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Investigating the Resistance Behavior of the Clayey Sand Soil Improved with Nano-Silica and Carbon Fibers

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ABSTRACT

Resistive subsoil is a basic construction necessity in civil works because it is the foundation of a structure that distributes the loads effectively, and the structure will settle and crack under the applied loads if the soil is not strong enough. In many cases, the existing natural soil cannot fully support the desired structure and needs to be improved for its resistance properties. Soil stabilization methods are: 1) mechanical, 2) chemical and 3) physical , and this study tries to examine how the combined carbon fibers-nanosilica, as a new stabilizer, improves the mechanical characteristics of the soil by studying the effects of nano-silica and recycled polyester fibers on the engineering features of the clayey sand soil, especially the shear and unconfined compressive strengths. To this end, two different-ratio soil-fiber and soil-nano silica combinations, ranging, respectively, between 0 and 0.6% and 0 and 1% were used, and the results showed that adding the mentioned stabilizers increased the soil strength.

Keywords: Clayey sand soil, Nano-Silica, Carbon Fibers

1. INTRODUCTION

A thorough understanding of the behavior of the soil, as a material that inevitably form an inseparable part of most civil projects, highly improves the design methods and makes realistic analyses possible. In recent years, more than 1 million m^2 of geotextile has been used to reinforce the soil; however, it involves such serious problems as creep, low resistance and modulus of elasticity, and sensitivity to aggressive environments. The carbon fiber-reinforced polymer (CFRP) was introduced to the structural engineering more than two decades ago and is still used in the geotechnical engineering [1-3]. It has all the merits of the geotextile, lacks creep, has higher strength and elasticity modulus, and is reliable in aggressive environments [4-6]. But in Geotechnics, its miraculous performance and the amazing effect of nanotechnology have remained hidden due to its complexities and the geotechnical researchers' microscopic view to soil. As research in nanotechnology is interdisciplinary and covers a variety of topics, ranging from the chemistry of catalyzing nanoparticles to the physics of quantum dot lasers, in each specific topic, researchers need knowledge beyond their expertise because they should understand the extensive related implications and learn how to contribute to this novel, exciting field. Although nanomaterials are rarely used in the geology and Geotechnics engineering and are still in the exploration stage, the development of science and technology helped researchers make geotechnical studies more effective and economical through their use [7,8].

Many researchers have used fibers, cement and other similar materials to stabilize and improve the soil [9-15]. In their laboratory research, Arabani et al used nanoclay to improve the mechanical properties of the cement-stabilized soil using the CBR and unconfined compressive strength tests and showed that increasing the nanoclay increased its strength significantly [16]. Gao tested the nano-magnesium mechanism in strengthening the clayey soil and showed that it increased its unconfined compressive strength. Increasing water reduced it and adding 6% nano-magnesium highly improved its strength and stability [17]. Correia and Figurid conducted extensive research on stabilizing soil with carbon nanotubes [18,19]. Pham and Nguyem's tests on nanosilica-stabilized clayey soils showed that adding this stabilizer reduced its coefficient of swelling (cs) [20]. Tang et al. studied the behavior of short polypropylene fiber-reinforced clayey soil stabilized with cement and showed that the shear and unconfined compressive strengths of the cemented and un-cemented soil increased [21]. Zaimoglu and Yetimoglu conducted a series of unconfined compressive, direct shear and CBR tests to study the effects of randomly-distributed polypropylene fibers on the strength of fine-grain soils [22,23], and Ates found that using glass fibers and cement increased the mechanical resistance of the sandy soil and reduced its settlement rate under rupture. Studies on reinforcing soil with natural and synthetic fibers show that the latter increase the maximum strength more, and tri-axial tests on cement-stabilized fiber-reinforced soils show that propylene fibers increase the peak and shear strengths and improve the internal friction and cohesion; fibers also increase the unconfined compressive strength in both cemented and un-cemented soils [24].

