Characteristics of Soft Clays Enhanced by Graphene Oxide

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Abstract. With its eventual release into the atmosphere, graphene oxide is considered an emerging environmental pollutant. As a result, its possible environmental and biosafety threats are attracting more publicity. Due to the underlying soil properties, adding graphene oxide directly into the soft soil is difficult to change soil properties. This study aims to see if graphene oxide can be used as a stabilizing medium to increase the strength and compressibility of soft clay. The soft clay used in this analysis has a shear strength of 33.0 kPa. It has a curing time of 1 day and 7 days and is stabilized with 0.1 percent graphene oxide. It was discovered that as the curing time of graphene oxide increases, the soil compressibility (C<sub>c</sub> and C<sub>s</sub>) decreases. The coefficient of consolidation (C<sub>v</sub>) decreases as the curing time of graphene oxide is increases. The graphene oxide content and curing time increased the soil's shear strength. After 7 days of curing, the unconfined compressive strength can increase by 350 percent.

Keywords: Soft clay; stabilized; graphene oxide; consolidation; unconfined compressive strength.

1. Introduction
Soft clays are all part of the well-known group of soils that are difficult to work with. Such soils are primarily found in coastal areas under layered deposits. Soft clays are characterized by a lack of bearing capacity, high compressibility, and a long consolidation period. From field investigation to modeling behavior, there are many issues with soft clays. Coring undisturbed samples in soft clays are difficult due to drilling disruption. Due to inconsistency, such a task is often impossible to complete [1]. Although advanced field equipment may be used to obtain appropriate core samples, there is a risk of disruption during specimen preparation for laboratory tests. In-situ experiments can be used to reduce the impact of disruption on soft clay products. The field vane test, for example, is commonly used to assess the profile of undrained cohesion in upper soft clay layers (less than 10 m depth). Condensation treatments (such as preloading or compression), methods of applying pore water pressure (such as osmosis or dewatering), displacement-replacement, stage loading, and application of reinforcement materials (such as geogrids), supporting embankments with piles or stone columns, and deep chemical stabilization in situ were among the pre-proposed methods for treating soft clays [2, 3, 4, 5, 6].

Most of these methods are very expensive to apply. There are currently many nanomaterials widely available, the use of these materials is significant in various applications and geotechnical soil strengthening/strengthening techniques. Graphene oxide (GO) is becoming more commonly used in...
various applications, and the effects of this nanomaterial accessing the natural environment are important. Because of GO in water's high solubility, its deposition in the soil has the potential to change the mechanical and physical properties of the soil dramatically. With very high hydrophilic functional groups on its surface, GO is likely to interact strongly with some of the soil's components, having a significant effect on the soil's physical and chemical properties. As a result, further research is required into the impact of GO on soil properties, the charge distribution in soils, water-holding properties in soils, and the presence of oxygen in soils, all of them are essential for microorganism development. Because of its large specific-surface area and stable diffusion in water, even a small amount of GO has a significant effect on soil properties. It was also discovered that GO existing among the soil particles improves the soil's water absorption capacity. The findings suggest that coating soil particle surfaces with GO could seriously change the soil's physicochemical condition.

Nippon et al. [1] looked into GO nanosheets' impact on the geotechnical characteristics of cemented soil. Using different GO concentrations, the effect of GO on the soil's compaction properties, limits of consistency, unconfined compression power, and direct-shear parameters was investigated (0.02, 0.05, and 0.1 percent wt. percent of cement). The plasticity and compressibility parameters of the treated soil samples were reduced when GO was applied. As the GO concentration increased, the tensile and shear strength of the stabilized soil samples improved. As the GO content of the cement increased, so did its unconfined compressive strength. The effect of graphene oxide nanosheets (GO) on the geotechnical properties of cemented soil was investigated by Naseri et al. [7]. Various concentrations of GO (0.02, 0.05 and 0.1 wt% of cement) were added to the soil to evaluate the influence of GO on the soil’s compaction characteristics, consistency limits, unconfined compression strength (UCS) and direct shear parameters. The addition of GO decreased the plasticity and compressibility parameters of the treated soil samples. The tensile and the shear strength of the treated soil samples were increased with an increase in the GO concentration. The unconfined compressive strength was increased as the GO content increased in the cemented soil samples. The obtained results showed that the GO as a stabilizing agent has a considerable influence on the mechanical properties of stabilized soil.

