

Experimental Investigation and Analysis of the Shear Properties of GO Cement Soil under Chloride Erosion and Wetting–Drying Cycles

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Abstract: The effects of chloride erosion and wetting–drying cycles on the shear properties of graphene oxide (GO) cement soil were investigated through direct shear testing. Specimens with different GO dosages were first tested, followed by further direct shear tests at various NaCl concentrations and wetting–drying cycle counts. SEM was also used to examine the microstructure. The results show that the shear strength, cohesion and internal friction angle of cement soil initially increased with GO dosage but declined at higher dosages. The optimal GO dosage was 0.06% by mass of cement. For cement soil containing the optimal GO dosage, shear performance decreased with higher NaCl concentrations and more wetting–drying cycles. After 15 cycles in a 30 g/L NaCl solution, the shear strength retention ratio was 62.17%. SEM observations revealed a dense microstructure at the optimal GO dosage. Higher NaCl concentrations and more wetting–drying cycles promote the development of pores and microcracks in cement soil, leading to a decline in its macroscopic shear performance.

Keywords: Cement Soil; Graphene Oxide; Wetting–Drying Cycles; Chloride Erosion; Shear Strength; Microstructure

1. Introduction

The ease of construction, relatively low cost, and good adaptability of cement soil make it suitable for soft ground improvement, roadbed reinforcement, foundation pit support, and coastal engineering [1]. However, in coastal areas, saline soil regions, and areas with fluctuating groundwater levels, cement soil is frequently exposed to chloride erosion and wetting–drying

cycles. Chloride erosion can reduce the stability of hydration products and weaken the bonding between soil particles, while repeated water absorption and swelling, followed by moisture loss and shrinkage, promote pore expansion and microcrack development. These processes ultimately lead to the deterioration of the compressive and shear properties and durability of cement soil [2]. Therefore, enhancing the structural stability of cement soil exposed to saline environments and repeated wetting–drying cycles is essential for its reliable performance in engineering applications.

Nanomaterials are now used more widely to improve cement-based materials and stabilized soils [3]. Graphene oxide is a two-dimensional layered material with a high specific surface area and abundant oxygen-containing functional groups. It can improve the cemented structure through pore filling and changes at interfaces [4]. Zhang et al. [5] found GO improved the shear strength of cement soil based on triaxial tests, with an optimal dosage identified for shear performance. Their microstructural analysis further indicated that GO promoted cement hydration and reduced internal porosity. Wang et al. [6] found that GO increased the degree of hydration and made the interfacial transition zone in cement mortar denser. This helped limit microcrack growth and improve the mortar's mechanical performance and durability. Ge et al. [7] showed that better GO dispersion promoted hydration product formation and improved the pore structure of cement. These changes also contributed to higher compressive and flexural strengths.

Research on GO has largely addressed the mechanical behavior of cement-based materials. In contrast, less attention has been given to the shear properties and microstructural of GO

cement soil exposed to both chloride erosion and wetting–drying cycles. Accordingly, the mechanical properties of cement soil with different GO dosages were assessed through direct shear tests to identify the optimal dosage. Then, the variation trend of shear strength of cement soil samples under different NaCl concentrations and wetting–drying cycles was studied. Finally, SEM analysis was used to explore how the microstructural features of GO cement soil influence its macroscopic mechanical behavior under saline and wetting–drying conditions.

2. Materials and Methods

2.1 Materials

The clayey soil had natural and air-dried water contents of 20.69% and 3.01%, respectively, and a unit weight of 19.2 kN/m³. Its liquid limit, plastic limit, and plasticity index were 41.5%, 21.9%, and 19.6%, respectively. Figure 1 shows the particle size distribution. P·O 42.5 ordinary Portland cement served as the binder. The GO had one or two layers, with sheet diameters of 0.5–5 μm and a thickness of about 1 nm. A polycarboxylate superplasticizer (PCE) served as the dispersant, and NaCl solutions provided the chloride erosion conditions.