As all the mentioned studies have used fibers and nanomaterials separately and ignored the importance of the simultaneous use of carbon fibers and nanomaterials as high-strength reinforcements, this study is mainly aimed to evaluate their simultaneous usability to improve the soil strength parameters using the design-expert software for data analysis.

2. MATERIALS AND METHODS

2.1. MATERIALS

This research has used the Sieve 40-passed clayey soil, classified as SC based on the unified classification system, with flowability and plasticity limits of, respectively, 32.42 and 20.88 and maximum dry weight of 16.03 KN/m^3 (Fig. 1).

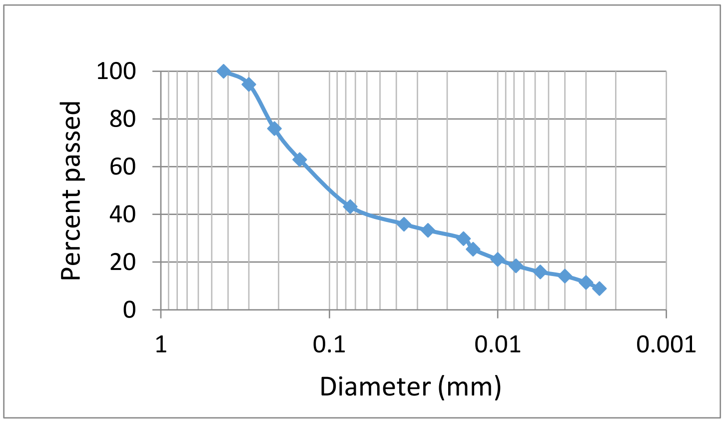

Figure 1. Soil gradation

The reinforced polymer carbon fibers used in this study (Fig. 2) are 6 mm long and 6 μm in diameter; specifications of the fibers are listed in Table 1 and those of the nano silica are given in Tables 2 and 3.

Figure 2. Polymer carbon fibers

Table 1. Specifications of carbon fibers

Moisture (%)	Tensile strength (GPa)	Amount of carbon (%)	Color
0.2	3.6	> 98	Black

Table 2. Physical characteristics of the nano silica

Purity (%)	Particle size (nm)	Color	Density (gr/cm^3)	Area of specific surface (m^2/gr)
> 99	11-13	White	2.4	200

Table 3. Chemical characteristics of the nano silica

SiO_2 (%)	Ti (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)
> 99	< 120	< 70	< 50	< 20

2.2. TEST METHOD

Tests are carried out in 3 sets. In the first, the nano silica powder is first dry-mixed with distilled water and then mixed thoroughly with a suitable hydrometric mixer for at least 1 hr at a certain ratio to obtain a uniform-concentration solution, but since materials remain lumpy, even if the mixer works well, and manual mixing too cannot create a uniform solution, the best method seems to be using a 100,000 rpm mixer where the nano silica powder is added, in 3 steps, to the soil with distilled water at 0.5 and 1% ratios relative to the weight of the dry soil and mixed quite uniformly. Then the nano-silica is mixed with the soil layer by layer, poured into the prepared mold, compacted thoroughly and placed under the direct shear machine under saturated conditions. As nano-silica particles are small in size and their amount is small compared to the soil volume, their effects on the percent moisture and on the maximum dry specific gravity are neglected. In the second set, the fibers are first separated, then mixed with 0.3 and

0.6% soil by giving some initial moisture so that the fibers may not stick together during mixing and then added to the soil, with water, in 5 steps to have a uniform mixture. Next, the soil is mixed with fibers layer by layer, poured into the prepared mold, fully compacted and placed under the direct shear machine under saturated conditions. In the third set, fibers and nano silica are used simultaneously.

2.3. PREPARING SAMPLES FOR DIRECT SHEAR TESTS

The amount of soil should be quite enough to enable preparing as many similar samples as needed. Using the density, moisture content and unit volumetric weight method, the samples are compacted in the shear box by kneading or pounding each layer until the accumulated soil mass is compressed to the desired volume. Boundaries of the compacted layers should be so placed that they may not coincide with the shear plane defined by the shear box halves, and the box walls are covered with a thin layer of grease to reduce the mold wall-sample friction during consolidation; same is done between the box halves to reduce the friction during the shear action. To prepare the samples, obtain their optimal moisture and find their maximum dry specific weight, the standard compaction test (ASTM D698) is repeated at least 3 times to ensure full confidence of the results. After compaction, the samples are transferred into the 6 x 6 × 2 shear box and placed under saturated conditions.