In the laboratory study of Zhou et al. [8], GO was mixed with soil (clay sand, SC) to study the engineering properties and microstructure of modified soil. Experimental results revealed that the physical, mechanical, and microscopic properties of clay sand can change significantly by adding an accurate amount of GO. The addition of GO (up to 0.08% by weight) to the soil in general resulted in a decrease in the void rate of the soil under a certain hydrostatic uniformity pressure, while increasing the unconfined shear force. Such remarkable soil modifications in small amounts of GO can be attributed to a very specific surface area of GO and a stable dispersion in water. In investigation by Pateriya et al. [9], graphene oxide (GO) solution was added as a nanomaterial in low-cement fly ash (Class F - fly ash) to improve the various properties of available local alluvial soils. Several tests such as light pressure test, unrestricted pressure test, direct shear test, fluid limit, and plastic limit test on the newly formed matrix were performed to verify their respective behavior to stimulate the actual site condition on the specified matrix in the laboratory. A microscopic scanning (SEM) analysis was also performed to study the structure of the newly formed matrix. Adding a small percentage of GO to the original fly ash matrix reduces the plasticity index and at the same time maximal dry density, unrestricted compressive strength and cohesion value effectively use the new soil matrix.

A novel thiol-functionalized graphene oxide/Fe-Mn (SGO/Fe-Mn) composite was prepared and investigated by Huang et al. [10] for in situ immobilization of Hg in contaminated soil. Batch tests showed that application of SGO/Fe-Mn at doses of 0.4% and 0.8% effectively reduced H2O, H2SO4 and HNO3, CH3COOH, and CaCl2-extractable Hg by 90.3–98.9% and 96.5–98.9%, respectively, upon equilibrium after 72 d. An increasing of soil moisture content from 0 to 12.5% significantly enhanced the immobilization efficiency from 75.0% to 97.6%. The application of SGO/Fe-Mn enhanced soil cation exchange capacity, available N and K, and total organic carbon, and can be used to effectively improve soil properties. Moreover, immobilized Hg in soil by this composite remained stable over one year. The purpose of this study is to evaluate the suitability of graphene oxide as a stabilization material in order to enhance the soft clay strength and decrease its compressibility. Laboratory tests were carried out on natural clayey soil and clayey soil–graphene oxide mixtures with different curing periods.
2. Experimental work

2.1 Soil
Clay soil was transported from a location south of Baghdad, Iraq. The physical properties of the soil were determined using standard tests. Table 1 shows the properties of the soil. Figure 1 illustrates the grain size distribution for the soil used. The classification of the soil is (CL) according to USCS.

![Grain size distribution of the soil particles.](image)

**Table 1.** Geotechnical properties of tested soil.

| Property | LL (%) | PL (%) | PI (%) | Gs (%) | Sand (%) | Silt (%) | Clay (%) | $\gamma_{d,\text{max}}$ (kN/m$^2$) | $w_{\text{opt}}$ (%) | $q_{u}$ (kPa) | USCS |
|----------|--------|--------|--------|--------|----------|----------|----------|-----------------|-----------------|------------|------|
| Value    | 32     | 17     | 15     | 2.7    | 7        | 44       | 49       | 16.7            | 21              | 67         | CL   |
| ASTM Standard [11] | D4318 | D854   | D6913  | D698   | D2166    | D2487    |          |                 |                 |            |      |

2.2 Graphene Oxide
A modified hammer method can easily produce graphene oxide from pure graphite powder. Since it entirely depends on the raw chemical substances and the technique of constructing this GO solution at the laboratory level, this aggregation can also modify the final properties of GO. Direct use of the graphene oxide solution available on the market under the brand name "Graphene supermarket" in a particular study. Experimental studies were performed before the first stage of preparation in order to manage the effectiveness of the preparation process.

Two major points for the homogeneous bottom flooring preparation were verified via control tests. The first step is to check how shear strength changes over time in different water contents (20 percent, 22 percent, 28 percent, 32 percent, and 36 percent). The tests assess how long it will take to repair the re-reinforced soil after a break in the mixing phase. Five samples were separately arranged and spread out in three layers in molds of standard compaction to get to this point. Every layer is kindly stapled with a special hammer to remove any trapped air. The samples were then covered in a polythene sheet and placed in nylon bags for seven days. It was discovered that rebuilding the remodeled soil took about five days. After 5 days of mixing, the shear electricity variance is calculated in relation to various liquidity indices. Figure 2 presents the shear strength against liquidity indices results. Every day, the undrained shear strength was evaluated with a portable shear device. The shear strength of the soil reduces as the liquidity index value increases.

