Effect Of Multi-Walled Carbon Nanotubes on Compressive and Shear Properties of Environmental Cement Soils

Yulong Que[1,2], Jingshuang Zhang[1,2,*]
[1]*School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan, Anhui, China*
[2]*State Key Laboratory for Safe Mining of Deep Coal Resources and Environment Protection, Anhui University of Science and Technology, Huainan, Anhui, China*
**Corresponding Author*

Abstract: In saline-alkali areas, projects like subgrade and slope protection engineering face the problem of cement soil strength deterioration. This is caused by complex environmental factors such as underground salts and dry-wet cycles. To address this, multi-walled carbon nanotubes (MWCNTs) are introduced as reinforcing additives to improve the mechanical properties and long-term properties of the cement soil. unconfined compressive compressive strength tests, direct shear tests, and dry-wet cycle and chlorine salt erosion test were conducted to evaluate the influence of MWCNTs on the mechanical properties of cement-stabilized soil. The results show that the optimum content of MWCNTs is 0.1%. At this content, the compressive strength of cement soil is increased by 53.89%, under 200 kPa vertical pressure, the shear strength showed improvement of 40.47%. After 15 dry-wet cycles and accelerated aging with a 30 g/L chlorine solution, the maximum loss rates of unconfined compressive strength and shear strength were 40.67% and 41.23%, respectively. The mass loss rate was only 0.9%. The compressive properties of cement soil with different content of MWCNTs has a good positive correlation with cohesion and shear properties. The results provide experimental data for the practical application of MWCNTs in complex environments.

Keywords: Multi-Walled Carbon Nanotubes; Cement Soils; Dry-Wet Cycles; Chlorine Salt Erosion; Compressive Properties; Shear Properties

1. Introduction

As a novel engineered material composed of water, soil and cementing material [1], cement soil shows economic advantages in the field of Civil Engineering. Compared with traditional concrete materials, cement soil has lower cost and higher durability; Compared to natural soft ground, the compressive strength and shear strength are significantly improved. These properties make it widely used in engineering scenarios such as foundation treatment, slope stabilization, foundation stabilization and embankment construction. As key mechanical parameters, compressive strength, shear strength and the associated internal friction angle, cohesive force and other indicators are decisive in soil pressure calculation, foundation bearing capacity assessment and stability analysis. Engineering practice shows that if these parameters are too low, it can lead to a decrease in safety factor and even threaten engineering safety. However, under the context of climate change, cement soil material face severe challenges from the coupled effects such as of dry-wet cycles, saline and alkaline erosion, and other factors, leading to the loss of their strength. And the combined effects of these environmental factors and loads make the strength of cement soil structures face major technical challenges.

To address the problem of insufficient compressive resistance and shear capacity of cement soil in complex environments, the nanomaterial MWCNTs [2] are invoked in this paper to enhance the compressive and shear strength of cement soil in complex environments. As nanoscale fibrous materials MWCNTs are widely adopted in material preparation and research of high-properties cementitious materials by virtue of their excellent mechanical applications. For the durability damage mechanism of MWCNTs hydraulic soil structures in dry and wet weather environments as well as salt-containing environments, Lu et al. [3] found that the resistance to chlorine salt erosion was significantly increased by the incorporation of MWCNTs. Gao et al. [4] demonstrated that MWCNT addition significantly improved concrete's durability against sulfate erosion.

The current study shows that although scholars have investigated the effect of MWCNTs on the durability of cementitious materials under salt erosion environment [5,6] There are few studies on the durability of MWCNTs-modified cementitious materials under the coupling of dry-wet cycles and salt erosion. Meanwhile, although the enhancement effect of MWCNTs on the unconfined compressive strength of research on cementitious materials has been widely validated, there is a relative lack of research on the improvement effect of its shear resistance and the related mechanism, especially on the correlation analysis between unconfined compressive and shear resistance. Based on this, the following work is carried out in this paper, different MWCNTs content (0%-0.14%) cement soil sample are prepared, and the optimal ratio is determined by unconfined compressive strength, shear strength, internal friction angle and cohesive force. The optimal ratio sample are subjected to dry-wet cycles (3, 6, 9, 12, and 15 times) coupled with chlorine salt erosion (4.5, 18, and 30 g/L). The mass-loss test, the UCS, and the straight shear test are used to determine the correlation between the unconfined compressive and shear properties. limit unconfined compressive test and straight shear test to fully characterize the unconfined compressive stress-strain curve, unconfined compressive strength, shear stress-displacement curve, shear strength, mass loss rate, and analyze the relationship between compressive properties and shear properties. The results provide experimental data for the practical application of MWCNTs in complex environments.

2. Materials and Methods

2.1 Raw Materials

The test soil was soil from a foundation pit 10 meters deep in Huainan, China. The plastic limit of the soil sample was 21.9%, the liquid limit was 41.5%, and the plasticity index was 19.6%. The cement used in the experiment was P·O42.5 ordinary Portland cement, and its chemical composition is shown in Table 1; the MWCNTs nanotubes used in this study were commercially obtained from Shenzhen Turing New Materials Co., Ltd., with key specifications summarized in Table 2; choosing polyvinylpyrrolidone (PVP) as a dispersant can significantly improve the dispersibility of MWCNTs, the homogeneity index of PVP is shown in Table 3.

