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Study on piezoresistive properties of graphene modified soil

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Soil material conductivity serves as a tool for assessing the pressure-sensitive properties of soil structure. Changes in the microstructure and electrical resistance of a composite material consisting of soil with the addition of graphene and water under vertical pressure were studied. The main conclusions are as follows: as the water content of a composite material increases, its resistance gradually decreases; the effect of pressure on the resistance becomes less significant when the water content exceeds 8%. In addition, the resistance value of the composite material gradually decreases with increasing graphene content, resulting in stronger pressure sensitivity. A mechanism has been proposed to improve the sensitivity of clayey soil to pressure by adding graphene.

Keywords: clay soil; silt; graphene; pressure sensitivity; electrical resistivity.

Дослідження п'єзорезистивних властивостей графен-модифікованого ґрунту. *Zheng Xiao, Li Lianchun, Shang Wentao, Li Yan, Li Yu, Song Peng*

Провідність матеріалу ґрунту є інструментом для оцінки чутливих до тиску властивостей структури грунту. Досліджено зміни мікроструктури, провідності композитного матеріалу, що складається з ґрунту з додаванням графену та води, при вертикальному тиску. Основні висновки такі: зі збільшенням вмісту води в композитному матеріалі його опір поступово знижується; вплив тиску на опір стає меншим, коли вміст води перевищує 8%. Крім того, значення опору композитного матеріалу поступово знижується зі збільшенням вмісту графену, що призводить до сильнішої чутливості до тиску. Запропоновано механізм покращення чутливості до тиску глинистого ґрунту з додаванням графену.

1. Introduction

Silt is widely used as a subgrade filling material, but due to its dispersed nature, it is difficult to compact. Typically, compaction tests are used to evaluate its density, but these tests are time-consuming and costly. Current research is focused on using sensors buried in the soil to monitor the compactness of the soil and obtain its mechanical parameters. However, the sensors are not well compatible with the surrounding soil, resulting in large testing errors and leading to misjudgments in engineering analysis. The development of self-inductive sensors using the soil itself can solve the problem of compatibility with sensor components and quickly determine the internal stress of the soil using its pressure-sensitive properties.

Currently, much research has been carried out on cementitious materials in which conductive components form a network in the cement matrix. Conductive additives not only improve the conductivity of cement-based materials, but also improve their mechanical properties to some extent. Research on graphene-cement composites has mainly focused on their mechanical properties and durability, with limited information on the conductivity and sensitivity of graphene-cement composites. Sedaghat et al. [5] compared the electrical resistivity of composite materials with various graphene contents and found that the resistivity decreased with increasing graphene content. A mass fraction of 10% graphene could reduce the electrical resistivity of the cement matrix by 7 orders of magnitude. Le et al. [6] reported that graphene-cement composites exhibit good conductivity in both air-dry and completely dry states, and changes in potential caused by structural damage correspond well to changes in elastic modulus, making them suitable for structural damage monitoring.

Research on the application of graphene in soil has also made preliminary progress. Naseri et al. [7] used graphene oxide nanosheets to modify soil and studied the influence of graphene oxide concentration on the modified soil. The addition of graphene oxide reduced the plasticity and compression parameters of the soil samples, while its tensile and shear strength increased with increasing concentration of graphene oxide. The experimental results indicate that graphene oxide, as a stabilizer, has a significant impact on the mechanical properties of stabilized soil. Zhang [8] incorporated graphene into expansive soil and compared it with soil without the addition of graphene. The addition of graphene had a good modification effect on the triaxial mechanical characteristics of cement stabilized expansive soil; and with an increase in the graphene content, the compressive strength and shear strength of cement stabilized expansive soil increased first and then decreased, and reached the best value when the graphene content was 0.1%.The effects of graphene oxide nanomaterial on mechanical properties were investigated by Aziz [9], and a promising potential for enhancing the engineering properties of cemented soil was observed.

The above-mentioned studies primarily focus on the mechanical properties of graphene-reinforced soil, with less attention paid to the pressure-resistance characteristics of graphene-reinforced soil. This paper aims to experimentally investigate the pressure sensitivity of graphene-reinforced silt, and the findings will contribute to the development of new types of soil mechanics sensors.

2. Experimental investigation

2.1 Test soil samples

The test soil sample is silt. The plasticity index of the silt is 9, and the mass of particles with a diameter greater than 0.075mm accounts for 40.5% of the total mass. The physical and mechanical properties are listed in Table 1.

