Enhancement of Clay Compressibility and Strength Using Nano Magnesium Oxide

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Abstract. In order to satisfy the requirements of environmentally friendly construction projects and minimize greenhouse gas emissions, it was necessary to focus on utilizing nanomaterials instead of conventional materials to enhance clay soils; nano Magnesium Oxide was suggested for this study. The compression and unconfined compressive strength tests were achieved to assess the compressibility behavior and strength of silty clay treated using nano magnesium oxide. Additionally, an investigation into the alteration of the clay microstructure was conducted using field emission scanning electron microscopy (FE-SEM) tests. The silty clay utilized in this research is characterized by a compression index 0.23 and an undrained shear strength of 53 kPa. The soil was treated by adding different percentages of nano-MgO (0.4%, 0.5%, 0.6%, and 0.8%), and the curing period was seven days. The treated soil samples were prepared based on the optimal water content and maximal dry density of the natural soil. The results indicate that utilization of nano Magnesium Oxide leads to a reduction in both values of the index of compression (Cc) and recompression index (Cr), in addition to a decrease in the value of the coefficient of compressibility (a_v). Also, the test finding for unconfined compressive strength demonstrates a noticeable increase in strength as the percentage of nano-MgO increases, accompanied by a reduction in failure strain. Adding 0.6% (the optimum percentage) of nano Magnesium oxide enhances the strength by about 114% and decreases the value of the compression index by about 36% compared with natural soil.

Keywords: Compressibility; silty clay; unconfined compressive strength; nano-MgO.

1. INTRODUCTION

Natural clay soil suffers from unfavorable issues, such as high compressibility, swelling, high sensitivity to moisture, and insufficient bearing capacity, rendering it unsuitable for meeting the demands of contemporary construction. The more usual technique for decreasing the disadvantages of clay soil is by employing various materials, like fly ash [1] and lime [2], and the most commonly utilized binder is cement owing to its exceptional strength, cost-effectiveness, and availability of sources [3]. Nevertheless, real environmental hazards associated with energy and CO2 emissions occur due to cement manufacturing and use [4,5]. Cement manufacturers contribute 5-7 percent to carbon dioxide (CO_2) emissions worldwide, contributing to serious environmental issues like global warming [6-8]. The cement particles are rather large, so they cannot penetrate the voids in the soil mass by themselves except through injection pressure. Hence, the cement treatment causes severe disruption to the environment [9]. Besides, the highly alkaline circumstances generated by cement may adversely affect the stability of pollutants (heavy metals) in reclaimed soils and plant growth performance [10]. Although the influence of the surrounding environment when chemical grout materials (acrylate grout, epoxy grout, and sodium silicate) are used is a small disruption, it can lead to significant groundwater pollution [9]. In light of the mentioned these concerns about using traditional materials as soil stabilizers, we must prioritize using alternative soil stabilizers as a matter of sustainability.

Regarding the requirement for environmentally friendly building construction, the following are the key novelties of the agent for additives: reducing the consumption of natural resources, reducing the amount of energy used, reducing greenhouse gas emissions, and restraining pollution of the earth, air, and water [11]. New substances known as nanomaterials have at least one spatial dimension that is less than 100 nanometers. They have unique structural characteristics due to their small particle size, which results in various unique effects, such as a significant surface area, great surface activity, and the interface effect [12]. The potential advantages of nanotechnology for innovative approaches to soil enhancement were examined by [13]; the authors demonstrated that when compared to conventional grouting techniques, soil improvement based on nanomaterials results in minor subsurface disturbance and is environmentally friendly. With the advancement of nanotechnology, nano-magnesium oxide is a high-function material. Compared to conventional magnesium oxide, it has a surface effect, an interface effect, a small size effect, and different chemical and physical properties, according to [14]. Gao [15] employed different percentages of nano Magnesium Oxide to investigate the clay soil reinforcing mechanism. They carried out unconfined compressive strength tests for samples with altered water content. The findings indicate that nano Magnesium Oxide can greatly increase the solidification impact by increasing the cementation, filling the porous, and soil particle water sorption.