Table 1. Chemical Composition of Ordinary Silicate Cement

Ingredient	CaO	SiO_2	Al_2O_3
Quantity contained (%)	66.3	21.7	6.6

Table 2. Basic Physical Property Parameters of Multi-Walled Carbon Nanotubes

Pipe diameter (nm)	Tube length (nm)	Fineness (%)	Ash (%)
3-15	15-30	＞97	＜2.5

Table 3. Homogeneity Index of Polyvinylpyrrolidone Dispersant

Piracetam (%)	Total nitrogen (%)	K-Value (%)	PH
≤0.001	11.5-12.8	27.0-32.4	3.0-5.0

2.2 Sample Preparation for MWCNTs Cement Soils

Firstly, the MWCNTs were dispersed: PVP with a mass four times that of the MWCNTs was thoroughly mixed with the MWCNTs, and deionized water was added at a water-cement ratio of 0.5 before placing the mixture in a beaker. Ultrasonic dispersion was first performed (ultrasonic time, 40 min, with the water temperature maintained constant during the process via a circulating water temperature control system to avoid the impact of ultrasonic heating on dispersion). This was followed by mechanical stirring, ultimately yielding a uniform and stable MWCNTs dispersion.

Next, the MWCNTs cement soil sample were prepared in accordance with the standard (GB/T 50123–2019): crush the intact soil and dry at 105 °C for 8 h. after 2 mm screening, sealed and stored. Subsequently, air-dried soil and cement were added to a mixer at a cement content of 15% and with constant-speed stirring for 3 min. Add MWCNTs dispersion batchwise and stirring continued until the mixture was homogeneous. Eventually, the mixed soil was layered into three different molds (Φ61.8 mm × 20 mm, Φ50 mm × 50 mm, and 70.7 mm cubes), with each layer compacted and the contact surface roughened to ensure strong interlayer bonding.

Finally, curing was performed: After sample molding, the mold is sealed with a preservative film, and the sample is demolded after standing for 24 h. Cure at 20 °C and at a relative humidity not less than 95% for 28 d.

2.3 Test Methods

UCS and straight shear tests were first carried out on the maintained MWCNTs hydraulic soil sample.

Firstly, conduct unconfined compressive strength tests and direct shear tests on the cured MWCNTs cement soil sample to determine the unconfined compressive strength, shear strength, internal friction angle and cohesive force to determine the optimal content of MWCNTs. Then, the sample were prepared with the optimal content, and the dry-wet cycle and chlorine salt erosion coupling test was carried out, with 3, 6, 9, 12, and 15 cycles set, and clear water and three concentrations of 4.5, 18, and 30 g/L of NaCl solution were selected as the erosion medium. Finally, the sample were systematically analyzed through mass loss tests, unconfined compression tests, and direct shear tests to evaluate their unconfined compressive stress-strain curves, unconfined compressive strength, shear stress-displacement curves, shear strength, and mass loss rate. The complete testing process is shown in Figure 1.

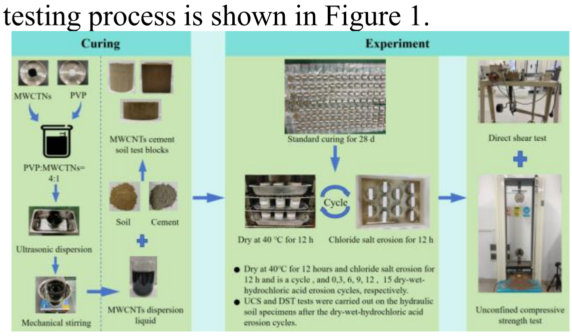


Figure 1. Complete Testing Process Test

2.3.1 Unconfined compressive strength test

UCS complied strictly with (GB/T50123–2019), and was conducted using a WDW-20 universal testing machine with a constant loading rate of 1 mm/min on 28 d standard-maintained hydromulch sample.

2.3.2 Direct shear test

Direct shear tests are carried out in strict accordance with the specification (JGJ/T233–2011), with rapid shear testing performed by means of a strain-controlled direct shear device (the specific parameters are shown in Table 4). Four vertical pressures of 100 kPa, 200 kPa, 300 kPa and 400 kPa were set up in the test, and the cement soil samples cured for 28 d were tested.

Table 4. Basic Parameters of the Test Straight Shear

Instrument name	Model number	Serial number
Three-speed electric strain gauge straight shear	EDJ-2	201

2.3.3 Dry-wet cycle and chlorine salt coupling test

The Φ50 mm×50 mm and Φ61.8 mm×20 mm cement soil sample were prepared using the optimal content of MWCNTs, and the dry-wet cycle and chlorine salt erosion coupling test was carried out after 28 d of standard maintenance. The experiments were conducted in a DHC constant-temperature drying oven, and it was set that the soil sample were put into the oven at 40 °C for 12 h, and then immersed in the solution at a temperature of 20 °C for 12 h (the liquid level was 30 mm above the sample, and the media were water and 4.5, 18, 30 g/L NaCl solution) as a single dry-wet cycle and chlorine salt erosion coupling test process, and the test set 0,3,6,9,12,15 dry-wet cycles. Mass loss rates and strength loss rates quantified the coupled deterioration from wet-dry cycling and chloride salt erosion, with strength tests performed per Sections 2.3.1 and 2.3.2.

3. Results and Discussion

3.1 Experimental Analysis of Optimized Contents of MWCNTs

Cement soil samples containing 0-0.14% MWCNTs were tested for unconfined compressive strength and direct shear strength.

3.1.1 Unconfined compressive strength

The relationship of MWCNTs content on the unconfined compressive strength of cement soil was obtained by conducting UCS tests on MWCNTs cement soil with different contents, as illustrated in Figure 2.

The experimental results in Figure 2 shows MWCNTs increase cement-soil's unconfined compressive strength at all tested content (0.06-0.14%).The strength of cement soil showed a trend of increasing and then decreasing with the content of MWCNTs, and the unconfined compressive strength was enhanced by 12.84%, 34.32%, 53.89%, 20%, and 2.5% at the content of 0.06%, 0.08%, 0.1%, 0.12%, and 0.14%, respectively, as compared with the cement soil samples without MWCNTs, when the content is 0.06 %, 0.08 %, 0.1 %, 0.12 % and 0.14 %. Among them, the most significant enhancement effect was observed at 0.1% contents, which was determined as the optimal contents level. This was attributed to the contents of MWCNTs leading resulting in higher proportions of high-density C-S-H as well as the promotion of calcium hydroxide growth in the cement and MWCNTs [7]. The strong van der Waals interactions cause MWCNT clustering at higher concentrations. These aggregates compromise the interfacial bonding with cement hydration phases, introducing weak zones in the composite that degrade its adhesive capacity and load-bearing properties [8].