2.2 Graphene material

Graphene is a two-dimensional nanomaterial with excellent mechanical, electrical, and thermal properties. The fewer the layers of graphene, the larger the specific surface area, and the less graphene mass is required to form a complete conductive network, but the preparation cost is higher. The large specific surface area of graphene leads to an increased amount of water required for compacting during the formation of composite materials. Therefore, in this experiment, graphene prepared by physical methods with a single layer rate of up to 30% and consisting of 1-5 layers of graphene powder is used. The specific properties are detailed in Table 2.

Table 1 Physical and mechanical properties of silt

Kind of soil	Specific gravity of solid particles	Maximum dry density (g/cm^3)	Optimum water content (%)	Liquid limit (%)	Plastic limit (%)
silt	2.69	2.06	16	22.1	13.1

Table 2 Properties of graphene

Layer diameter (μm)	Layer thickness (nm)	Layer number	Single layer rate (%)	Purity (wt%)	Specific surface area (m2/g)
2~10	1.0~1.75	1~5	>30	>96	360~450

2.3 Sample preparation

The sample preparation process is as follows: first, the sieved soil sample is placed on a tray and dried in a sealed oven at a temperature of 105°C for 24 hours until a constant weight is achieved. Then, the dried soil sample is cooled to room temperature and placed in a non-absorbent tray. The soil is mixed according to the specified initial water content of 0%, 4%, 8%, 12% and 16%. During the mixing process, the amount of water required for sample preparation is calculated based on the experimental soil and water content. A spray bottle is used to evenly moisten the dried soil sample, while simultaneously mixing. Once the soil sample is thoroughly mixed, it is placed in a plastic bag, sealed completely, and then moisturized in a humidifying container for one day and one night before use.

Graphene is added in proportions of 0%, 0.25%, 0.50%, 1%, 2%, and 4% based on the dry weight of the soil. After the graphene is thoroughly mixed in, the samples are prepared. The samples are placed in a compaction mold with a diameter of 8cm and height of 4cm; the sample mass is determined to be 162.50g. The samples are then compacted under the self-weight of the top cover.

2.4 Experimental Principles and Instruments

The deformation under pressure is measured using a dial gauge positioned above the sample. The electrical resistance of the compressed sample under pressure is measured by leading the wires out through copper pads on the top and bottom of the sample, and then using a resistance tester for measurement.

A TH2512B+DC low resistance tester is a mini-desktop instrument that provides real-time automatic testing, featuring high accuracy, stability, and a wide testing range. The resistance testing range of the instrument is from 1μΩ to 20kΩ. During the testing process, the instrument automatically selects the optimal range, allowing for direct acquisition of high-precision resistance value *R*.

2.5 Experimental Method

In order to investigate the influence of water content and graphene content on the pressure sensitivity of silt, different experiments were conducted with varying water and graphene contents. The pressure on the specimen was applied using the lever principle, with loading pressures starting from 0 and increasing to 25kPa, 50kPa, 100kPa, 200kPa, 400kPa, 800kPa, and 1600kPa respectively. During each level of pressure loading, the deformation and resistance value of the specimen were recorded once the deformation stabilized and the resistance value stabilized.

3. Results

3.1 Influence of water content

The resistance of the composite material decreases as the water content increases. Fig.1 shows that the resistance is higher when the water content is 4%, and an increase in the water content has a less significant impact on the resistance when the water content exceeds 8%. Analysis shows that at low contents, water disperses in the internal pores of the composite material, forming a water film around the soil particles, facilitating the movement of soil particles under pressure. The composite material is more sensitive to pressure in the range of 0 to 400 kPa at a water content of 4%, but becomes insensitive to pressure when it exceeds 400 kPa. When the water content is high, the water is adequately distributed in the internal pores of the composite material. The conductive component of the composite material is the water rather than the particle contact surface, thus its sensitivity to pressure is less significant under pressure.