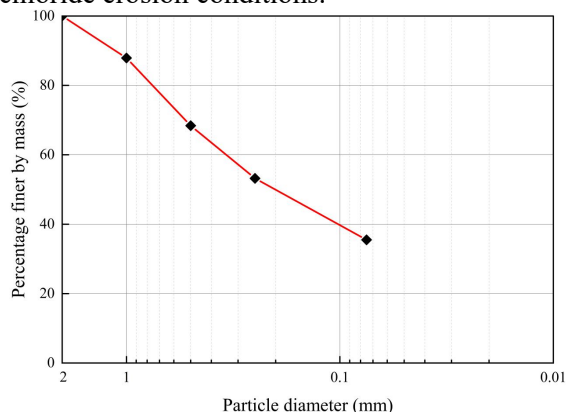


Figure 1. Particle Size Distribution of the Soil

2.2 Specimen Preparation and Test Methods

The mix proportions of cement soil were designed following the Specification for Mix Proportion Design of Cement Soil (JGJ/T 233–2011). Specimen preparation followed the Standard for Geotechnical Testing Method (GB/T 50123–2019).

(1) Preparation of cement soil mixtures. Cement accounted for 15% of the dry soil mass, and the water-cement ratio was 0.5. GO was incorporated at dosages of 0, 0.02%, 0.04%, 0.06%, 0.08%,

and 0.10% by mass of cement, while the PCE dosage was fixed at 0.2% of the cement mass. To reduce GO nanosheet agglomeration, an aqueous PCE solution was prepared first. After the required amount of GO was added, the mixture underwent water-bath ultrasonication to obtain a uniform GO dispersion. Clay and cement were weighed in the specified proportions and then premixed in a mixer for 3 min to ensure an even distribution of cement throughout the soil. Finally, the prepared GO dispersion was gradually introduced into the premixed cement and soil. Further mixing produced a uniform GO cement soil mixture.

(2) Preparation of cement soil specimens. After the mixing is completed, the GO cement soil mixing material is evenly divided into three layers and loaded into a $\Phi 61.8 \text{ mm} \times \text{H}20 \text{ mm}$ cylindrical mold. After each layer is filled, the compaction molding is carried out, and the contact surface is pulled. After molding, the specimens were sealed together with their molds using plastic wrap. After 24 h, the specimens were removed from the molds and cured for 28 d at $20 \pm 2 \text{ }^\circ\text{C}$ and a relative humidity of at least 95%.

(3) Test methods. After curing, the cement soil specimens underwent direct shear tests under normal stresses of 100, 200, 300, and 400 kPa. The optimal GO dosage was selected based on the experimental results. Direct shear tests were then conducted on specimens with the selected GO dosage after 3, 6, 9, 12, or 15 wetting–drying cycles at NaCl concentrations of 0, 4.5, 18, and 30 g/L. The microstructures of the specimens were also examined using SEM.

3. Shear Properties of GO Cement Soil under Chloride Erosion and Wetting–Drying Cycles

3.1 Shear Properties at Different GO Dosages

Figure 2 presents the shear strengths obtained from direct shear tests on cement soil specimens at different normal stresses and GO dosages.

Figure 2 shows that, under different normal stresses, the shear strength increased with GO dosage before declining at higher dosages. With 0.06% GO, the specimens exhibited shear strengths of 895.66, 1148.75, 1220.77, and 1414.73 kPa under four vertical pressures, respectively. The values obtained at 100, 200, and 400 kPa were the highest among all GO dosages. However, at 300 kPa, the specimen containing 0.04% GO exhibited the highest shear strength, exceeding that of the 0.06% GO specimen by

10.95 kPa. Overall, the 0.06% GO specimens showed relatively high shear strength under most normal stresses. The shear failure behavior of cement soil is mainly governed by interparticle cementation, interfacial bonding, and frictional resistance. GO nanosheets can partly fill interparticle pores and promote the formation of hydration products on soil particle surfaces and at interfaces. These effects contribute to stronger interparticle cementation and interfacial bonding [4]. At GO dosages of 0.02%–0.04%, interparticle bonding remained relatively weak, with more pores present within the specimens. When the GO dosage increased to 0.10%, the nanosheets tended to agglomerate, resulting in less uniform dispersion and a reduced reinforcing effect.