The impact of different amounts of nano-MgO on the Atterberg limits and unconfined compressive strength of the soil with the curing period (1 and 28 days) was inspected. The result showed that the plasticity index

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had significantly decreased. The decrease was proportional to both the N-MgO contents and the curing duration, and the unconfined compressive strength greatly increased over the curing period. Furthermore, it was also noted that the mechanical behavior of soil altered from ductile to brittle, according to [16]. Triaxial shear tests were conducted by [17] to investigate the relation between the soil shear property and various nano-MgO dosages. The findings indicate that the cohesive force and soil failure strength can be notably increased by adding nano-MgO but with limited influence on the internal friction angle. According to the SEM analysis, adding nano Magnesium Oxide can affect soil shear properties by reducing its void ratio and enhancing the cementation between soil granules.

Clay cohesion and soil stiffness can both be significantly increased by adding nano-MgO. Furthermore, the nano Magnesium Oxide converted the layered sheet structures of soil particles into focused particles, as pointed out by [18]. In their study [19], they treated soft subgrade soil with altered percentages of nano-MgO to inspect the alterations in the engineering characteristics of soft soil. The findings indicated a significant enhancement in the characteristics of the soil, such as the California Bearing Ratio value increased, the swelling ratio decreased, and EDXR-Spectroscopy analyses revealing the existence of significant chemical interactions between the soil and the nanomaterial that could result in the creation of magnesium silicate hydrate (M-S-H), which would strengthen the bonds between soil particles and enhance the rigidity of the soil.

The employment of nano-MgO to improve dynamic performance and resistance to freeze-thaw cycles in problematic soil (loess) was investigated by [20]. The results showed that the water-absorbent influence of the nanomaterial converts the water from free to bound, significantly enhancing dynamic performance and resistance to freeze-thaw cycles. Since the compressibility of nano-MgO-treated silty clay has yet to be studied and remains unknown, this paper seeks to offer a comprehensive understanding of nano-MgO-treated soil. In this study, the oedometer test, unconfined compressive strength, and FE-SEM were carried out on untreated and treated soil with various percentages of nanomagnesium oxide to evaluate the effectiveness of treated soil with nano-MgO.

2. EXPERIMENTAL MATERIALS AND THE METHODOLOGY

2.1 Soil Tested

From a building site in southern Baghdad city, soil samples were collected at depths between 0.5 and 2 meters beneath the ground's surface. Laboratory experiments were conducted on remolded soil to determine the soil sample's engineering characteristics. The results from the experiments are scheduled in Table 1. The soil's grain size distribution is illustrated in Figure 1. The soil is categorized as low-plasticity clay "CL" by the Unified Soil Classification System (USCS).

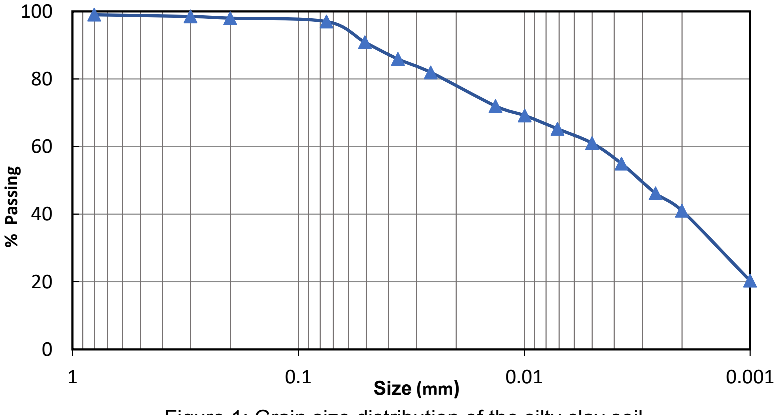

Figure 1: Grain size distribution of the silty clay soil.

Table 1: The soil's physical characteristics.

Physical properties	value	ASTM Specification Test [21]
Sand (%)	3	D422
Silt (%)	35	
Clay (%)	62	
Specific gravity, Gs	2.73	D854
Liquid limit (%)	43	D4318
Plastic limit (%)	19	
Plasticity index (%)	24	
Classification Soil	CL	D2487
Maximum dry unit weight (kN/m^3)	16.3	D698
Optimum moisture content (%)	18.5	

2.2 Nano Magnesium Oxide

This study adopted nano-magnesium Oxide (nano-MgO) to enhance the geotechnical properties of silty clay soil. All of the nanomaterial utilized was obtained from commercial markets. The nano-magnesium Oxide was produced by an American manufacturing firm. Table 2 lists some characteristics of the nano-MgO used in this investigation. The scanning electron microscope (SEM) of nano-MgO is displayed in Figure 2.

Table 2: Characterization of a nano-magnesium Oxide.