3.2 Influence of graphene

Overall, with an increase in the graphene content, as depicted in Fig. 2, the more the graphene particles are distributed in the pores of the silt particles, the lower the electrical resistance of the composite material. Analysis shows

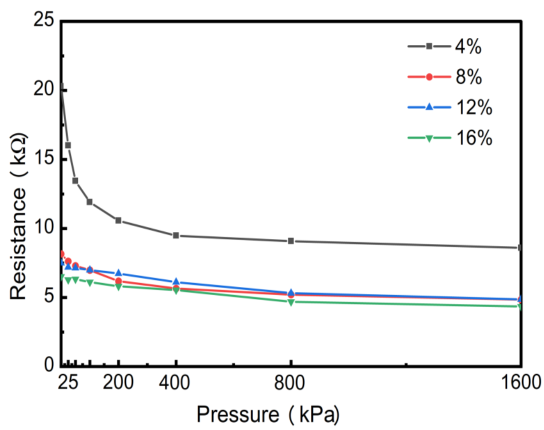

Fig.1. Influence of water content on pressure sensitivity of composite material

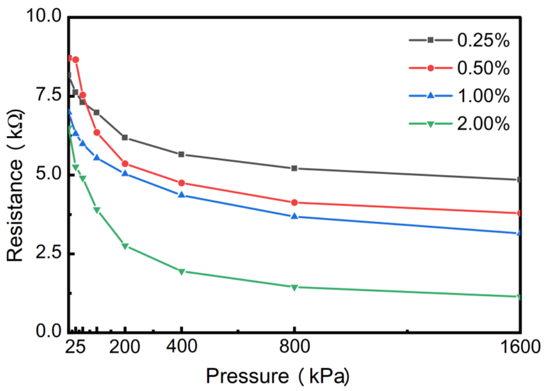

Fig. 2. Influence of graphene content on pressure sensitivity of composite material

that graphene fills the inter-particle pores of the silt, gradually improving the conductive network, thus reducing the resistance value. Under a certain graphene content, with increasing pressure, the contact area between graphene and silt particles gradually increases, which leads to a decrease in the resistance value. The pressure sensitivity is significant at 800 kPa, but when the pressure exceeds 800 kPa, the pressure sensitivity of the compoite material decreases.

3.3 Effect of pressure

Fig.3 reveals the changes in pressure sensitivity and porosity ratio of the composite material under pressure. The sample contains 4% water and 1% graphene. The experiment shows that with increasing pressure, both resistance and the porosity ratio decrease nonlinearly; the change is faster at lower pressures and slower at higher pressures. The pressure sensitivity of the composite material is greater at lower pressures and smaller at higher pressures. Under pressure, the porosity ratio of the composite material decreases, the distance between graphene and soil particles decreases, and the contact area increases, resulting in a decrease in the resistance value.

Fig.4 shows the SEM images of the composite material with the same porosity ratio under different pressure conditions. It can be observed that as the pressure increases, the compression of graphene “wrapping” around the soil particles becomes more apparent. When the soil body is subjected to a small external force, the particles with smaller diameters will lose stability and fill these voids, leading to the rearrangement of soil particles and irreversible sudden deformation of the soil structure.

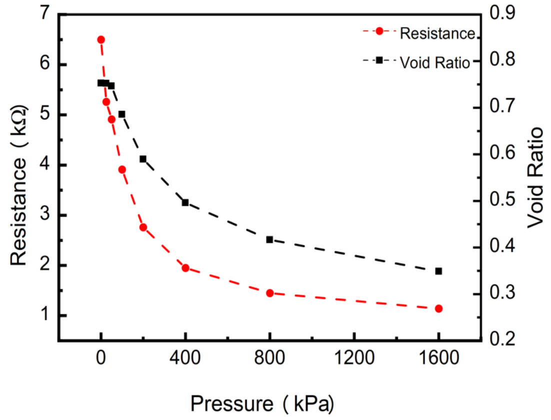

Fig.3. Pressure sensitivity of composite material

In Figure 4 at 200 kPa, there are relatively large voids around the soil particles, and the particles are spaced apart, with some soil particles in contact with graphene particles. At 400 kPa, the larger voids have reduced and the contact area between graphene and soil particles has increased. The changes in voids and the contact area between graphene and soil particles are significant at pressures below 400 kPa, hence the composite material is more pressure sensitive at pressures less than 400 kPa. At 800 kPa and 1600 kPa, it can be observed that the density of graphene increases due to the pressure causing a tighter contact between graphene and soil particles, leading to less obvious pressure sensitivity at higher pressures.

4. Conclusion

Graphene, as a novel material, holds great promise in the field of civil engineering. This paper investigates the pressure sensitivity of graphene-reinforced silt by using graphene as a modifying material for silt. Additionally, scanning electron microscopy is employed to observe the distribution and morphology of graphene in the soil, allowing for a micro-level exploration of the mechanism behind graphene modification of soil.