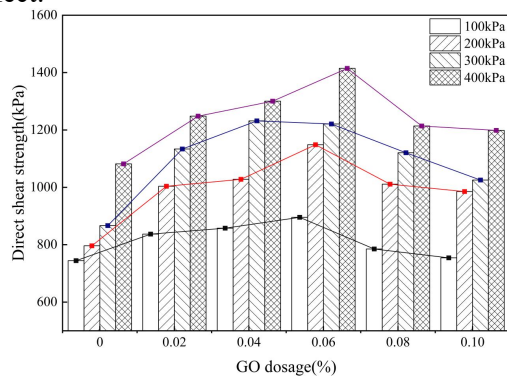


Figure 2. Shear Strength of Cement Soil at Different GO Dosages

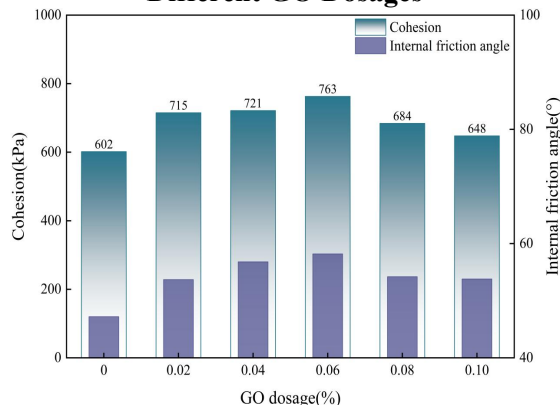


Figure 3. Cohesion and Internal Friction Angle of Specimens at Varying GO Dosages

The peak shear strengths at different normal stresses in Figure 2 were used to calculate the cohesion and internal friction angle according to the Mohr–Coulomb failure criterion. Figure 3 presents the results.

Figure 3 shows that both internal friction angle and cohesion of cement soil initially improved with GO dosage but decreased at higher dosages. At a GO dosage of 0.06%, the cohesion and internal friction angle reached their maximum

values of 762.7 kPa and 58.2, respectively. Both parameters declined when the GO dosage was further increased to 0.10%.

Unconfined compression tests on cement soil using the same mix proportions, GO dosage levels, and specimen preparation and curing conditions showed that the compressive strength increased with GO dosage at first but declined at higher dosages. The unconfined compressive strength reached 6.56 MPa at a GO dosage of 0.06%, indicating the optimal dosage under these test conditions [8].

Based on the combined results for shear strength, cohesion, and internal friction angle, specimens containing 0.06% GO exhibited the best overall shear performance among the tested dosages. Therefore, 0.06% GO was selected as the optimal dosage under the present test conditions and used in subsequent tests involving combined chloride erosion and wetting–drying cycles.

3.2 Effects of Chloride Erosion and Wetting–Drying Cycles on the Shear Properties

Figure 4 presents the shear strength of specimens containing 0.06% GO under different NaCl concentrations and wetting–drying cycle counts. Figure 4 presents that the shear strength declined with repeated wetting–drying cycles at a constant NaCl concentration. At a fixed cycle count, higher NaCl concentrations also led to lower shear strength. In the 30 g/L NaCl solution, shear strength fell from 1126 kPa before cycling to 700 kPa after 15 cycles. These results suggest that chloride erosion and wetting–drying cycles jointly weakened the ability of GO cement soil to resist shear.