3.1.2 Shear strength

The variation of shear strength of cement soil sample with MWCNTs content under different vertical pressures was obtained based on direct shear test as shown in Figure 3.

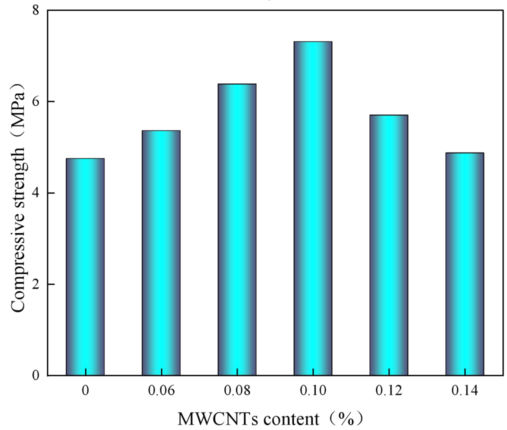


Figure 2. Unconfined Compressive Strength of Cement Soil Samples with Different MWCNTs Content

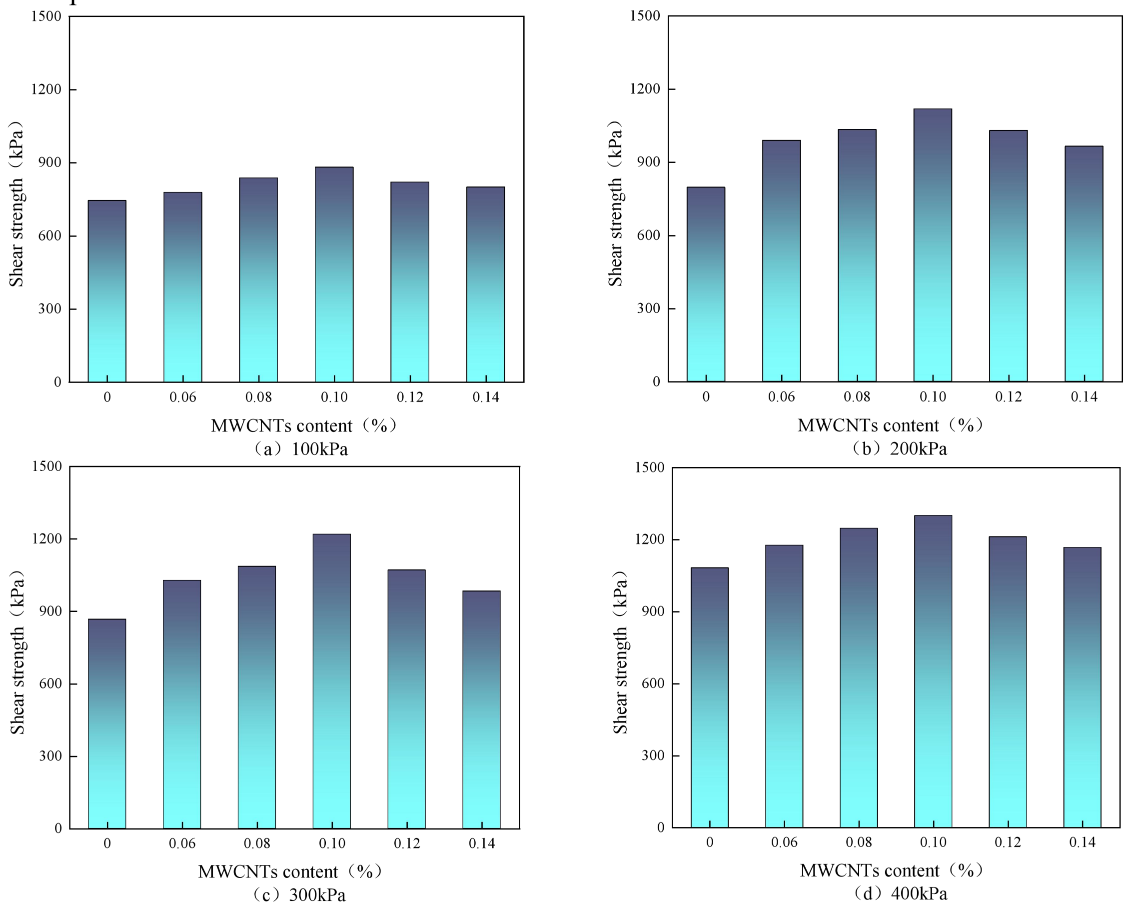


Figure 3. Variation of Shear Strength of Cement Soil Sample with MWCNTs Content under Different Vertical Pressures

