2020; Karimiazar et al., 2022). The additive N-Si served to enhance the hydration process of the N-W Cem, thereby minimizing the cracks due to volume reduction (shrinking) and hence improving the strength of the soil. The cracks transfer from deep cracks into less numbers of hair cracks as shown in Figure 12. N-W Cem and N-Si mixture could provide hardness and strength to the soil mixture by bonding between the kaolin particles and the additive particles as mentioned in equations (1-4). The N-Si acts as accelerated pozzolanic reactions and acts as cohesion materials between the soil particles by a slightly viscous gel which was produced by the N-Si materials that absorbed water. The cohesion occurred between the clay particles saturated with the viscous gel, which was stronger than the cohesion between the clay particles because it absorbed water, which in turn led to a high friction force between the mud particles. Besides that, in the double-mixed mixtures of N-WCem and N-Si, the viscous gels, which are formed by the hydration of N-Si, united with the Ettringite fibers as shown in Figure 9.

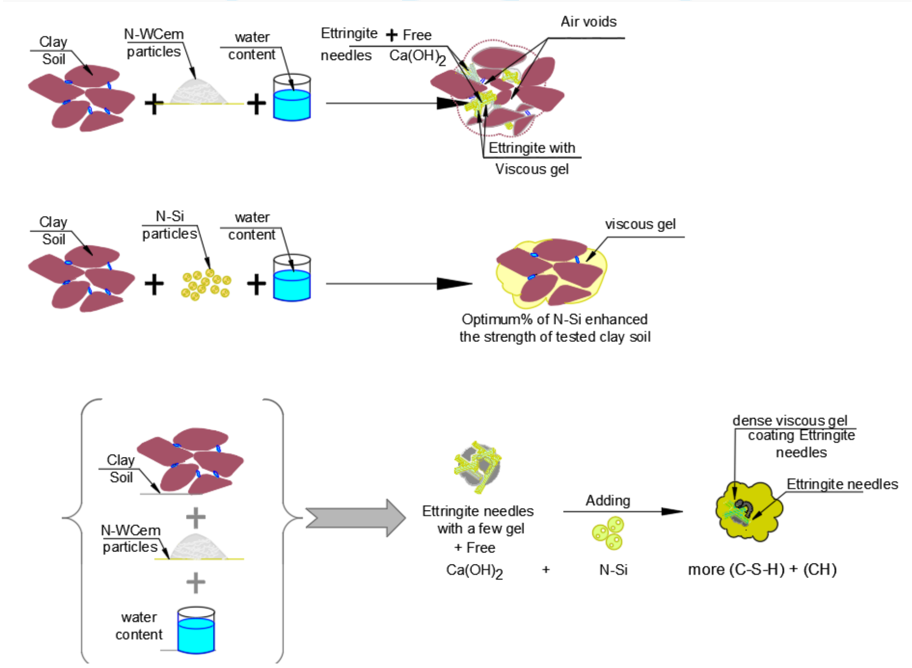


Fig. 9. The diagram illustrates the effect of the treatment of clay soil by the addition of N-Si only, N-WCem only, and mixed of them.