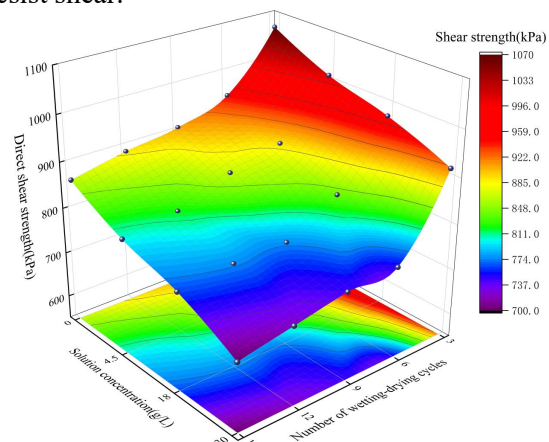


Figure 4. Variation in Shear Strength of GO with Wetting–Drying Cycles and NaCl Concentration

The progressive deterioration of the pore structure and cemented interfaces is closely

associated with changes in the shear properties of cement soil. During wetting–drying cycles, repeated water absorption and swelling, followed by drying and shrinkage, promote the initiation and growth of microcracks. These microcracks also provide pathways for chloride ions to penetrate the specimens. Once chloride ions enter the soil, salt accumulation, crystallization pressure, and weakening of interfacial bonds further contribute to the deterioration of the pore structure and cementation network [2].

4. Durability of GO Cement Soil under Chloride Erosion and Wetting–Drying Cycles

To evaluate GO cement soil of the durability under chloride erosion coupled with wetting–drying cycles, the shear strength retention ratio was adopted as the evaluation index [9]. This ratio represents the shear strength retained after exposure to chloride erosion and wetting–drying cycles relative to that of specimens without chloride exposure or wetting–drying cycles. A higher shear strength retention ratio indicates a smaller reduction in shear strength and, consequently, better material durability. Using the shear strength of specimens without chloride exposure or wetting–drying cycles as the reference value, the shear strength retention ratio was calculated using the following equation:

$$R = \frac{f_n}{f_0} \times 100\% \quad (1)$$

R denotes the strength retention ratio, while f_n and f_0 represent the specimen strengths after n wetting–drying cycles and without exposure, respectively.

Figure 5 presents the calculated shear strength retention ratios of cement soil containing 0.06% GO under different NaCl concentrations and wetting–drying cycle counts.

As shown in Figure 5, GO cement soil exhibited a gradual decrease in shear strength retention ratio with wetting–drying cycles accumulated. At a fixed cycle count, the retention ratio also declined as the NaCl concentration increased. For specimens without NaCl exposure, the shear strength retention ratios were 95.03%, 80.55%, and 76.73% after 3, 9, and 15 wetting–drying cycles, respectively. The corresponding values for specimens exposed to a 30 g/L NaCl solution were 81.53%, 66.07%, and 62.17%. After 15 cycles, the shear strength retention ratios were 76.73%, 71.23%, 67.85%, and 62.17% at NaCl concentrations of 0, 4.5, 18, and 30 g/L, respectively.

Specimens exposed to a 30 g/L NaCl solution showed a shear strength retention ratio of 62.17% after 15 wetting–drying cycles. Continued chloride erosion and repeated wetting–drying cycles can promote the development of pores and microcracks in cement soil. Shear strength is governed not only by interparticle cementation but also by interparticle friction, particle wedging, and interlocking. Even when the cemented structure deteriorates, friction and interlocking between soil particles can still provide resistance to shear deformation.

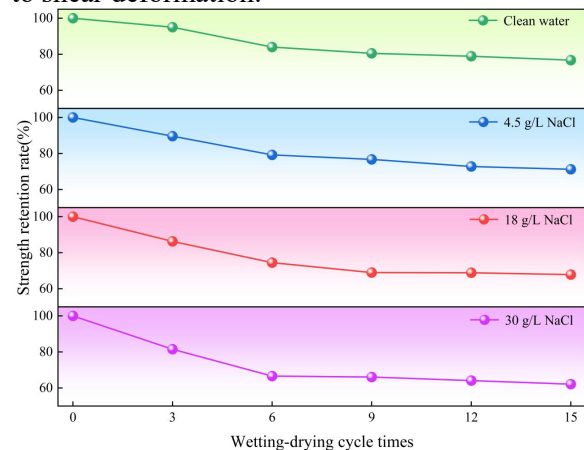
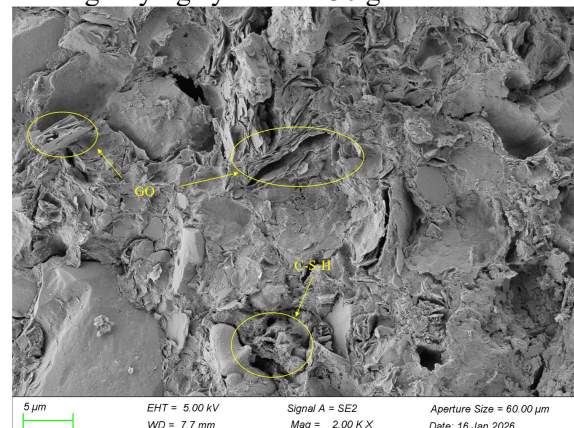