The soil water content was controlled at 21%. Aqueous solutions of various GO concentrations have been prepared by soaking before mixing them properly with water and soil to attain GO soil enhanced specimens with the percent required for GO weight. The GO solution's soil grains were lowered gradually below stirring to prepare the GO / soil mixtures. Since the mean dimension of soil grains was
about 0.2 mm, which was orders of magnitude larger than GO, they were simply distributed in a GO solution. Before gridding, the clay soil samples were dried in an oven at 105°C. Thereafter, the clayey soil and graphene oxide were blended under dry conditions to prepare the mixtures. After that, the prepared samples were mixed with a predetermined amount of stabilizer; dosage rates can be specified in a variety of ways. After that, the treated soil samples were put through a series of tests with varying curing times (1-day and 7-days).

3. Results and discussion

Table 2 shows the values of LL, PL, and PI of the tested soil before adding 0.1 percent graphene oxide.

**Table 2. Variation of limits of Atterberg for the tested soil with GO.**

| GO (%) | Curing age  | LL (%) | PL (%) | PI (%) |
|--------|-------------|--------|--------|--------|
| 0      | Untreated soil | 32     | 17     | 15     |
| 0.1    | No-curing    | 35     | 17     | 18     |

The water properties associated with soil particles are the key determinants of soil plasticity. Its water layer has more viscosity, stability, and shear strength than free water. A large number of functional groups on GO nanosheets' surface gives GO a high-water property in a semi-neutral pH, which attracts a large quantity of water. As a result, it is assumed that coating soil particles with GO would increase the amount of bound water, resulting in an enlargement in the soil boundary liquid. The observed effect of GO on the plastic index and liquid soil boundaries is due to this process. The plastic limit is characterized as the minimum soil water content necessary to keep the plastic state. Adding GO to the clay sand had no impact on the soil's plastic boundary under the conditions studied. The processes that comprise this observation allow for detailed investigations. Figure 3 shows the Variation of void ratio versus pressure of tested soil samples with different curing days.

Results of consolidation tests (performed according to ASTM D2435) for the tested soil samples are shown in Table 3. GO apparently behaves like a binder that forms a binding action between soil particles to fill in the fine inner fracturing that helps increase the strength and durability of the newly formed soil matrix. It is concluded that the higher the formation of the GO reduces the volume by making it denser and reduces the value of the optimum moisture content leading to the formation of a more compact matrix recently. Similar behaviors have been mentioned by former researchers \[8,9\]. Researchers summarized that the more the GO ratio, the more the soil matrix-density increases. Therefore, stabilized soil responds to an extra stable trend in contrast to unstabilized soil. It can be viewed that the proportion of vacancy in the soil has reduced continuously with the uniformity pressure. After including the GO,
the low void ratio gives conclusive proof that the "free" area between soil particles, which can be without difficulty compressed through an external force, has decreased. GO panels can clearly fill pores in the soil. It is difficult to flush the water trapped among the soil grains and the nanosheets GO from the soil samples, decreasing the percentage of spaces gathered from compression tests. However, as the treatment period increases, the GO absorbs the free confined water from the treated soil, increasing the voids ratio.

![Figure 3. Variation of void ratio versus pressure of tested soil samples.](image)

**Table 3.** Variation of Cc and Cs for tested soil samples.

|                  | Loading | Cc  | Unloading | Cs  |
|------------------|---------|-----|-----------|-----|
| Untreated soil   |         | 0.230|           | 0.044|
| Treated with graphene oxide, 1-day curing | Loading  | Cc  | 0.1860    |     |
|                  | Unloading| Cs  | 0.0290    |     |
| Treated with graphene oxide, 7 days curing | Loading  | Cc  | 0.1681    |     |
|                  | Unloading| Cs  | 0.0327    |     |

The "coefficient of consolidation" defines how lengthy it will take for a quantity of consolidation to take place; it is ruled via two factors: the amount of water squeezed out and the rate at which that water can flow out [12]. The lesser Cc in a soil, the much less the grain size, consequently permeability. It is intended to study the stabilizer curing period's impact on the consolidation coefficient at different pressures. Figure 4 shows the change of the consolidation coefficient with the applied pressure of the untreated soil and soil treated with graphene oxide at different curing times. The values of Cc are calculated using the Casagrande method.