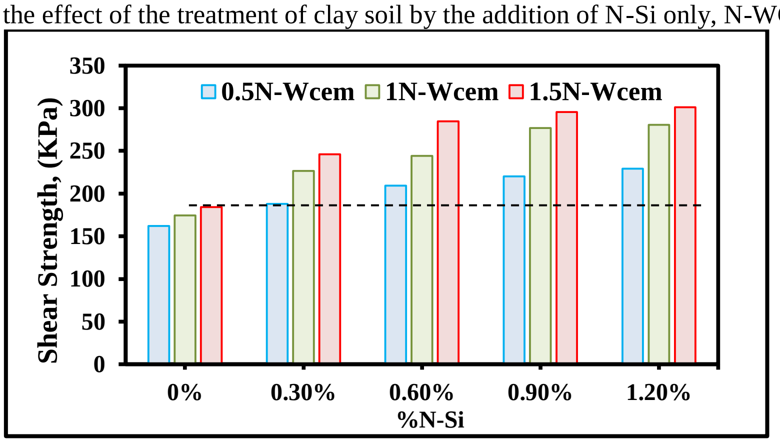
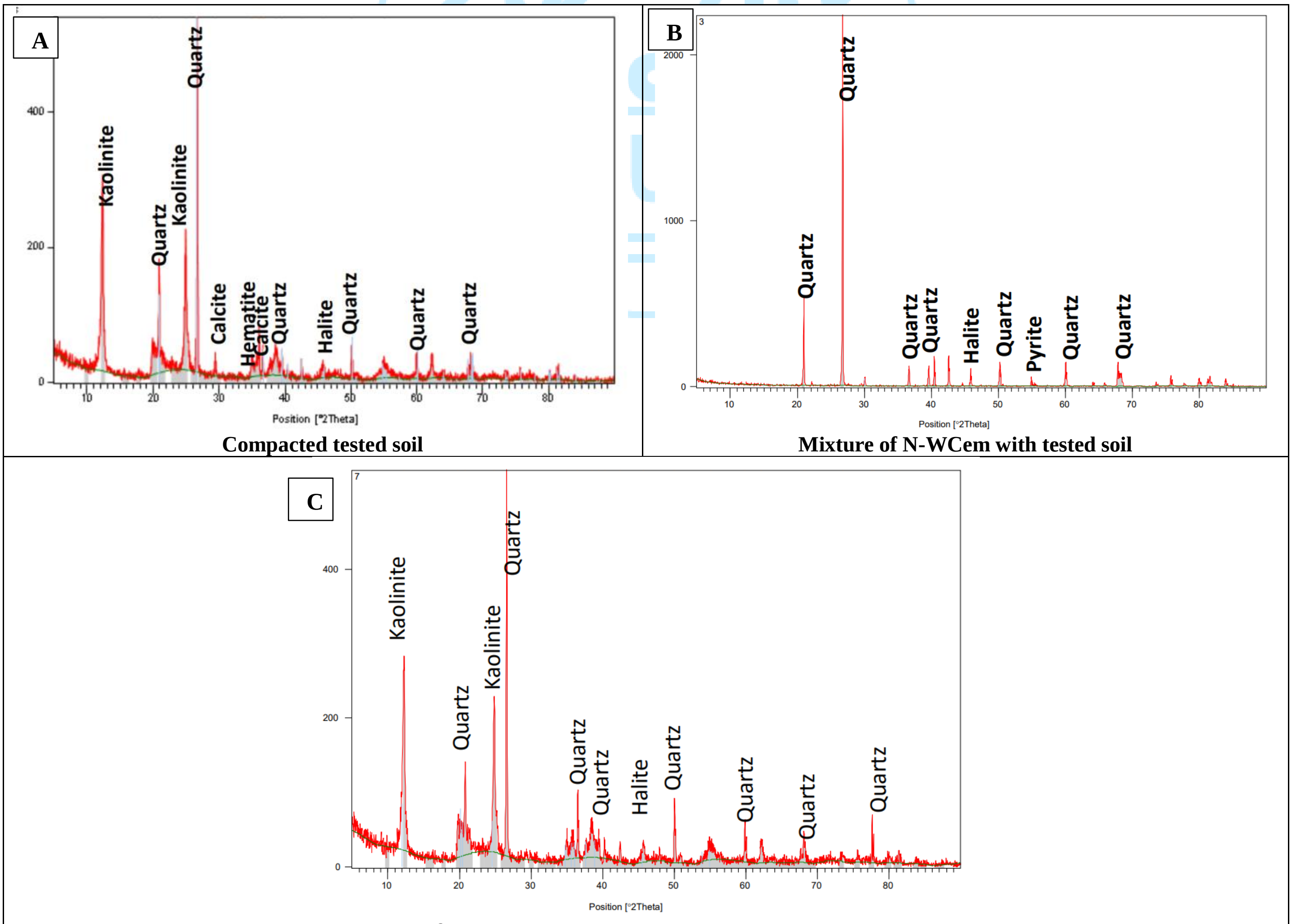


Fig. 10. Comparison of the UCS of modified soil mixtures after 28 days of curing ages in the presence of different percentages of N-WCem and N-Si.

Figure 10 illustrates the powerful effect of the additive N-Si on the UCS of clay soil mixed with N-WCem as a stabilizer after 28 curing days. Figure 10 shows that the mixture that contains 0.3% of N-Si with the minimum percent of N-WCem (0.5%) elevates the UCS approximately as the enhancement effect with using the maximum percent of N-WCem (1.5%) only. So, the addition of N-Si acts on (1) accelerating pozzolanic reactions, (2) increasing the water absorption leading to elevates and acting in the production of more viscous gel which elevates the cohesion forces in between the clay particles, and (3) the viscous gel acts as a coating gel for the clay particles and the Ettringite needles. So, the addition of N-Si decreases the use amount of N-WCem in the stabilization of the clay soil, which is beneficial both environmentally and economically.