From Figure 3, it can be seen that the shear strength of the cement soil shows a tendency of increasing and then decreasing with the increase of MWCNTs contents. When the vertical pressure was 100 kPa, the shear strength of the cement soil sample content with 0.06%, 0.08%, 0.1%, 0.12%, 0.14% MWCNTs was increased by 4.48%, 12.44%, 18.41%, 10.2%, and 7.46% compared with that of the sample not content with MWCNTs; when the vertical pressure was 200 kPa, the shear strength of the cement soil sample content with 0.06%, 0.08%, 0.1%, 0.12%, and 0.14% MWCNTs increased the shear strength of the cement soil sample compared to the sample without MWCNTs by 24.19%, 29.77%, 40.47%, 29.3%, and 21.16%, respectively; when the vertical pressure was 300 kPa, the shear strength of the cement soil sample content with 0.06%, 0.08%, 0.1%, 0.12%, and 0.14% MWCNTs increased the shear strength of the cement soil sample compared to the sample without MWCNTs by 218.59%, 25.21%, 40.6%, 23.5%, and 13.46%, respectively; and when the vertical pressure was 400 kPa, the shear strength of the cement soil sample content with 0.06%, 0.08%, 0.1%, 0.12%, 0.14% MWCNTs increased by 18.59%, 25.21%, 40.6%, 23.5%, and 13.46%, respectively, over the sample without MWCNTs. The shear strength of the sample with MWCNTs was enhanced by 8.73%, 15.24%, 20.18%, 11.99%, and 7.88%, respectively. The most significant enhancement was observed when MWCNTs were content at 0.01%. This phenomenon occurs because incorporating MWCNTs into cement can refine the material's microstructure, which greatly increases its shear strength as well as improves the load transfer efficiency from the cement matrix to the reinforcement. In addition, the bridge-coupling effect of carbon nanotubes ensures load transfer through voids and cracks under shear [9]. Excessive MWCNT content leads to localized agglomeration within the matrix, which disrupts the capillary architectural configuration of composites and consequently reduces the shear strength of the MWCNT cement soil.

3.1.3 Internal friction angle and cohesive force

Using shear strength test data from cement soil samples with varying MWCNT contents under vertical loads of 100 kPa, 200 kPa, 300 kPa, and 400 kPa, we generated scatter plots and performed linear regression analysis to obtain shear strength-normal stress relationship curves with their corresponding fitting equations. The cohesion (c) and internal friction angle (φ) were calculated from the intercept and slope of the fitted equations, respectively, with all results compiled in Table 5. Additionally, the variations of both cohesion and internal friction angle with MWCNT content were plotted as shown in Figure 4.

Table 5. Evolution of Shear Strength Parameters (c, φ) with MWCNT Concentration

MWCNTs contents (%)	Shear strength fitting curve	c (kPa)	φ(°)
0	τ_f=601.6+1.08σ_v	601.6	61.88
0.06	τ_f=684.4+1.23σ_v	684.4	70.47
0.08	τ_f=730.7+1.28σ_v	730.7	73.33
0.10	τ_f=791.5+1.35σ_v	791.5	77.35
0.12	τ_f=729.7+1.21σ_v	729.7	69.33
0.14	τ_f=699.2+1.12σ_v	699.2	64.17

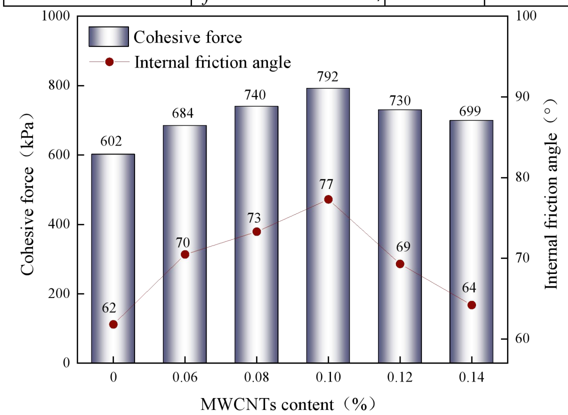


Figure 4. Internal Friction Angle and Cohesive Force of Cement Soil Sample with Different MWCNTs Contents

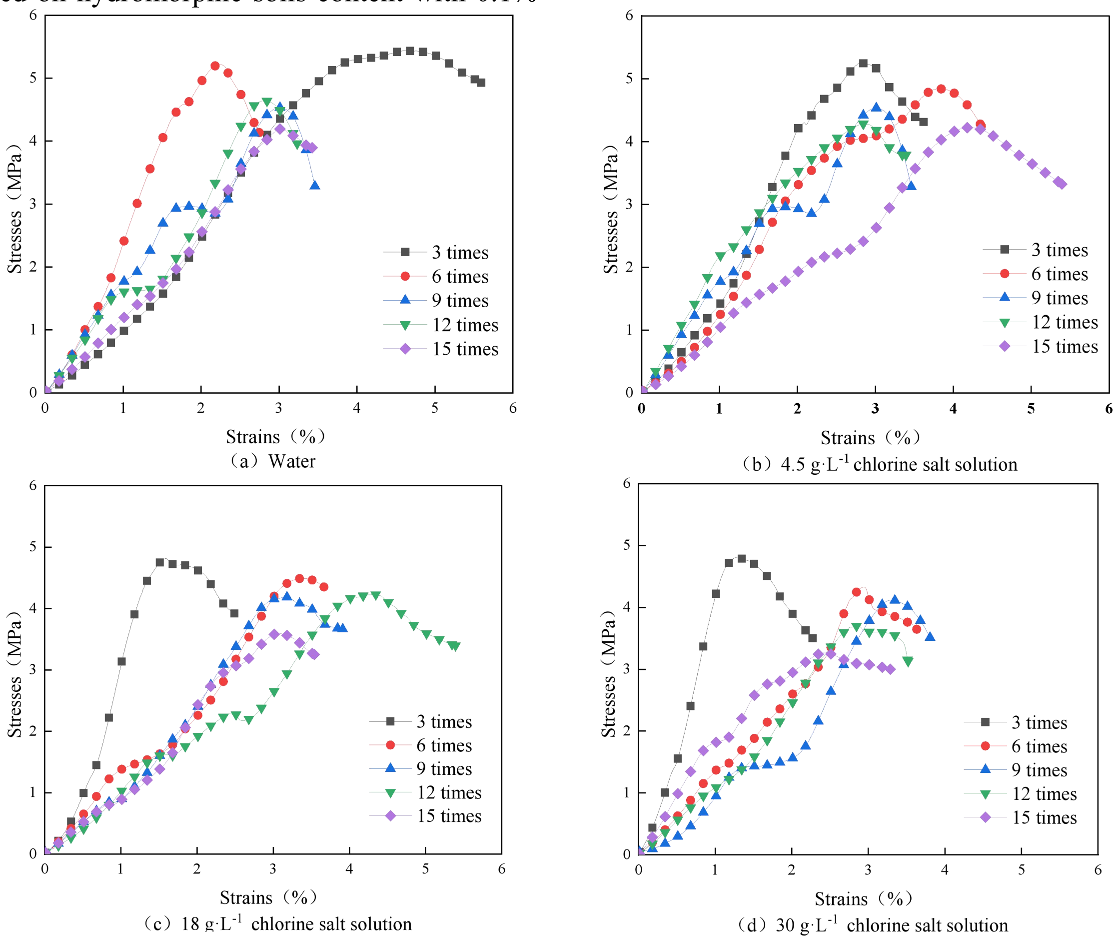
From Figure 4, with the increase of MWCNTs contents ratio, the c and φ of MWCNTs cement soils all show the trend of increasing first and then decreasing. When the MWCNTs contents ratio is 0.1%, the c, φ of MWCNTs cement soil reaches the peak value, and after exceeding 0.1%, the c and φ values decrease with the increase of contents. This is due to the fact that interfacial interactions between MWCNTs and the hydrates of the cement (e.g., C-S-H and C-H) will produce high bond strengths, and furthermore, the addition of carbon nanotubes enables fine-grain size distribution and reduces the porosity of the cement composites. As a result, the newly formulated composites become more compact [9], resulting in enhanced cohesion and internal friction angle in the MWCNTs cement soil. Excessive MWCNT loading induces particle agglomeration, degrading the capillary network and diminishing shear strength parameters c and φ. The enhancement effect of MWCNTs contents on the cohesive force of the hydraulic soil is higher than the enhancement effect on the internal friction angle. When the contents of MWCNTs is 0.1%, the soil cohesive force of the cement soil reaches 791.5 kPa, and the internal friction angle is 77.35 °, which is 31.57% of the enhancement of cohesive force and 25.13% of the enhancement of the internal friction angle compared with that of the ordinary cement soil. This is due to the fact that MWCNTs, as a nanoscale reinforcing material, can increase the proportion of cement hydration products and effectively bond fine soil particles through its huge specific surface area and surface activity, thus dramatically improving the cementation properties of the cement soil at the microscopic scale and obtaining a more significant enhancement of the cohesive force.

