Compressibility Characteristics of Soft Clays Treated by Graphene

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Abstract. It is extremely difficult to obtain a change in soil properties by incorporating graphene directly into the soft soil. Therefore, the stability of the soil or cementitious materials can be improved by treating them with graphene. Graphene is easily manufactured from pure graphite powder. Based on this aggregation, it may alter the final properties of graphene, because it completely depends on the raw chemicals and the method of building this material. The mechanical behavior of a new compound graphene was studied through consistency and compression. The soft clay used in this study is characterized with shear strength of 33.0 kPa. It is stabilized with 0.1% of graphene with curing periods of 1 day and 7 days. It was observed that the void ratio decreased with addition of graphene under a given consolidation pressure. In addition, each of the swelling potential, the coefficient of volume compressibility and the coefficient of consolidation decrease with increasing the period of curing of graphene.

Keywords: Compressibility; soft clays; improvement; graphene; consolidation.

1. Introduction

Soils containing a high percentage of clay fraction are a type of problematic soil. Before erecting any structure on this type of soil, cautious through design analysis must be carried out to characterize the softening and high compressibility of the soil. These unfavorable issues merit a thorough investigation of the basic characteristics and shear strength of the soil. Apart from clay, sand and silt make up the other two principal types of soil. A certain percentage of clay is in soil since it holds other particles together and is resistant to water.
Soil settlement is a big problem when relating to structures such as roads, buildings and construction of dams on soft soils. These structures might be unstable and undergo bearing capacity and/or tilting failures due to the high compression and strength deficiency properties of soft soil.

Several methods have been used to treat the problem of low shear strength and high compressibility of soft clays. Different materials were added to soft clays such as lime (Alrubaye et al., 2016), silica fume (Fattah et al., 2014; Alrubaye et al., 2018), graphene (Al-Saadi et al., 2017), graphene oxide (Zhou et al., 2017) and geo-foam beads and bypass cement dust (El-Kady and Badrawi, 2018).

Due to the contrast in interaction, composition, and characteristics between different constituents in nano-composites, a number of controlling factors influence the action that nano-particles play as reinforcement fillers in a polymer-matrix. As an example: (i) fillers must exhibit special mechanical characteristics like strength and modulus of elasticity; (ii) they must include high aspect-ratio and high surface-area to maintain interaction with polymers; and (iii) they must be well-dispersed and away from agglomeration. The dispersion of nano-particle in the composition to the point at which individual particles become coated with the polymer is extremely critical. Increasing dispersion assist achieving good transfer of load to the nano-filler network, causing more uniform distribution of stress. The mismatch between the characteristics of nano-particle and polymer is mitigated by the increasing of interfacial area between the filler and composition, resulting in improved strength. Alignment of the filler in the composition, which is essential, is not critical.

Graphene is recently used in various applications in geotechnical engineering, and the effects of this nanomaterial showed great importance. Due to its high solubility in water, and its presence in soil significantly changes the physical and engineering properties of the soil.

Zhu et al. (2013) made a review on the studies related to the characteristic analysis of graphene and graphene nano-composites (GNCs) and their demonstrated superior actions in storage of energy and conversion, electrochemical- and bio-sensing, environmental remediation and flame retardant application and atomic thickness membrane separation. The applications of graphene and GNCs are highly dependent on their chemical composition, synthetic method, nano-scale morphology, and structure of the hybrids.

Naseri et al. (2016) demonstrated that the use of graphene oxide (GO) nanotubes affect the properties of cemented soils. Various concentrations of GO (0.02, 0.05 and 0.1% by weight of cement) were mixed with the soil to assess the effect of GO on soil compression properties, consistency limits, and shear strength parameters. The results demonstrate that the addition of GO as a stabilizing agent reduced the plasticity and improved shear strength parameters of the treated cement soil mixture.

Bhattachary (2016) concluded that nano-filled polymeric compositions have achieved noticeable electrical, mechanical and thermal characteristics. The treatment of carbon nano-tube, clay montmorillonite platelets and graphene was evaluated as suggested nano-fillers to make nano-composites. The different functionalization procedures of developing the nano-fillers to improve the interaction with polymers were reported. The essentials of filler dispersion in the polymeric composition was presented. In addition, the difficulties and future vision for nano-filled polymeric products were highlighted.