3.2.4 The Effect of N-Wcem and N-Si Addition on the XRD of Modified Clay Soil Mixtures

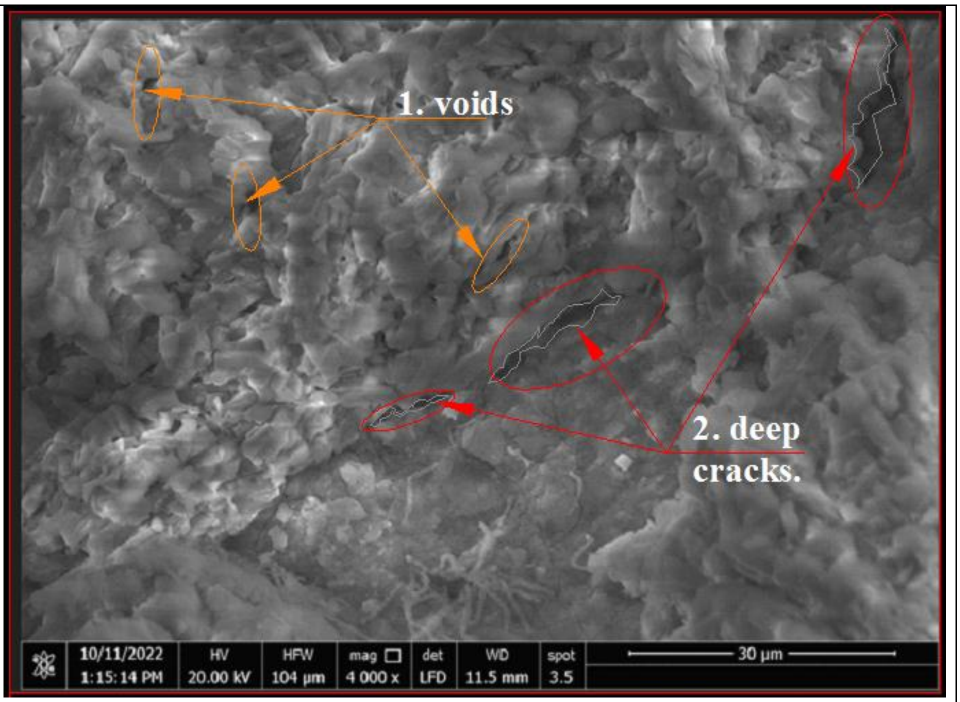
XRD tests were piloted to investigate the clay behavior before and after stabilizing with N-WCem as well as a mixture of N-WCem and N-Si. Figure 11 illustrates the XRD patterns of raw soil and soil treated with N-WCem as well as a mixture of kaolin clay soil, N-WCem, and N-Si. It was clear that untreated soil is composed mainly of Kaolinite, quartz, calcite, Hematite, and Halite minerals. In adding the N-WCem to the tested soil sample, the peaks of kaolinite, calcite, and Hematite decline with the appearance of a pyrite peak. While in the sample containing nanoparticles mixture (N-WCem and N-Si) with the tested soil, the peaks of calcite, and Hematite decline only. Figure 12 illustrates the SEM of modified clay soil mixtures. Figure 19 [B] shows the SEM results of tested soil plus N-WCem containing the Ettringite needles and some voids. In Figure 19 [D], the mixture contains the same percentage of N-WCem with the presence of the N-Si almost the voids closed leading to a reduction in porosity (Changizi and Haddad, 2017). The mixture containing N-WCem, and N-Si gains more strength and more bonding between clay sheets which delays the sudden failure in comparison with the mixture containing N-WCem only. The mixture [B] which contains the N-WCem only has a rapid failure in comparison with the mixture [C]. The mixture [C] which contains N-Si only has a more fragile and low loading capacity (Figure 7). The soil samples treated with N-WCem only as well as the soil samples treated with nanoparticles mixture exhibited peaks of C-S-H (Calcium Silicate Hydrate) gel formed during the pozzolanic reaction of N-WCem in the presence of water. The strength improvement in the soil treated with the N-WCem is due to the production of C-S-H gel. Consequently, N-WCem and N-Si particles diminished the pore volume and elevated the bond strength between the flaky structures coated with the gel. These results agreed with Saeed et al. (2014).