This chapter shows that suitable content of MWCNTs can increase the strength of hydromorphic soils, and dosing too much nanomaterials will rather decrease the strength of hydromorphic soils, so the following study is based on hydromorphic soils content with 0.1% MWCNTs.

3.2 Analysis of Mechanical Properties of MWCNTs Cement Soil under Dry-Wet Cycle and Chlorine Salt Erosion

3.2.1 Unconfined compressive stress-strain curve

Figure 5 shows the stress-strain characteristics of cemented soil content with 0.1% MWCNTs under the dry-wet cycles and chlorine salt erosion.



（a）Water （b）4.5 g·L^{-1} chlorine salt solution （c）18 g·L^{-1} chlorine salt solution （d）30 g·L^{-1} chlorine salt solution

Figure 5. Stress-Strain Curves of MWCNTs Cement Soil Sample under Varying Chloride Salt Concentrations and Wet-Dry Cycles Numbers

From Figure 5, it can be concluded that all curves show a two-stage deformation pattern, with damage occurring directly after entering the elastic stage. (1) The elastic stage shows an approximately linear relationship, and its slope characterizes the elastic modulus of the material, reflecting the elastic response of the synergistic load-bearing of the cement hydration products (C-S-H gel) and the soil particles skeleton in the dense structure; (2) The damage stage shows a softening behavior after the peak stress, corresponding to the microcrack extension through the resulting the cementation failure process, with rapidly developing penetrating cracks visible on the sample surface. It is noteworthy that these curves are missing the compaction phase in the typical three-stage deformation characteristics, a phenomenon that can be explained by multiscale mechanisms, firstly, MWCNTs act as a nano-reinforced phase that improves matrix compactness through interfacial interactions with the cement hydration products [10], and secondly, pre-damage due to environmental effects (including microcrack networks triggered by dry-wet cycle, and chlorine salt erosion produced by the Friedel's salt) weakens the particle cementation; finally, the structural degradation of the interfacial transition zone (ITZ) changes the deformation mechanism from compaction-dense dominated to friction-slip dominated. This particular mechanical response provides an important basis for evaluating the durability of modified cement soils in harsh environments.

3.2.2 Peak unconfined compressive stress after dry-wet cycle and chlorine salt erosion

Figure 6 shows the UCS variation of MWCNT cement soil samples subjected to different wet-dry cycle counts at various chloride concentrations.

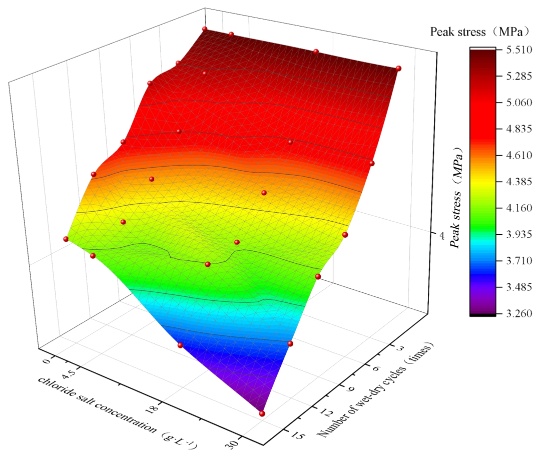


Figure 6. Three-Dimensional Surface of Plot UCS for MWCNTs Cement Soil Versus Wet-Dry Cycles and Chloride Salt Concentration

As can be seen in Figure 6, the overall trend of the unconfined compressive strength of the MWCNTs cement soil sample shows a continuous decrease with the increase of the number of dry-wet cycles. This is because Cl^- will enter into the sample, and the hydration products of C_3A in cement generate low-soluble Friedel's salt as well as chlorine salt solution crystallized in the void spaces inside the cement-modified soil test piece, which filled the internal voids of the sample, and after many dry-wet cycles, excessive Friedel's salt generates expansive forces that both promote internal crack initiation and inhibit further hydration of cementitious materials, leading to a reduction in the strength of the cement soil sample [11]. Following 15 cycles of wet-dry exposure to pure water, the sample strength decreased from 5.5 MPa to 4.2 MPa, a decrease of 23.64%.