The degradation in Cc caused by an increase in curing time is due to a change in soil texture caused by a reaction occurring within the soil. As a result, the time needed to gain primary consolidation will be more for graphene-enhanced soil for a given consolidation degree and drainage direction. GO has a much larger surface area (2600 m²/g) than soil particles (0.0147 m²/g). This illustration shows that, despite the low concentration or weight fraction of GO sheets, their surface region is enough to cover every soil grain with an average greater than 100 GO layers. It's also worth noting that if the soil grains are intensely enveloped in GO nanosheets, the soil particles' minerals would be tough to leave out. This may be harmful to the microorganism population, as the interplay of soil minerals and microorganisms is essential for their existence.
Furthermore, as soon as the soil particles are covered with GO nanosheets, any pollutants found in soil can be challenging to remove, making contaminated soil recovery more difficult. Both of these viable outcomes of GO on soil biology are vital and warrant additional study. The water trapped among the soil grains and the GO nano-sheets is hard to drive out from the soil specimens, lowering the void ratio acquired from consolidation studies. The “bound water layer” impact became less important once the GO content surpassed 0.08 percent. This is because the dispersion of GO is proportional to its concentration. In other statement, a higher GO percent in soil (e.g., 0.10 wt. %) causes the accumulation of GO nanosheets, which reduces the efficacy of GO soil stabilization.

Figures 5 and 6 also show that the soil's shear intensity increased as the GO content and curing time increased. This indicates that the existence of well-distributed GO improved the interconnection between soil particles. This finding is in line with the e–p relationship findings in Figure 3. The unconfined compressive intensity of untreated and treated samples is shown in Table 4. Soil shear strength is primarily determined by soil inter-particle interactions, such as friction. Graphene has been used as a stabilizer to enhance the mechanical Characteristics of various matrixes, together with polymers, plastics, and ceramics, due to its effective mechanical properties. Soil behaves like a hydrogel with a loose shape than these ordinary matrices, and the soil skeleton is created by using connected networks of soil grains. As GO nano-sheets are utilized in the soil, the interplay between neighboring soil particles strengthening inter-particle connections. The launch of metal ions from the soil particles should enhance GO nanosheets binding to the soil. Furthermore, the GO will alter the bound water shape and the double-layer on soil grains, thereby bettering the soil network's integrity. Figure 7 and Table 5 point out that enhanced soil has some friction in comparison to untreated soil.

**Table 4.** Unconfined compressive strength of tested soil samples.

| GO (%) | Curing age | $q_u$ (kN/m²) | % increase in $q_u$ |
|--------|------------|---------------|---------------------|
| 0      | Natural soil | 67            | -                   |
|        | No curing   | 129           | 92.5                |
| 0.1    | 1 day       | 158           | 135.8               |
|        | 7 days      | 303           | 352.2               |

**Figure 4.** Variation of consolidation coefficient of tested soil samples.
Figure 5. Unconfined compressive strength of tested soil samples

Figure 6. Mohr circles at failure in unconfined compression test of tested soil samples.

Figure 7. Samples after failure by the unconfined compression test.
Table 5. Measured angle of internal friction for the natural and treated soils.

| GO (%) | Curing age | Orientation of failure plane, θ (deg) | Internal angle of friction, φ (deg) |
|--------|------------|--------------------------------------|-----------------------------------|
| 0      | Natural soil | 0                                    | 0                                 |
|        | No curing   | 60                                   | 7.5                               |
| 0.1    | 1 day       | 62                                   | 8.5                               |
|        | 7 days      | 70                                   | 12.5                              |

where

\[ \theta \text{ (deg)} = 45 + \phi/2 \]  \hspace{1cm} (1)

\[ \phi \text{ (deg)} = (\theta - 45) \times 2 \]  \hspace{1cm} (2)

4. Conclusions

- The treated soil's void ratio will increase with GO as the curing time increases because of the confined free water being absorbed.
- The soil compressibility (C_c and C_s) decreases as the GO curing time is increased.
- As the period of GO curing time increases, the coefficient of consolidation (C_v) decreases.
- The soil's shear strength increased as the GO content and curing time increased. After 7 days of curing, the unconfined compressive strength can increase by 350 percent.

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