3. RESULTS AND DISCUSSION

3.1. RESULTS OF THE DIRECT SHEAR TESTS

This study has used the statistical response surface method to analyze the test results and improve the soil parameters (cohesion and internal friction angle) to achieve the best combination of the additives.

3.1.1. COHESION PARAMETER

In Table 4 that shows the ANOVA results for the cohesion parameter, most of the terms have suitable significance, except term B, which has remained in the regression equation to observe the hierarchy order (considering the significance of term AB2). The P-value for the model reveals that the probability that this model is formed due to any lab errors is less than 0.01% and the highest importance here belongs to nano-silica, showing its high effects on the mixture cohesion. Although the fibers' effects are not so high all by themselves, they perform well when used together with the nano-silica, which is especially magnified when the nanosilica and fibers have nonlinear interaction behavior.

Table 4. Selected model's ANOVA analyses of the cohesion parameter

Source	Sum of squares	*P*-value
Model	5721.53	0.0001 >
A-Nano silica	4125.98	0.0001 >
B-FRP	24.29	0.5331
AB	76.91	0.2724
A^2	483.84	0.0139
B^2	203.74	0.0811
AB^2	1267.12	0.0002

Figure 3 shows the cohesion coefficient versus % FRP and nano-silica.

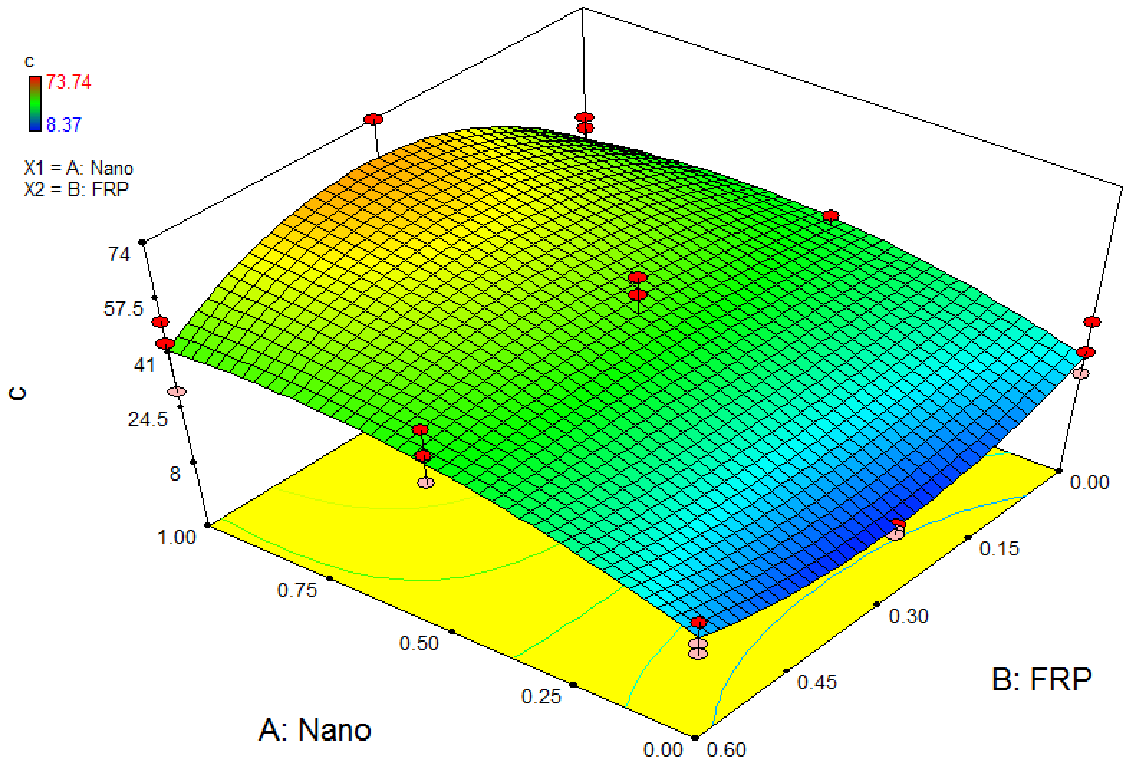

Figure 3. Cohesion coefficient versus % FRP and Nano-silica

As shown, increasing fibers by 0-0.3% reduces the cohesion and above 0.3% it highly increases it, but increasing Nano-silica increases the cohesion; a simultaneous Nano-silica-fiber increase increases the cohesion rate more than when they are increased separately; specifically, at higher Nano-silica percentages, fibers increase the cohesion, but above 0.3%, fibers reduce the cohesion.

3.1.2. INTERNAL FRICTION ANGLE

In Table 5 that shows the ANOVA results for the internal friction angle, the P-value for the model indicates that the probability that this model is formed due to any lab errors is less than 0.01%. Here, the highest significance belongs to fibers, showing their high effects on the internal friction angle. Although the effects of fibers alone are not high at high percentages, when used together with Nano-silica, they show magnified behavior in nonlinear interactions; however, the effects of fibers alone are much more than their combination with the Nano-silica.

Table 5. Selected model's ANOVA analyses of the internal friction angle

Source	Sum of squares	*P*-value
Model	371.63	0.0001 >
A-Nano silica	141.91	0.0001 >
B-FRP	225.07	0.0001 >
AB	1.53	0.5701
B^2	3.10	0.4205
AB^2	93.12	0.0002