Graphene nano-materials (GMs), such as graphene-oxide (GO) and “reduced graphene oxide” (GO), were extensively used in different applications. For this purpose, He et al. (2017) showed the effect of the highly relevant environmental indices on the aggregation, stability and transformation of GMs in aquatic environments with concerned risks. In addition, the transport of GMs and micro-bial communities developments were also presented depending on the present conclusions.

Pateriya et al. (2019), investigated the use of graphene oxide (GO) as a nano material in low-cement fly ash "Class F" to improve the properties of available local alluvial soils. Several tests such as unconfined compression test, box shear test, and Atterberg's limits tests on the newly formed soil mixture were performed to verify their behavior to stimulate the site condition on the specified soil mixture in the laboratory. A microscopic scanning (SEM) analysis was also used to study the newly formed soil structure mixture. Adding a small amount of GO to the soil-fly ash mixture reduces the plasticity index,
and increase maximum dry density, unrestricted compressive strength and cohesive value of the new soil mixture.

The aim of this study is to evaluate the effectiveness of using of graphene as a stabilizing agent in order to decrease the compressibility of soft clays. Laboratory tests were carried out on natural clayey soil and clayey soil–graphene mixtures with different curing periods.

2. Experimental Work

2.1 Soil

The soil was brought from an earth embankment site south of Baghdad. Specific tests were conducted on the remolded soil to find physical properties of the soil. The test results are shown in Table 1. The distribution curve of grain size particles of the soil used is shown in Fig. 1. The soil is classified as "CL" according to the Unified Soil Classification System (USCS).

2.2 Graphene

Graphene used is pure graphite powder. Before the first stage of preparation, experimental tests were conducted to specify the effectiveness of the preparation method. Quality control tests were performed to verify two main points for the homogeneous bottom floor preparation. The first is to determine the shear strength variation at different water contents with time (20%, 22%, 28%, 32% and 36%). The tests determine the time required to restore the treated soil after the mixing process. To achieve this test, five soil samples were prepared individually and laid out in three layers in the Proctor compaction mold. Each layer is gently tamped with a special tamper to extract any trapped air. The soil samples were then covered with a waterproof sheet and left for seven days. The shear strength was measured every day, using a portable shear device. The results show that the shear strength of the soil decreases with an increase in the liquidity index value. It was found also, that the time required to recover the remodeled soil is about 5 days. The second point is to determine the shear strength variance after 5 days against different liquidity indices. Figure 2 illustrates the results of the shear strength variance unrestricted by different liquidity indices.

Table 1. Physical properties of the soil used

| The Property                        | Value |
|-------------------------------------|-------|
| **Consistency limits**              |       |
| Liquid limit, LL (%)                | 32    |
| Plastic limit, PL (%)               | 17    |
| Plasticity index, PI (%)            | 15    |
| Activity                            | 0.30  |
| Liquidity Index, LI                 | 0.266 |
| **Specific gravity, G<sub>s</sub>** | 2.70  |
| **Grain size distribution**         |       |
| Gravel % (larger than 4.75 mm)      | 0.0   |
| Sand % (0.075 to 4.75 mm)           | 7.0   |
| Silt % (0.005 to 0.075 mm)          | 44    |
| Clay % (less than 0.005 mm)         | 49    |
| **Standard compaction**             |       |
| Maximum dry unit weight, γ<sub>d,max</sub> (kN/m<sup>3</sup>) | 16.7  |
| Optimum moisture content, Ω<sub>opt</sub> (%) | 21    |
| **Unconfined compression strength, q<sub>u</sub> (kN/m<sup>2</sup>)** | 67    |
| **Classification of the soil (USCS)** | CL    |
The soil water content was controlled at 21%. Aqueous solutions of different concentrations of graphene were performed by soaking, before being mixed well with water and the soil to obtain graphene soil-mixture percent by weight. The soil particles in the graphene solution were gradually dropped under stirring. Since the average size of soil particles was approximately 0.2 mm, which is the order size of orders higher than graphene, they were easily dispersed in a graphene solution.