Appearance	Purity (%)	Average particle size (APS) (nm)	Density (g/cm^3)
White powder	99.9	10-30	3.58

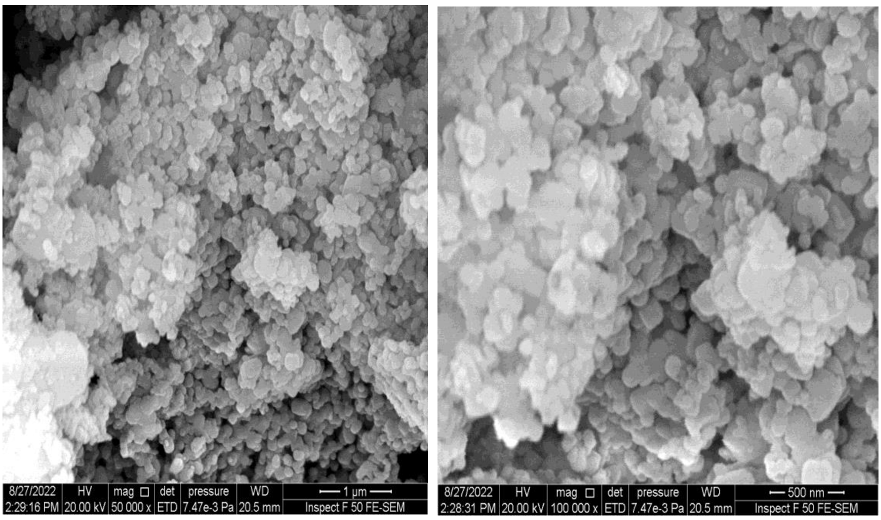

Figure 2: SEM image of nano-magnesium oxides

2.3 Methodology

The dry natural soil is initially crushed and sieved through sieve #4 (4.75 mm). The amounts of nano-magnesium Oxide selected were 0.4%, 0.5%, 0.6%, and 0.8% of the soil's total dry mass. Mixing the nanomaterials with the dry soil in two steps is the best technique for getting homogeneous samples, according to [22]. This procedure was adopted in the current study. The soil was thoroughly stirred and divided into layers, after which the proper amount of nano-MgO was sprayed onto each layer. Before being put into the mixing tray, every layer was blended separately till a homogeneous (uniform color) mixture was achieved. The mixture of soil and nanomaterial was then agitated by a mechanical, horizontal, cylindrical mixer for a certain time. Furthermore, the water amount determined depending on the optimum moisture content was added step by step to the dry mixture (soil and nanomaterial) until getting homogeneous samples. Subsequently, the mixture was enclosed within a plastic pouch for 24 hours to allow the process of hydration.

3. LABORATORY TESTING

3.1 Compression Test

Compression tests were performed utilizing an oedometer to analyze the impact of various amounts of nano-MgO on the compressibility behavior of silty clay soil. The remolded sample is prepared in an oedometer ring with a height of 20 mm and a diameter of 75 mm; the dry density and water content in each remolded sample were maintained at 1.63 g/cm3 and 18.5%, respectively. Then, they were wrapped with plastic film and kept at laboratory temperature for seven days in an airtight container, and the samples were kept in oedometer rings throughout the curing to prevent sample disruption. On the ends of the sample, filter paper and porous stone were placed and loaded in the following sequence: 12.5, 25, 50, 100, 200, 400, 800, and 1,600 kPa (load increment ratio of 1), followed by unloading. Then, at the end of every load increment, the changes in the specimen's thickness were measured over time to determine the compression.

3.2 Unconfined - Compressive Strength Test (UCS)

According to ASTM D2166 [21], unconfined compressive strength tests were conducted. After preparing mixtures of soil and nanomaterial and ensuring the homogeneity of the mixtures, the mixtures were placed in a mold with a diameter of 38 mm and a height of 76 mm on three layers. The dry density and water content were kept constant in each specimen at 1.63 g/cm3 and 18.5%, respectively. Twelve samples were prepared, three for each percentage of nano-MgO, as presented in Figure 3. The specimens were then wrapped with plastic film and kept at laboratory temperature for seven days in an airtight container.

Figure 3: Soil samples prepared with various percentages of nano-MgO.

4. RESULTS AND DISCUSSION

4.1. Compressibility

The relation between the applied pressure along with the corresponding void ratio ($e_{\circ}$) for both natural and soil treated with various amounts of nano-MgO was plotted in Figure 4. The compression index is the most significant factor that determines the amount of consolidation settlement anticipated. The linear slope of the compression portion of the e-log p curve is the same as the compression index. Table 3 provides a summary of the results of the oedometer tests, which reflect the compression index (Cc), recompression index (Cr), and coefficient of compressibility (a_v) of natural and treated soil.