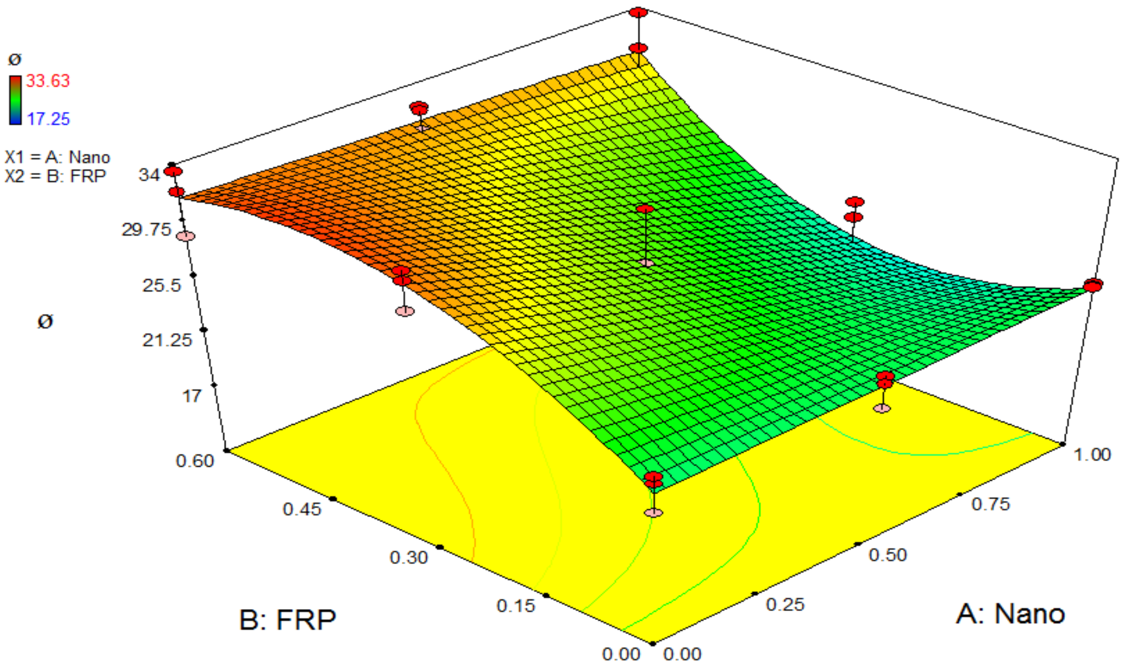

Figure 4. Internal friction angle versus % FRP and nano-silica

As shown, increasing fibers by 0-0.3% highly increases the internal friction angle, but a more increase reduces the slope of variations; meanwhile, increasing the nanosilica increases the mentioned angle. The simultaneous nanosilica-fiber increase effect on the cohesion rate shows the not so favorable effect of the use of nanosilica on the internal friction angle; when fibers and nano-silica are used together, a decrease in nanosilica increases the internal friction angle.

3.2. OPTIMIZATION