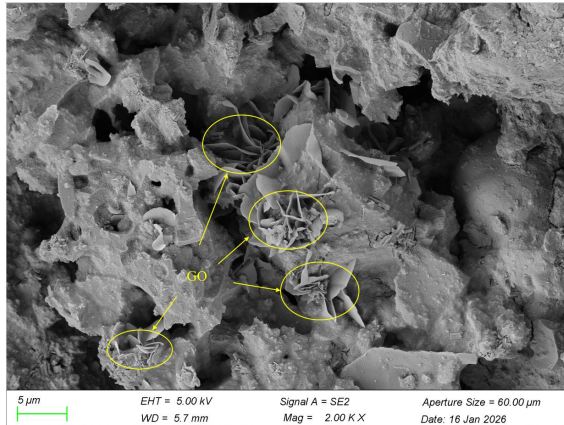
Figure 5. Shear Strength Retention Ratio of GO Cement Soil Versus the Number of Wetting–Drying Cycles at Different NaCl Concentrations

5. SEM Microstructural Analysis

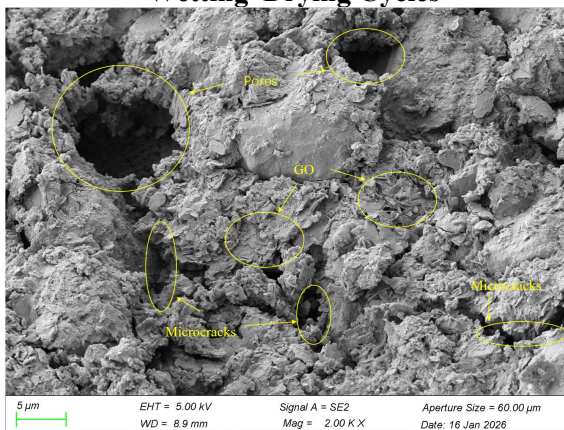
Figure 6 compares the microstructures of specimens with different GO dosages and exposure conditions. Figure 6(a) and (b) show the microstructures of specimens containing 0.06% and 0.10% GO, respectively, without exposure to NaCl solutions or wetting–drying cycles. Figure 6(c) shows the 0.06% GO specimen after 15 wetting–drying cycles in a 30 g/L NaCl solution.



(a) 0.06% GO, without Chloride Erosion or Wetting–Drying Cycles



(b) 0.10% GO, without Chloride Erosion or Wetting–Drying Cycles



(c) 0.06% GO, after 15 Wetting–Drying Cycles in A 30 G/L NaCl Solution

Figure 6. Microstructure of Specimens with Different GO Contents before and after Chloride Erosion and Wetting–Drying Cycles

As shown in Figure 6(a), the specimen containing 0.06% GO exhibited a dense microstructure with continuous interparticle cementation. Some pores were filled with hydration products, while sheet-like structures and cementitious products were observed in localized regions. This may improve the compactness of cement soil by filling micropores and strengthening interparticle bonding.

Figure 6(b) shows an increase in pores and loosely bonded regions, accompanied by weaker interparticle cementation and localized concentrations of sheet-like structures. Compared with the specimen containing 0.06% GO, increasing the GO content to 0.10% resulted in a less uniform distribution of sheet-like structures, more pores and loosely bonded regions, and weaker interparticle bonding, leading to a reduction in microstructural compactness [10].