Table 3. Variation of Cc, Cr, and a_v of the natural soil and soil treated with nano-MgO.

Soil	Cc	Cr	a_v (m^2/kN)*10^{-4}		Decrease in Cc index (%)
			At pressure (100-200) kPa	At pressure (200-400) kPa	
Natural soil	0.23	0.053	6	3.6	
Soil+ 0.4% nano MgO	0.181	0.043	5.4	2.75	21.3
Soil+0.5% nano MgO	0.165	0.035	4.2	2.5	28.2
Soil+0.6 nano MgO	0.146	0.033	4.4	2.2	36.5
Soil+0.8% nano MgO	0.126	0.03	3.8	1.85	45.1

Figure 4 demonstrates that the initial voids of treated soil tend to decrease compared to natural soil's initial voids. The findings suggest that adding nano-MgO increases the soil's resistance to compression as the compression index (Cc) decreases; this confirms that incorporating nano-MgO into the soil matrix could fill pore spaces between soil particles and increase the free water absorption effect. Nano-MgO particles have a significantly smaller average diameter (10–30 nm) than soil particles. When combined with soil, the voids between the soil particles will be filled, decreasing the pores' size and enhancing the void's arrangement, decreasing the soil's compressibility. Additionally, the impact of cementation due to the creation of $Mg(OH)_2$ due to the reaction between MgO and water results in a reduction in compressibility, as pointed out by [23]. Figure 5 demonstrates how the compression index changes per the nano MgO content.

Since MgO is lightweight, when 15 percent of it is added to the soil, its unit weight decreases compared to its natural unit weight. As a result, blending the soil with magnesium oxide and preparing the sample for the oedometer cell was more difficult than for the other percentages concluded by [24]; this may explain why, despite the increase in nanomaterial from 0.6% to 0.8%, the compression index values improved were convergent. In order to figure out how resistant nano-treated soil is to vertical deformation during the unloading stage, recompression index (Cr) values were calculated for different percentages of nano-MgO content. The findings indicate that as the percentage of nano-MgO increases, the value of Cr declines gradually within a narrow range. The coefficient of compressibility (a_v) is a crucial parameter in characterizing soil compressibility and was determined based on the e-p curves within different pressure cycles. It has been noted that incorporating nanomaterials in different percentages into soil decreases the value of the coefficient of compressibility.

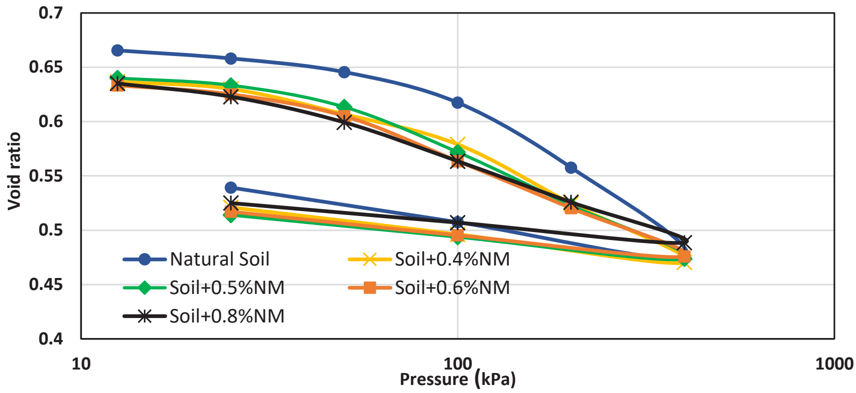

Figure 4: Compressibility behavior of silty clay treated with various percentages of nano-MgO.

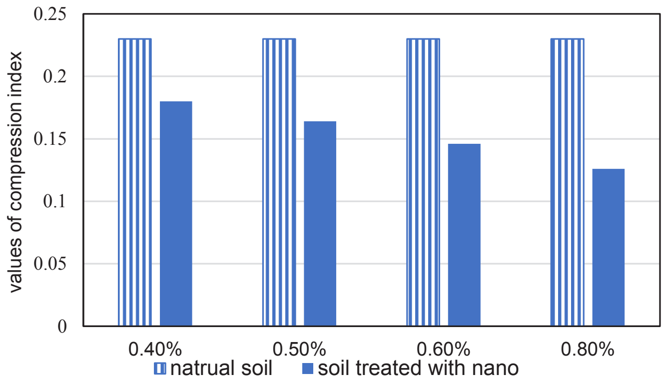

Figure 5: Variation compression index Cc with the percentage of nano MgO.