When the number of dry-wet cycles is certain, the unconfined compressive strength of MWCNTs cement soil sample shows a decreasing trend with the increase of solution concentration, and the decreasing trend is more obvious with the increase of solution concentration. This is due to the fact that when the cement soil is exposed to dry-wet cycles in NaCl solution, NaCl will migrate from the region of high concentration to the region of low concentration, thus eroding the material from the surface to the interior. The chemical reaction between the hydraulic soil and NaCl forms low soluble calcium chloroaluminate. During these dry-wet cycles, the production of calcium aluminate depletes the Ca^{2+} in the cement soil, this reduces C-S-H and CAH content in the cement-soil composite. This weakening diminishes the cementitious bonding strength of the cement soil. Moreover, at high chlorine salt concentrations, more residual crystals are seen to precipitate from the initial cycle, compared to low-concentration conditions, the crystalline expansion during drying creates additional void spaces within the cement soil, repeated cycles lead to increased mass and strength loss [9]. It results in a decrease in the overall amount of calcium silicate hydrate and calcium aluminate hydrate phases in the cement soil, the strength of the sample decreased from 5.5 MPa to 3.3 MPa, a decrease of 40.67%, following 15 dry-wet cycles exposure to 30 g/L NaCl solution

3.2.3 Shear stress-displacement curve

Figure 7 presents the shear stress versus displacement behavior of 0.1% MWCNT cement soil at a vertical pressure of 200 kPa.

As can be seen from Figure 7, the shear stress-displacement curves of MWCNTs cement soil specimens undergoing different numbers of dry-wet cycles in different concentrations of chlorine salt solutions have similar brittle fracture characteristics. The shear stress-strain curves of the soil samples show that the shear stress increases significantly with the increase of shear displacement at the beginning stage, upon reaching a critical displacement value (peak point), the shear stress exhibits a distinct maximum followed by progressive softening with increasing shear displacement.

The shear stress-displacement curve of cement soil shows approximate linear characteristics, and this mechanical behavior is the result of the joint action of the material's intrinsic properties and environmental erosion. From the viewpoint of material intrinsic properties, cement improvement changed the microstructural characteristics of the soil, on the one hand, the three-dimensional rigid skeleton formed by the cement hydration products (e.g., C-S-H gel) effectively suppressed the displacement rearrangement and mutual occlusion of soil particles; on the other hand, the cement curing substantially weakened the intrinsic plastic deformation capacity of the soil. In terms of environmental erosion, the synergistic effect of dry-wet cycles and chlorine salt erosion affects the material properties through two pathways: dry-wet cycles results in repeated expansion and contraction of cement hydration products, forming a well-developed network of microcracks within the soil body; and chlorine salt invasion chemically reacts with the cement phase to produce soluble products such as Friedel's salt, which continues to weaken the interfacial bond strength. This coupling effect of material structural change and environmental erosion ultimately results in cement soil exhibiting unique linearized shear behavior characteristics.