As shown in Figure 6(c), the specimen containing 0.06% GO exhibited increased pores and cracks and localized damage to the cemented structure

after 15 wetting–drying cycles in a 30 g/L NaCl solution. During wetting–drying cycles, repeated water uptake and loss can cause deformation of soil particles and cemented structures. These changes may further promote pore formation and the propagation of microcracks. Meanwhile, chloride migration into the specimen and subsequent salt accumulation may further weaken the bonding interfaces [2], contributing to the progressive deterioration of the original cemented structure.

6. Conclusions

- (1) The shear strength, cohesion, and internal friction angle of cement soil increased at lower GO dosages but declined as the dosage increased further. Under the tested conditions, the optimal GO dosage was determined to be 0.06%. At 200 kPa, the shear strength reached 1148.75 kPa, representing a 44.23% increase over that of cement soil without GO. Its cohesion was 762.7 kPa and internal friction angle was 58.2.
- (2) The shear properties of GO cement soil progressively deteriorated as NaCl concentration and wetting–drying cycle count increased. Exposure to both chloride erosion and wetting–drying cycles further aggravated this deterioration. After 15 wetting–drying cycles in a 30 g/L NaCl solution, the shear strength retention ratio was 62.17%.
- (3) SEM analysis showed that specimens containing 0.06% GO had a dense microstructure with continuous interparticle cementation. When the GO dosage increased to 0.10%, more pores and loosely packed regions appeared. After exposure to a 30 g/L NaCl solution and 15 wetting–drying cycles, microcracks propagated further, and local cemented structures were damaged. These microstructural observations help explain the decline in shear performance of GO cement soil under saline exposure and wetting–drying cycles.

References

- [1] Singh M J, Yao K, Hou Y J, et al. Deep cement mixing columns for infrastructure development: a review of research progress, challenges, and future research directions. *Geomechanics and Geoengineering*, 2025, 20(4): 911–936. DOI: 10.1080/17486025.2025.2477474.
- [2] Zhang S T, Pang J Y, Zhang J S, et al. Study on the durability of solidified mud under chloride and dry-wet coupling. *Scientific*

- Reports, 2025, 15: 1071. DOI: 10.1038/s41598-024-82856-z.
- [3] Lu J G, Yao H Y, Shahrou I, et al. Improved mechanical behaviour and microstructure of cemented soil with nanomaterials. *KSCE Journal of Civil Engineering*, 2024, 28(7): 2738-2749.
- [4] Yang J H, Han S, Wang Q W, et al. The influence of graphene oxide on the hydration and mechanical properties of cement-based materials with low water-binder ratio. *Cement and Concrete Composites*, 2024, 152: 105640. DOI: 10.1016/j.cemconcomp.2024.105640.
- [5] Zhang C, Wang W, Zhu Z, et al. Mechanical and microscopic properties of cement composite expansive soil with graphene oxide: Ecofriendly modification material. *International Journal of Geomechanics*, 2023, 23(6): 04023071.
- [6] Wang Y, Zheng C, Zhang Y, et al. Effect of graphene oxide-coated sand on the properties of cement mortar. *Acta Materialiae Compositae Sinica*, 2025, 42(6): 3350-3361.
- [7] Ge Y, Zhao L. Enhancement of cement mechanical properties by Ca^{2+} -mediated surface modification of graphene oxide. *Journal of Materials Science and Engineering*, 2025, 43(5): 860–867.
- [8] Zhang J J, Zhang J S, Miao P, et al. Experimental investigation and analysis of the impact of salinity erosion on the strength of graphene oxide cement soil. *Case Studies in Construction Materials*, 2024, 21: e03413.
- [9] Li H, Wang H J, Bai L J. Research on the strength damage and permeability characteristics of cemented paste backfill under chlorine salt erosion and dry–wet cycles. *Minerals*, 2024, 14(2): 177.
- [10] Liu J, Xie X. Effect of modified graphene oxide on properties of cement mortar. *Inorganic Chemicals Industry*, 2025, 57(7): 93–98.