Before gridding, the clayey soil samples were air dried at 105°C, and then mixed with the specific amount of stabilizer (graphene aqueous solution). The mixed soil was tested without and after 1 and 7-day curing.

To understand the rate and volume of soil consolidation upon lateral restriction, loading and depletion, a standardization test was performed (AS1289.6.6.1, 2001). The increase in excess pressure on a layer of increasingly compact cohesive soil leads to a reduction in void ratio with view of long-term strength which or the stability of the soil layer. The settlement process can be predicted based on the value and duration of settlement in the soil layer.

3. Results and Discussion

Table 2 presents the values of Atterberg limits before and after mixing the soil with 0.1% of graphene.

| Graphene (%) | Curing age | LL (%) | PL (%) | PI (%) |
|--------------|------------|--------|--------|--------|
| 0.0          | Natural soil | 32     | 17     | 15     |
| 0.1          | No curing  | 34     | 17     | 17     |

Soil plasticity depends on water content associated with the type of soil particles. Graphene nanosheets contain a large set of functional groups on the surface, giving graphene high water-properties in attracting a large amount of pore water. This film of coating soil particles with graphene may be expected
to increase the quantity of bound water, and lead to an increase in the soil boundary liquid. This behavior may cause the observed effect of graphene on the plasticity index and liquid soil boundaries. It shows that adding graphene in the clayey soil gives a little effect on the plastic boundary of the soil (Zhou et al., 2017).

Figures 3 and 4 show the void ratio with applied pressure plotted in logarithmic and normal scale, for e-log p and e-p relationships, respectively of natural and treated soils for 1-day and 7-day curing periods.

The most important parameter related to the amount of anticipated consolidation settlement is the compression index (Cc), that a soil layer subject to loads that are greater than experienced in the past (Fattah et al., 2014). It is simply defined as the slope of the linear compression segment of the e-log p curve. The results of compression and swelling indices which are obtained from consolidation tests of the samples with different curing periods are presented in Table 3.

Graphene apparently acts as a binder between soil particles and fill the fine inner fracturing within the soil that reduces the voids and this in turn improve the strength and durability of the treated soil mixture. This improvement in soil strength is referred to the formation of a denser soil mixture as a result of graphene addition. The same trends have been reported by former researchers Zhou et al., (2017) and Pateriya et al., (2019). Researchers concluded that the higher the graphene ratio, the recent the soil matrix density increases with a decrease in voids. Therefore, treated soil responds to more solid behavior compared to untreated soil.

Figures 3 and 4 show that the percentage of voids in the soil has decreased continuously with the uniformity pressure as a result of graphene addition and that the "free" pores within the soil block, is reduced through the application of external pressure.

**Figure 3:** Void ratio – logarithm of pressure relationships of treated and untreated soil

**Figure 4:** Void ratio – pressure relationships of treated and untreated soil
Table 3. Values of (Cc) and (Cs) of treated and untreated soils with different curing periods

|                      | Loading Cc | Unloading Cs | Decrease in indices (%) |
|----------------------|------------|--------------|-------------------------|
| Untreated soil       |            |              |                         |
|                      | $\frac{\varepsilon_1 - \varepsilon_2}{\log \left( \frac{\sigma_1}{\sigma_2} \right)} = 0.2300$ | $\frac{1}{5} - \frac{1}{10} \sigma = 0.0440$ |                         |
|                      | $\sigma_1 - \sigma_2$ | $\sigma_1 - \sigma_2$ |                         |
|                      | $e_1 - e_2$ | $e_1 - e_2$ |                         |
|                      | $0.009(\text{LL} - 10) = 0.1980$ | $0.0463 \left( \frac{\text{LL}(\%)}{100} \right) G_a = 0.0400$ |                         |
|                      | $0.2343 \left( \frac{\text{LL}(\%)}{100} \right) G_a = 0.2024$ | $G_a = 0.0396$ |                         |
|                      | $\sigma_1 - \sigma_2$ | $\sigma_1 - \sigma_2$ |                         |
|                      | $e_1 - e_2$ | $e_1 - e_2$ |                         |
|                      | $0.2343 \left( \frac{\text{LL}(\%)}{100} \right) G_a = 0.2024$ | $G_a = 0.0396$ |                         |
| Treated soil         |            |              |                         |
| with graphene,       | Loading Cc | Unloading Cs |                         |
| 1-day curing         | $0.176$    | $0.029$      | $23$                    |
|                      | $0.172$    | $0.030$      | $25$                    |
|                      | $0.176$    | $0.029$      | $34.1$                  |
|                      | $0.172$    | $0.030$      | $31.8$                  |