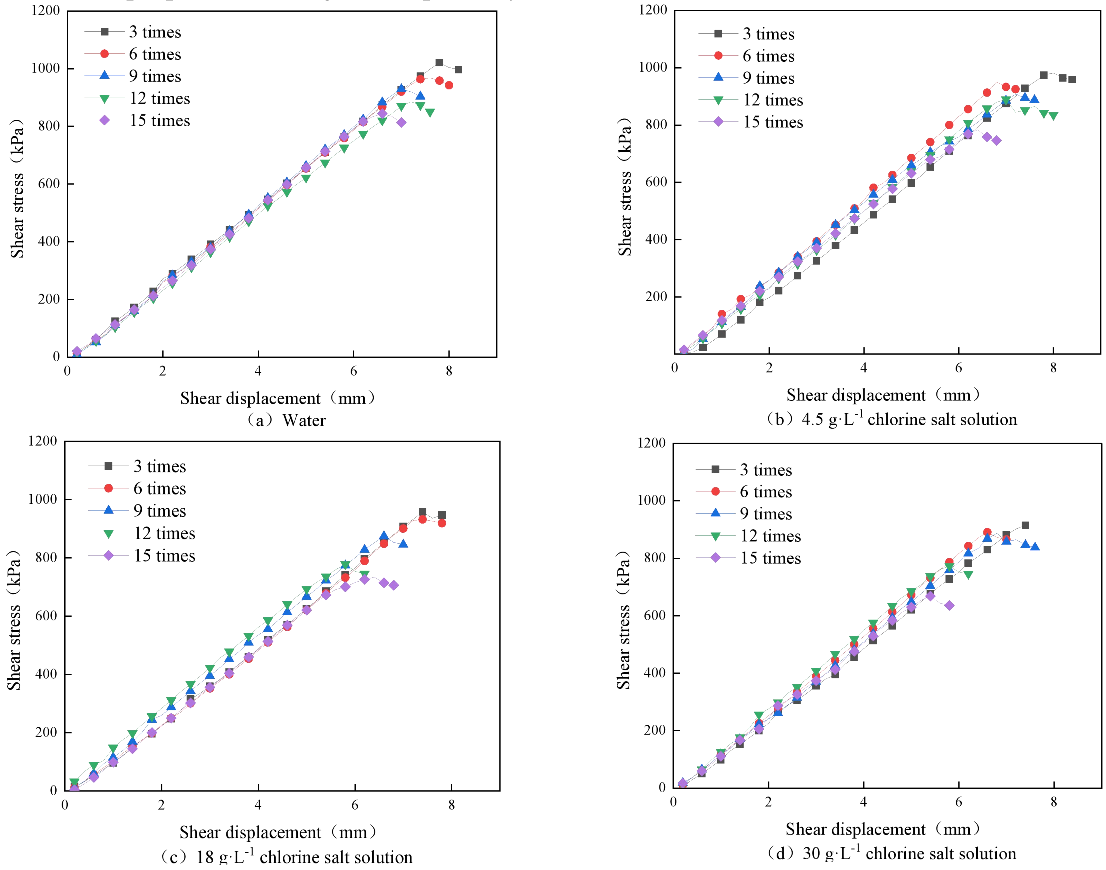


Figure 7. Shear Stress-Displacement Curves of MWCNTs Cement Soil Sample under Varying Chloride Salt Concentrations and Wet-Dry Cycles Numbers

The shear damage behavior mainly occurs in the weak interface region of cement bonding, showing typical brittle fracture characteristics. As shown in Figure 8, a clear upper and lower separation surface is formed after the damage of the sample, and the damage interface is flat and extends strictly along the weak interface of cementation, while the matrix of the soil body still maintains a complete structural morphology, and there is no phenomenon of particle fragmentation. This special damage pattern originates from two key mechanisms. First, the cement hydration products form a rigid three-dimensional network between the soil particles, transforming the original friction-dominated soil into a cement-dominated composite material. When the shear stress reaches the cementation strength, abrupt interfacial fracture replaces the progressive rearrangement of soil particles [12]; second, the rapid loading regime adopted in the direct fast shear test method further constrains the development of plastic deformation in the soil. This damage characterization fully confirms that the shear damage of cement-amended soils is essentially a structural fracture of the cement network rather than a mechanical damage of the soil particle aggregate.

(a) Top View

(b) Front View

Figure 8. MWCNTs Cement Soil Sample after Shearing

3.2.4 Peak shea stress after dry-wet cycle and chlorine salt erosion

Figure 9 shows a three-dimensional histogram of shear strength versus number of cycles and solution concentration of MWCNTs cement soil sample at a vertical pressure of 200 kPa for 0.1% MWCNTs contents.

From Figure 9, it can be concluded that the shear strength of MWCNTs cement soil decreases gradually with the increase of solution concentration. Under three loading cycles, the shear strength values of the cement-treated soil corresponding to solution concentrations of 0 g/L, 4.5 g/L, 18 g/L, and 30 g/L are 1020.58 kPa, 981.68 kPa, 957.61 kPa, and 915 kPa, respectively. The same pattern was also observed when the number of cycles was 6, 9, 12, and 15. This occurs because soluble salt ions interfere with hydration and ion exchange processes, resulting in the formation of flocculent (reticular) and clustered gels on the cement-soil sample surfaces, thereby modifying the material's spatial structure, and it also leads to a loose skeleton of cement soil sample, a low number of hydration products, and obvious pores on the surface . The alteration of the spatial structure of the cement soil sample affects the cohesive force and the internal friction angle of the cement soil, which leads to a decrease in the shear strength.

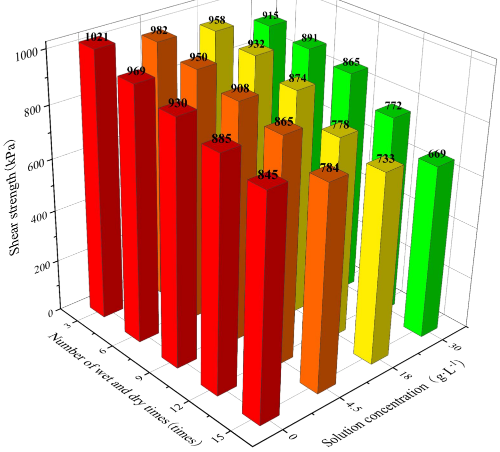


Figure 9. Three-Dimensional Surface of Plot Shear Strength for MWCNTs cement Soil Versus Wet-Dry Cycles and Chloride Salt Concentration

The shear strength of MWCNTs cement soil sample decreased gradually with the increase of the number of dry-wet cycles. When in clear water, the dry-wet cycle are 3, 6, 9, 12, 15 times, the shear strength of cement soil is 1021 kPa, 969 kPa, 930 kPa, 885 kPa, 845 kPa, respectively, which is because due to the poor resistance to expansion and contraction of internal structure of the hydric soil, the immersion and evaporation of water produces inhomogeneous tensile stresses inside the soil body, thereby inducing the formation of internal fractures and porosity development, accumulating to the expansion and penetration of fine cracks, leading to the weakening of the cementation between particles, and then the soil body is weakly bonded to each other. The soil body is also subjected to the uneven tensile stresses due to water ingress and evaporation, which leads to the continuous development of cracks and pores in the soil body, accumulating to the expansion and penetration of the finer cracks, leading to the weakening of the inter-particle cementation. Consequently, this leads to a reduction in the soil's cohesion [13], which leads to the decrease of the shear strength of the cement soil sample.

The rate of loss of shear strength of cement soils with MWCNTs presents the synergistic effect of dry-wet cycle and chlorine salt erosion has a more significant deterioration effect than a single factor. In the clear water environment, the strength loss rates were 8.78%-24.5% for 3-15 cycles; 8.78%-18.21% for 0 g/L-30 g/L concentration of chlorine salt solution at 3 cycles;

and 41.23% under the compound effect of 30 g/L chlorine salt solution and 15 cycles. This indicates that the synergistic effect of dry-wet cycle and chlorine salt erosion has a more significant deterioration effect than a single factor.