Tests performed with imposed percent additives cannot necessarily yield their optimum values; here, data optimization is a necessity. Figure 5 shows the optimal percent nanosilica and carbon fibers to achieve the best cohesion and internal friction angle.

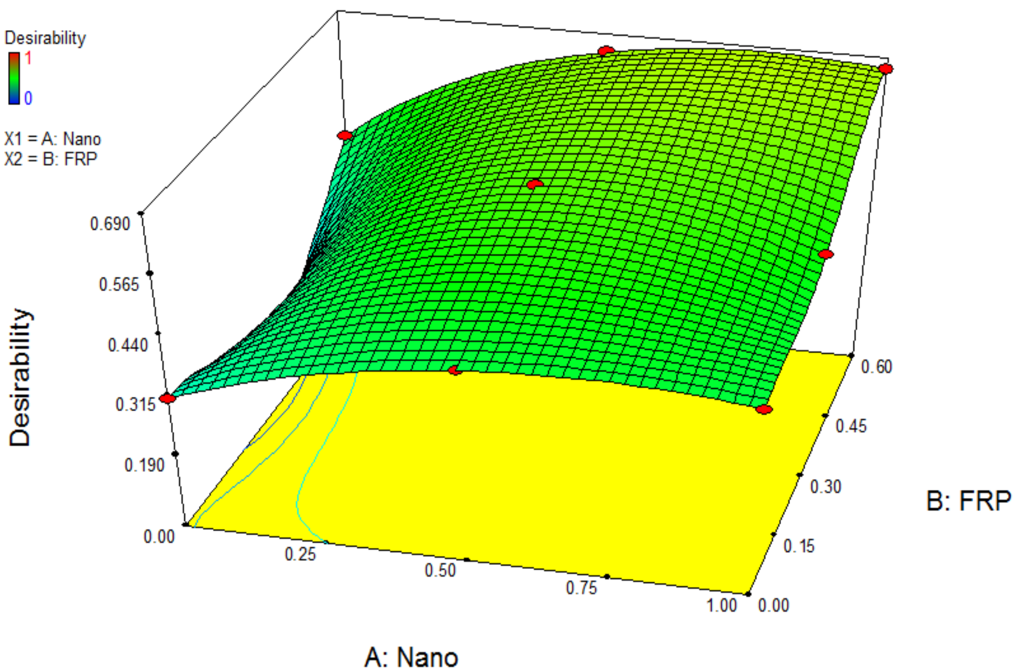

Figure 5. Optimum nanosilica and carbon fibers (%) to achieve the best internal friction angle and cohesion

The optimum amounts of fibers and nano silica are 0.59 and 0.8% by weight of the dry soil, where the internal friction angle and cohesion are expected to increase by 33.5 ° and 45.85 kPa, respectively.

3.3. PERFORMANCE OF ADDITIVES SOIL

Figures 6, 7 And 8 show the SEM images of the soil samples.