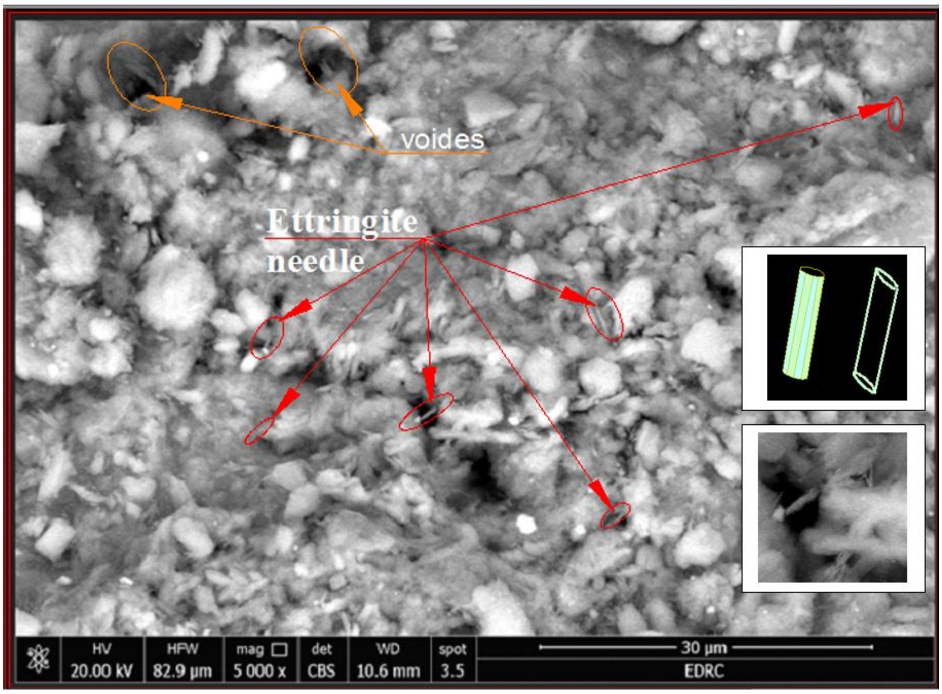


Compacted tested soil | **Mixture of N-WCem with tested soil**

A mixture of additive (N-Si) and, activator (N-WCem) with tested soil

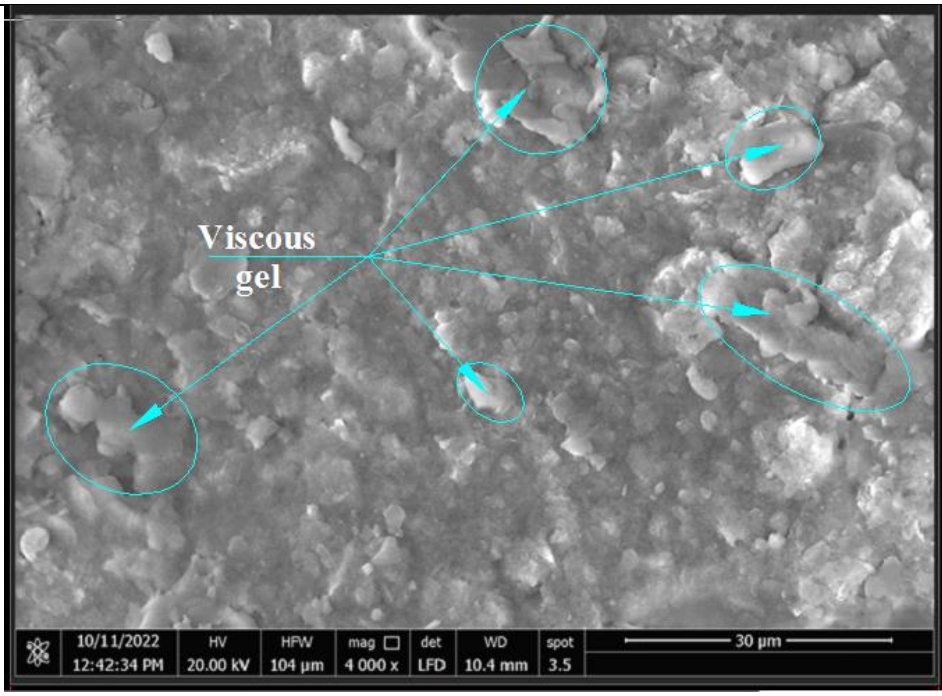
Fig. 11 The XRD of Modified Clay Soil Mixtures