The nanosheet can actually fill the pores within the soil and coating soil particles. It is difficult to expel the water trapped in the pores between the soil particles and the nanosheets graphene from the soil samples, for reducing the percentage of voids obtained from compression tests, but as the curing period increases, the graphene absorbs from the treated soil the free confined water and the emptiness ratio will increase as shown in Fig. 3. Table 4 presents the values of the coefficient of compressibility ($a_v$), and coefficient of volume change ($m_v$) of treated and untreated soils under different applied pressures and curing periods.

Another important parameter in consolidation tests is the coefficient of consolidation ($C_v$) which relates to how long a time will take to occur an amount of consolidation.

Figures 5 and 6 show the variation of the coefficient of consolidation versus pressure of treated and untreated soils under different curing time periods using Cassagrande logarithm of time method (based on $t_{50}$; 50% consolidation) and Taylor square root of time method (based on $t_{90}$; 90% consolidation), respectively.

Table 4. Values of ($a_v$) and ($m_v$) of treated and untreated soils with different pressures and curing periods

| $\sigma$ (kN/m$^2$) | (50 – 100) x $10^4$ | (100 – 200) x $10^4$ | (200 – 400) x $10^4$ |
|---------------------|----------------------|----------------------|---------------------|
| Untreated soil       |                      |                      |                     |
| $a_v$ ($m^3/kN$)     | $7.000$              | $4.400$              | $3.600$             |
| $m_v$ ($m^3/kN$)     | $4.046$              | $2.543$              | $2.081$             |
| Treated soil         |                      |                      |                     |
| $a_v$ ($m^3/kN$)     | $1.100$              | $5.200$              | $2.650$             |
with graphene, 
1-day curing

|          | m<sub>c</sub> (m<sup>2</sup>/kN) | 6.9841 | 3.302 | 1.683 |
|----------|--------------------------------|--------|-------|-------|

Treated soil with graphene,
7-day curing

|          | m<sub>c</sub> (m<sup>2</sup>/kN) | 6.1560 | 2.776 | 1.901 |
|----------|--------------------------------|--------|-------|-------|

**Figure 5.** Variation of coefficient of consolidation versus pressure of treated and untreated soil under different curing time periods using Casagrande method.

**Figure 6.** Variation of coefficient of consolidation versus pressure for treated and untreated soil under different curing time periods using Taylor method.

Figures 5 and 6 show that (C<sub>v</sub>) decreases with increasing curing time as a result of the change in the soil texture due to interaction within the soil. So, the required time to achieve a specific degree of consolidation and specific drainage path increases for the treated soil with graphene.

The decreases in Cv due to increase in percentage of curing time is a result of change in the soil texture due to reaction taking place within the soil. Thus, the time required to achieve primary consolidation increase for graphene treated soil for a given degree of consolidation and a given drainage path.

**4. Conclusions**

According to the laboratory results of this study, the following conclusions can be drawn:

1- Adding graphene sheets leads to coating of particles and filling the pores around soil particles and causing to increase the absorbed confined water, and leads to a decrease soil compressibility.

2- The void ratio decreased with addition of graphene under a given consolidation pressure. No swelling potential was indicated.
3- With increasing the curing time, the void ratio of the soil treated with graphene will increase due to absorbing the confined free water.

4- The coefficient of volume compressibility (mv) and the coefficient of consolidation (Cv) decrease with increasing of curing time period of graphene.

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