4.2 Unconfined Compressive Strength

The strength of soil treated with various percentages (0.4, 0.5, 0.6, and 0.8%) of N-MgO was assessed using an unconfined compressive strength test. For each soil and nano-MgO percentage mix, samples were loaded vertically at a constant displacement rate until failure. The stress-strain relationship relating to the unconfined compressive strength examination findings is depicted in Figure 6. It is obvious from the figure that the addition of nano-MgO to the soil, even at a low percentage, significantly enhances the unconfined compressive strength; subsequently, there is an increase in the undrained shear strength (Cu).

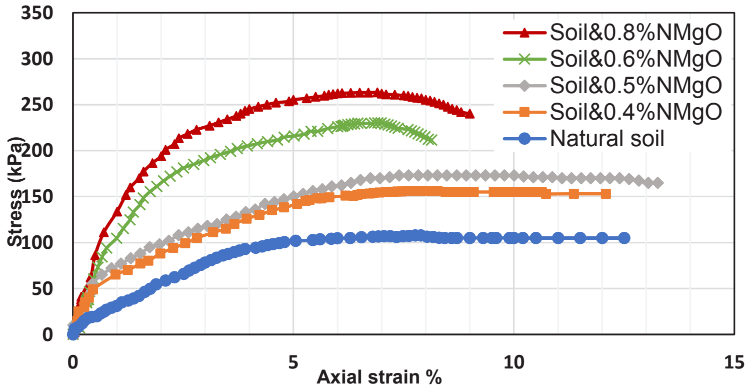

Figure 6: A stress-strain curve of natural soil and soil treated with various percentages of nano MgO.

Table 4 demonstrates the association between the undrained shear strength (Cu) and the amount of nano-MgO utilized to enhance the soil. The results demonstrated that the increasing trend in strength was linear.

The greatest increase rate in the value of c_u approaching 143% (roughly the equivalent of two and a half times of natural soil) was obtained at the utilization of 0.8% of nano-MgO. The lowest increase rate in the value of Cu, approaching 46%, was obtained at the utilization of 0.4% of nano-MgO.

Table 4. The result of q_u, and cu of the natural and treated soil.

Soil type	q_u (kPa)	c_u (kPa)	Increase in Cu (%)
Natural	107	53.5	
Soil+ 0.4% nano MgO	155.7	77.85	46.3
Soil+0.5% nano MgO	173	86.5	61.6
Soil+0.6 nano MgO	230	115	114.9
Soil+0.8% nano MgO	261	130.5	143.9

Typically, soil composition includes air, water, and solid particles that are bonded together to form the soil's structure. The soil's strength mainly affects its void ratio, water content, and density. The enhancement in strength can be ascribed to the fact that the addition of nano-MgO into the soil matrix reduces porosity and increases the connection between the particles, leading to enhanced and increased density due to the nano-MgO filling of voids within the soil matrix. Figure 6 shows clearly that the stress-strain diagram of the natural soil sample does not show a noticeable peak, while the stress-strain curve of treated soil with 0.6 to 0.8% demonstrates that it has a manifest turning point. Furthermore, the maximum strength (peak stress-strain) is achieved at a lower strain than the natural soil. These findings indicate that an increased nano-MgO percentage leads to a greater tendency for samples to exhibit brittle behavior.

The results show that the sample's strength improved by approximately 114% when adding 0.6% of nano-MgO. Moreover, by increasing the percentage of nano-MgO from 0.6 to 0.8%, the increasing rate of strength is around 145%. Despite the increase in the percentage of nanomaterial by twice, the increase in strength is not expected. In particular, it is possible that adding excessive nanoparticles results in dispersion issues, as indicated by [25]. Also, Yao et al. [26] mentioned that the overuse of nano Magnesium Oxide may cause internal fissures in the soil. Based on the discussion above, 0.6% is the optimal percentage of N-MgO.

4.3 FE-SEM Test

The field emission scanning electron microscopy (FE-SEM) technique helps demonstrate soil structure pores, soil particles, and their linkages at microscopic scales. A small amount of both natural and treated soil at 0.6 nano magnesium oxide was obtained from the shearing area and verified through the FE-SEM. Figure 7 illustrates the SEM outcomes.