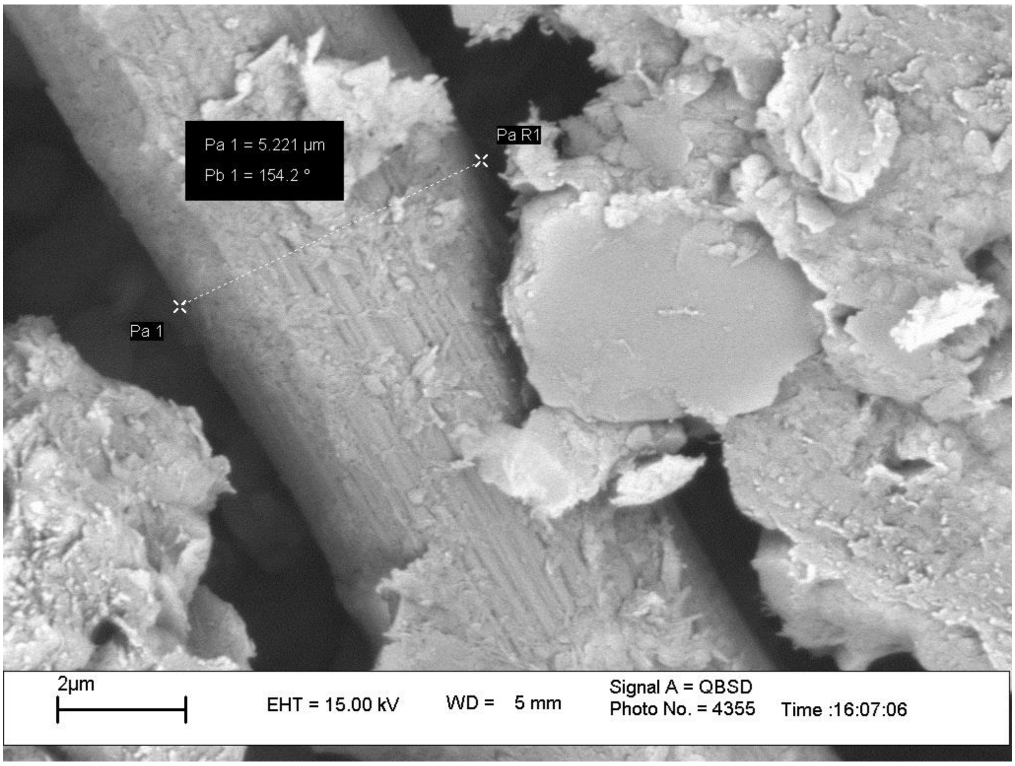

Figure 6. 2 µm-magnified SEM image of the sample

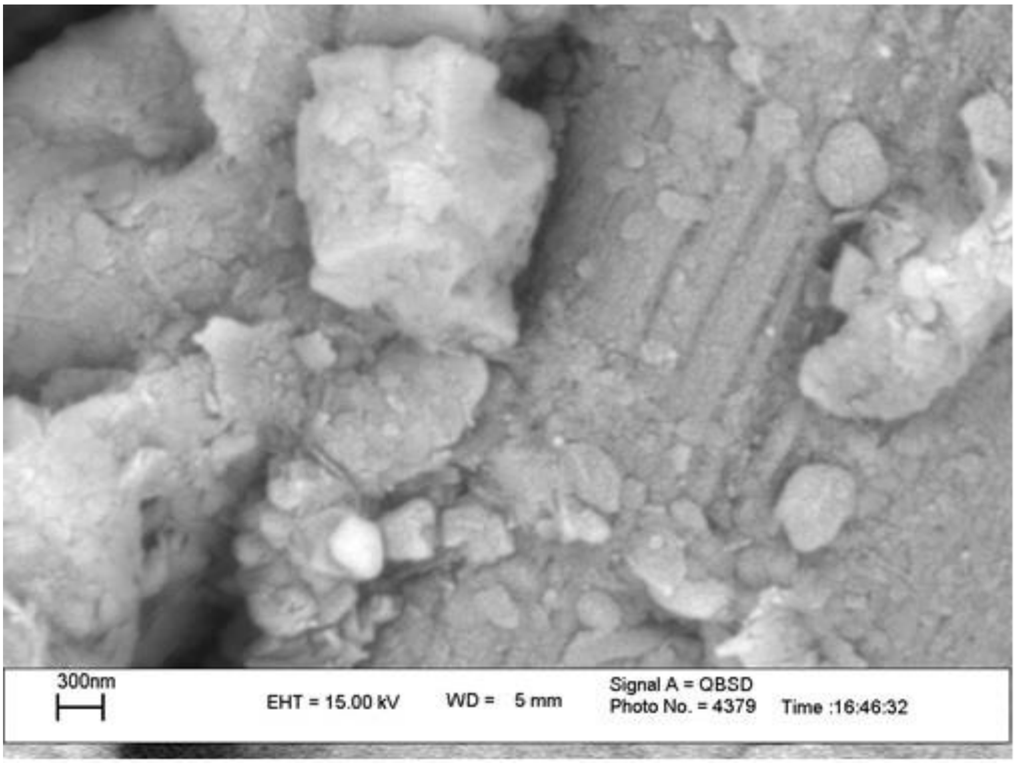

Figure 7. 300 nm-magnified SEM image of the sample

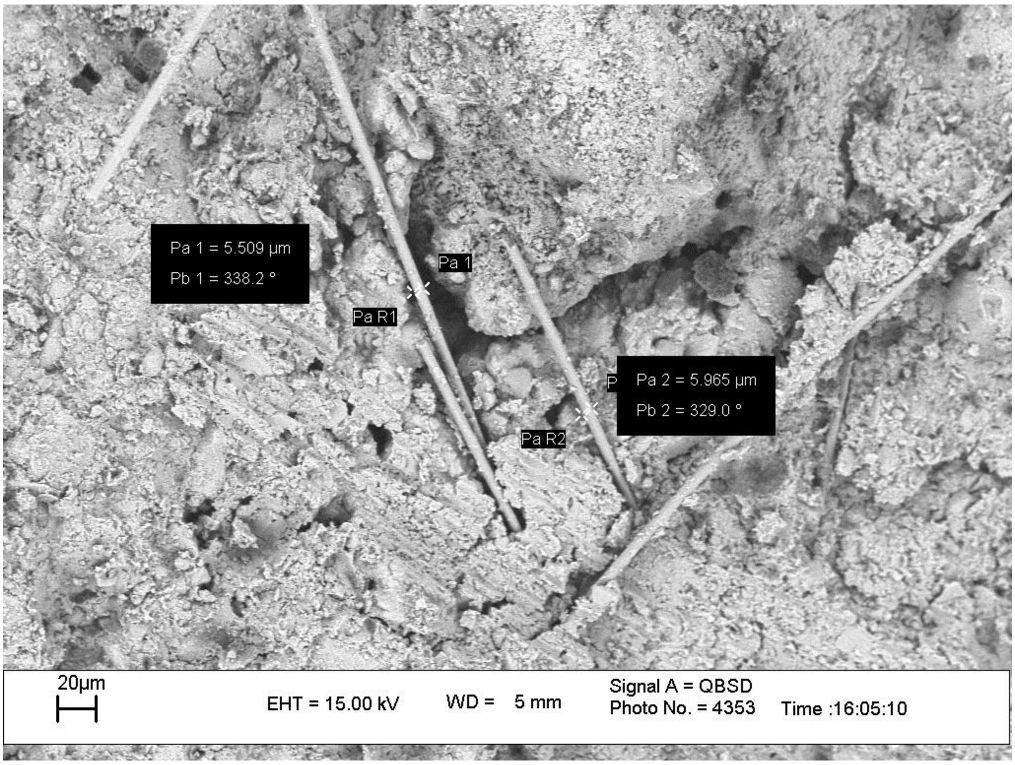

Figure 8. 20 µm-magnified SEM image of the sample

It can be claimed that increasing nanosilica and fibers (alone and together) increases the soil shear strength. SEM images cannot correctly show the shear stress increase mechanism; however, this increase can take place under three general modes: 1) adding nanosilica solution to soil, in the form of a viscous gel, causes the soil inter-particle cohesion to increase compared to the normal state; in other words, it can be said that the mentioned cohesion due to the nanosilica gel is stronger than that due to the surface absorption water; this viscous gel also affects the particles' internal friction angle, 2) nanosilica reduces the distance of the soil particles by filling the small inter-particle spaces and, hence, increases their internal friction angle by bringing them closer to one another and 3) using nanosilica and fibers together will cause the former to fill the empty spaces, bring soil particles closer to fibers, create more fiber cohesion and, hence, improve the soil cohesion because tests results have shown that fibers alone reduce the cohesion, but their simultaneous use with nanosilica solves this problem.