When the water content of the composite material is below 8%, the resistance decreases with increasing water content. However, when the water content surpasses 8%, the water effectively fills the pores between soil particles and its impact on resistance becomes less notable.

As graphene content in the composite material increases, the resistance gradually declines, and the pressure sensitivity becomes more pronounced. However, the pressure sensitivity decreases with increasing pressure.

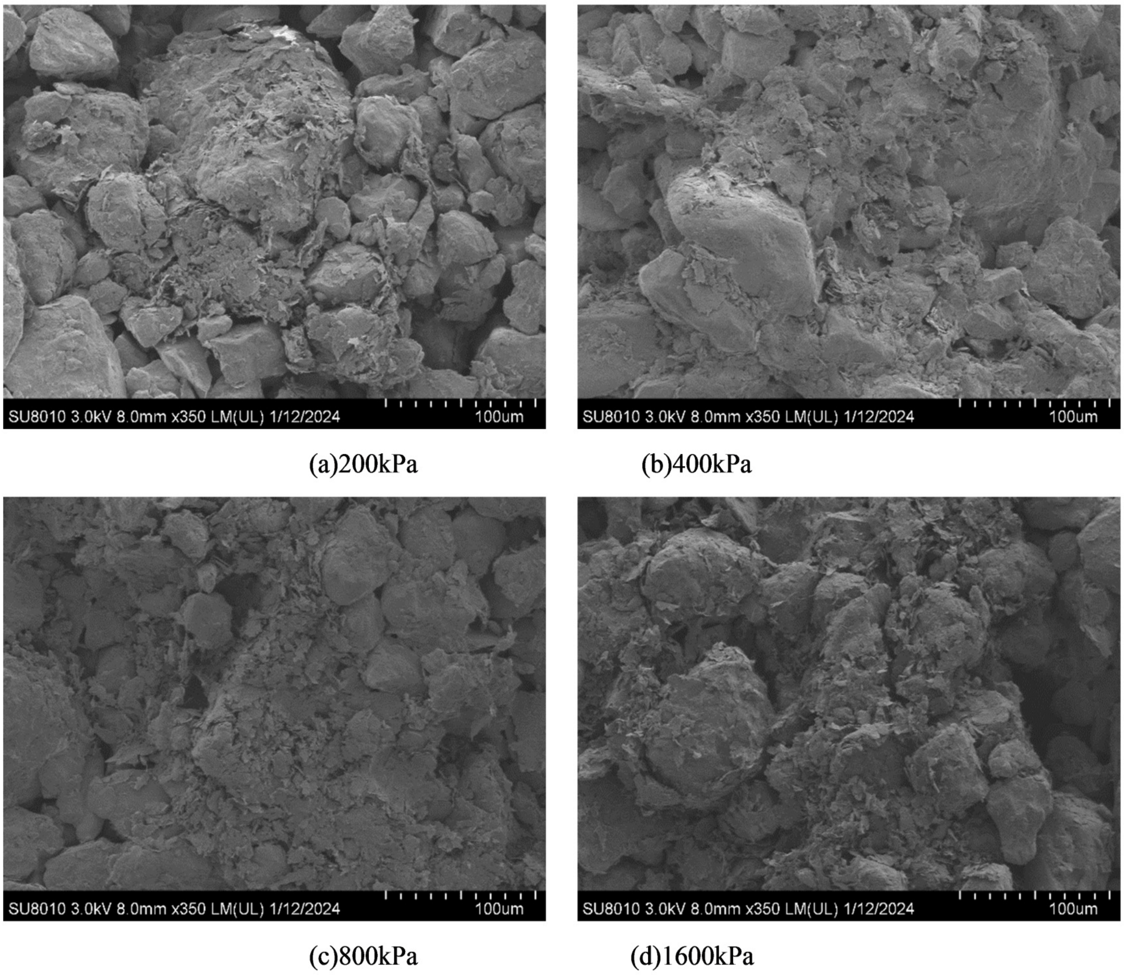

Fig.4 SEM images of the composite material at different pressures with the same porosity ratio after compression. a- 200 kPa; b- 400 kPa; c- 800 kPa; d - 1600 kPA/

Scanning electron microscope analysis revealed the mechanism of pressure sensitivity in graphene-modified silt. Below 400 kPa, the contact area between graphene and soil particles expands with increasing pressure, which makes the material more sensitive to pressure. At pressures of 800 kPa and 1600 kPa, the graphene density increases, leading to a closer contact between graphene and soil particles, thus reducing the pressure sensitivity at higher pressures.

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