<table>
<tr>
<td>Tested soil</td>
<td></td>
<td>

A) SEM of compacted tested soil (Kaolin clay): 1. voids 2. deep cracks.</td>
</tr>
<tr>
<td>Tested soil + N-WCem</td>
<td></td>
<td>

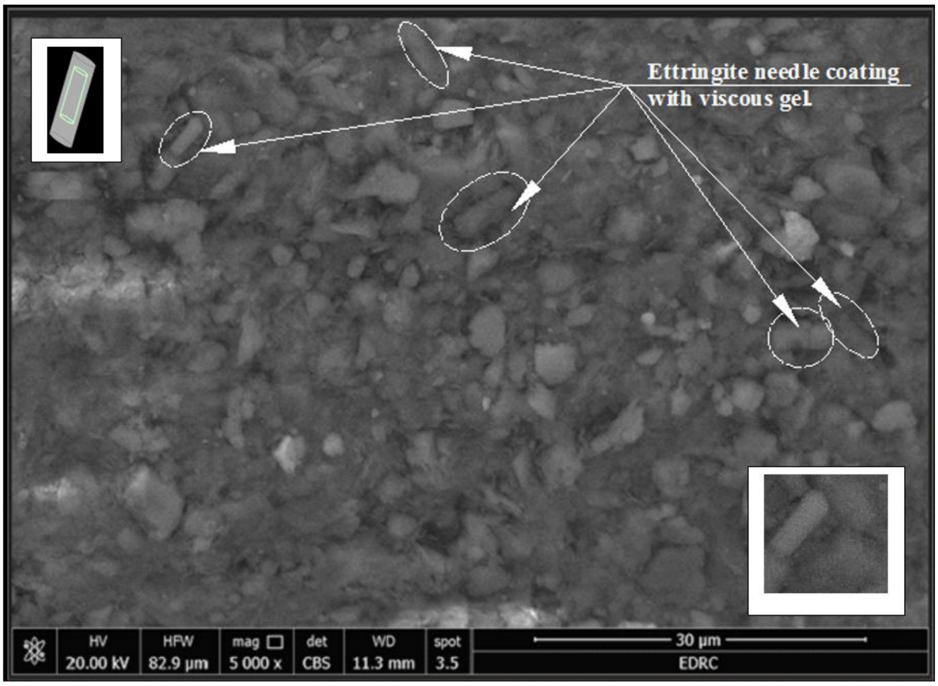
B) SEM results of tested soil plus N-WCem appear 1. Voids 2. Ettringite needle.</td>
</tr>
</table>

Tested soil + N-Si



C) SEM results of tested soil plus N-Si appear: 1. Viscous gel

Tested Soil + N-WCem + N-Si



D) SEM results of tested soil plus both additives N-Si and activator N-WCem:
1. Ettringite needle coating with viscous gel.

Fig. 12 The SEM of modified clay soil mixtures

4. Conclusion

The presented study aims to evaluate the modified kaolin clay soil with the addition of different percentages of N-WCem only and N-Si in the binary mixtures containing N-WCem. The following conclusion can be summarized: -

- The N-WCem only as well as N-Si in the binary mixtures containing N-WCem treated soil samples were found to have diminished PI due to a reduction in LL, while PL rose due to elevated water absorption and the cationic interactions with soil compounds.
- The addition of N-WCem only as well as N-Si in the binary mixtures containing N-WCem treated soil samples resulted in an elevation in the OMC and a diminishing in the MDD due to their hydrophobicity properties.
- The UCS readings indicated that the N-WCem only as well as N-Si in the binary mixtures increased the soil strength. The Nano-size particles possessed pozzolanic behavior besides that they acted as cohesion materials which produced more soil strength and accelerated soil stabilization.
- The optimum mixture or the green environmental mixture contains 0.5% N-WCem with 0.3% N-Si which gives UCS reading more than the mixture containing the highest N-WCem percentage (1.5% N-WCem).

Ethical Approval
This article does not contain any studies with human participants or animals performed by any of the authors.

Author Contributions
Ola Bakr Shalaby**:** I am a PhD student, and all parts of the work are parts of my PhD thesis under the supervision of the rest of the authors (Prof. Ayman L. Fayed; Prof. Nabil M. Nagy; Prof. Hala M. Elkady and Dr. Mohamed Salah). Dr/ Amr B. ElDeeb supervises the XRD part and SEM.

Conflict of Interest
On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of Materials
All materials are available.

Acknowledgments
All authors' names that participate in the manuscript are mentioned.

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