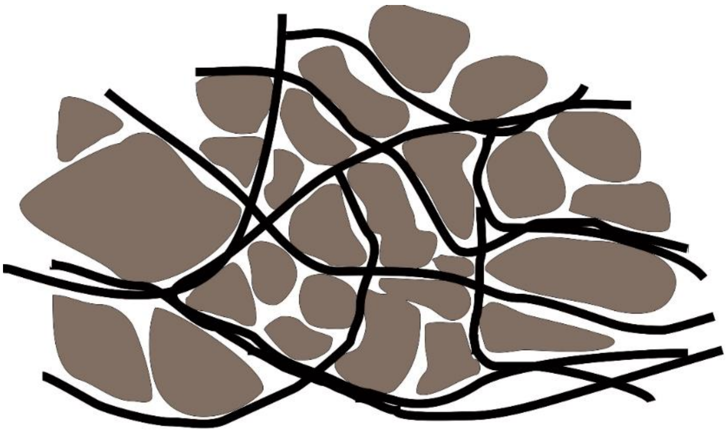

Figure 9. Fiber-reinforced soil sample

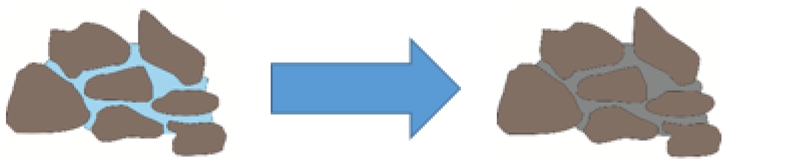

Figure 10. Effects of nanosilica on the soil inter-particle adhesion

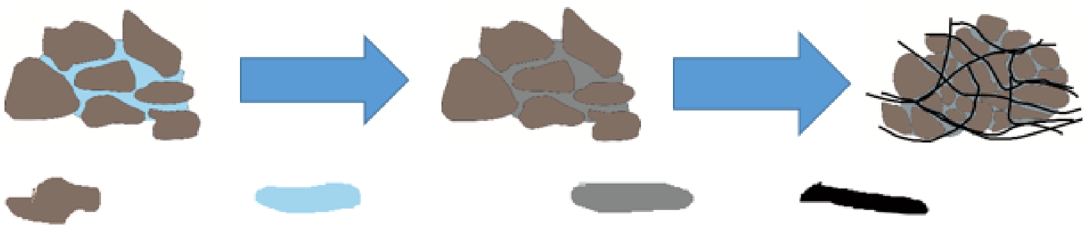

Figure 11. Effects of nanosilica and fibers on the soil inter-particle adhesion

4. CONCLUSION

This research studied the effects of nanosilica and carbon FRP (separately and combined) on the soil shear strength parameters by the direct shear machine. After preparing the samples, they underwent the direct shear test and the results were analyzed. At least 9 tests were done with 3 different vertical forces to draw each case, the results of which are as follows:

1. Fibers and nanosilica, used alone or together, increase the soil shear strength.
2. When only nanosilica is used, its optimal value to improve the shear strength parameters is 0.71%, where the cohesion increases by 63%.
3. When only fibers are used, their optimal value to improve the shear strength parameters is 0.6%, where the internal friction angle increases by 32%.
4. When fibers and nanosilica are used together, their optimal values to improve the soil strength parameters are, respectively, 0.59 and 0.8%, where the internal friction angle and cohesion increase by 28 and 88%, respectively.
5. The best nanosilica-soil mixing method is using a 100,000-rpm hydrometric mixer for a long time.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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