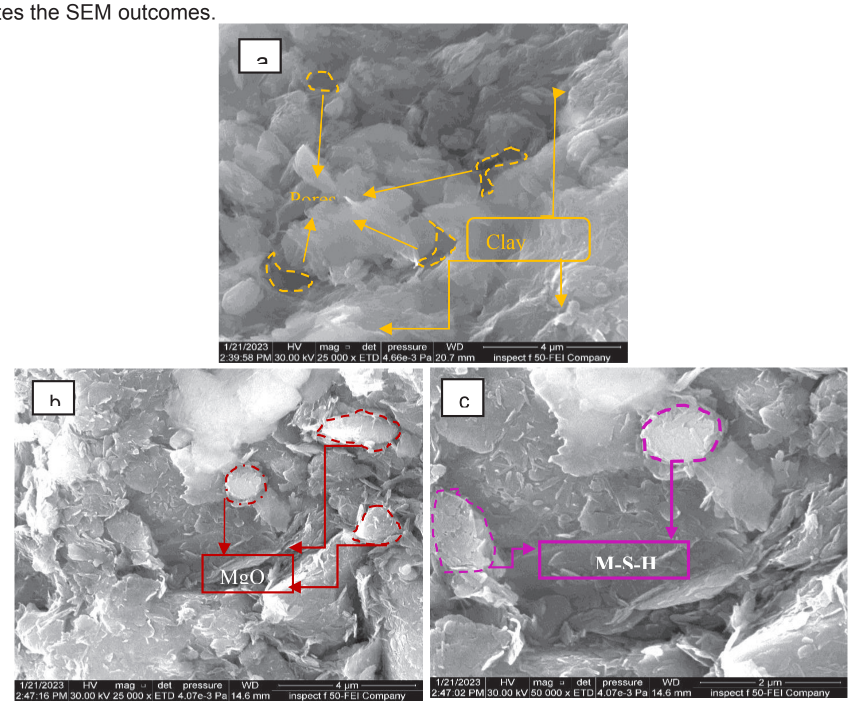

Figure 7: FE-SEM images;(a) natural soil zoom 25000 times, (b) soil treated with 0.6 nano-MgO zoom 25000 times, (c) soil treated with 0.6 nano-MgO zoom 50000 times.

Inside the clay soil, there are many micropores, as revealed in Figure 7(a). When nano-MgO is introduced to the soil, it fills these pores and strengthens the connections between the various natural soil particles, as presented in Figure 7(b). Additionally, when nanoparticles are incorporated into the soil, chemical reactions occur. First, When MgO reacts in the water, it releases OH^- and Mg^{2+} ions. Second, as mentioned by [27], the silicates (SiO_2) that exist in the clay and the results of nano MgO interactions with water (Mg^{2+} ions and hydroxide) interact to produce magnesium silicate hydrate (M-S-H) gel, as shown in Figure 7(c) and the effect of this process is soil particles bond together more strongly.

5. CONCLUSIONS

The current research was performed to investigate the effectiveness of nano-MgO on silty clay soil in terms of strength and compressibility. Four contents of nano MgO were added to the soil. The following are the major conclusions, depending on the laboratory tests of the present research:

- The compressibility and strength properties of the soil can be greatly improved by using nano-magnesium oxides as stabilizers. The enhanced mechanical performance is due to the nano MgO's ability to reduce pore size. It enhances the void's arrangement, increasing the density and enhancing the microstructure of the soil. Moreover, when Nano-MgO is incorporated into the soil, chemical reactions occur to produce magnesium silicate hydrate gel. The effect of this process is that soil particles bond together more strongly.
- For the natural soil, adding nano-MgO leads to a good reduction of compressibility. All the different contents of additive used revealed a worthy effect on the compression index Cc. Adding 0.6% of nano-MgO to the soil decreased the compression index value by around 36.5% of its value in the natural soil.
- The strength of soil treated continuously increases with nano MgO content. Adding 0.6% nano-MgO can increase the strength by about 114%.
- The amount of the optimum percentage (0.6% of the soil's dry weight) of nano-MgO is relatively smaller when compared with the requisite amounts of conventional additives employed for soil enhancement. Utilizing small amounts of this substance implies that it can be used effectively as an environmentally friendly additive.
- Despite the ability of nano-MgO as an additive material to enhance geotechnical characteristics, it is evident that its impact on strength is more pronounced than its impact on compressibility.

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