3.2.5 Effect of mass loss rate on the mechanical properties of MWCNTs cement soil

The weight of the cement soil sample before and after the test was measured by the coupled dry-wet cycle and chlorine salt erosion test, and the rate of mass loss was used to determine the damage of the sample, and the mass loss was calculated as shown in Eq. (1):

$$\Delta m = (1 - m_i/m_0) \times 100\% \quad (1)$$

Where, m_0 is pre-cycling mass (untreated sample), m_i is post-cycling mass (after i cycles of chloride-induced degradation).

In order to visually the soil spalling of MWCNTs hydraulic soil with different chloride salt solution concentrations under different numbers of dry-wet cycles, the mass loss percentage was employed as the primary degradation metric, and the relationship between the mass loss rate of hydraulic soil sample and the number of dry-wet cycle under the erosive action of different concentrations of chlorine salt solution was calculated by Eq. (1) as shown in Figure 10.

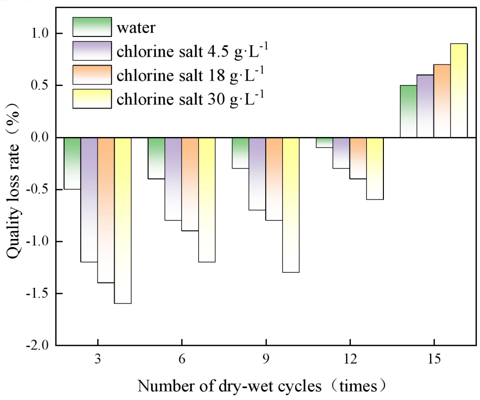


Figure 10. Variation in Mass Change Percentage of MWCNTs Cement Soil Samples with Cycling Frequency at Various NaCl Solution Concentrations

As can be seen from Figure 10, A positive correlation was observed between the cycling frequency and mass loss rate. The evolution of mass loss percentage in cement-stabilized soils exposed to varying saline concentrations exhibited the following dependence on wet-dry cycling frequency: clear water environment: -0.5% (3 times), -0.4% (6 times), -0.3% (9 times), -0.1% (12 times), 0.5% (15 times); 4.5 g/L chlorine salt environment: -1.2%, -0.8%, -0.7%, -0.3%, 0.6%,; 18g /L chlorine salt environment: -1.4%, -0.9%, -0.8%, -0.4%, 0.7%,; 30 g/L chlorine salt environment: -1.6%, -1.2%, -1.3%, -0.5%, 0.9%. The net mass change reflects the balance between positive contributions from water uptake and continued hydration, and negative effects from surface spalling, and the exfoliation effect gradually prevails with the increase of the number of cycles. Correspondingly, with the increase of the exfoliation effect, the integrity of the cement soil sample deteriorated, which led to a decrease in the unconfined compressive strength and shear strength of the cement soil.

The rate of mass loss in the chlorine salt environment increases with solution concentration, with a more significant initial stage mass increase and more severe final mass loss, this phenomenon can be attributed to chloride ions facilitating the generation of calcium chloroaluminate compounds [14], the early cycles exhibit considerable crystalline deposits, initially increasing the cement-soil's mass relative to low-concentration samples. Subsequent drying-phase crystallization pressures create micro-fractures and interface gaps, exacerbating surface exfoliation and causing accelerated mass deterioration over prolonged exposure, which results in a more pronounced reduction in unconfined compressive and shear strength of the cement soil sample at higher chlorine salt concentrations.

3.3 Correlation of Unconfined Compressive and Shear Properties

3.3.1 Relationship between unconfined compressive strength and cohesive force of cement soil with different content of MWCNTs

The results of nonlinear regression analysis in Figure 11 show that there is an exponential correlation (R^2=0.818) between the unconfined compressive strength (u) and cohesive force (c) of MWCNTs cement soils at different contents. The quantitative relationship was modeled in Eq. (2):

$$\delta_u = 0.915 \times e^{2.576c} \quad (2)$$

Where, c is the cohesive force in MPa, σ_u is the unconfined compressive strength in MPa.

The model has important engineering applications, cohesive force and unconfined compressive strength can be derived from each other, and this bidirectional derivability confirms the consistent regularity of the enhancement of unconfined compressive and shear strengths of cement soils by MWCNTs. The results further show that the unconfined unconfined compressive strength values of soils can be reliably estimated from their strength parameters (cohesive force and internal friction angle).

3.3.2 Relationship between unconfined compressive strength and shear strength of MWCCNTs cement soils after dry-wet cycle and chlorine salt erosion

Figure 12. Correlation of unconfined compressive and shear strengths in MWCNTs cement soil under combined chloride exposure and wet-dry cycling conditions.

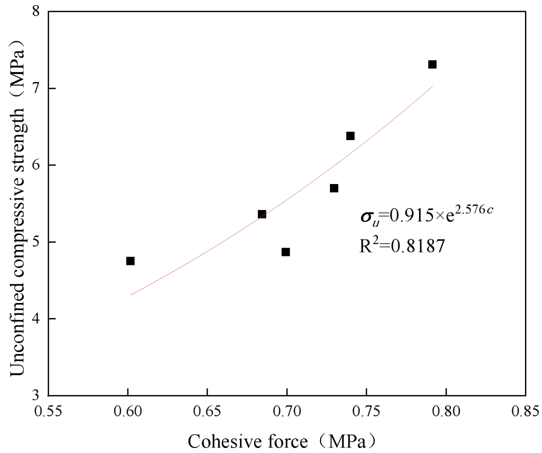


Figure 11. Relationship between Unconfined Compressive Strength and Cohesive Force of MWCNTs Cement Soil

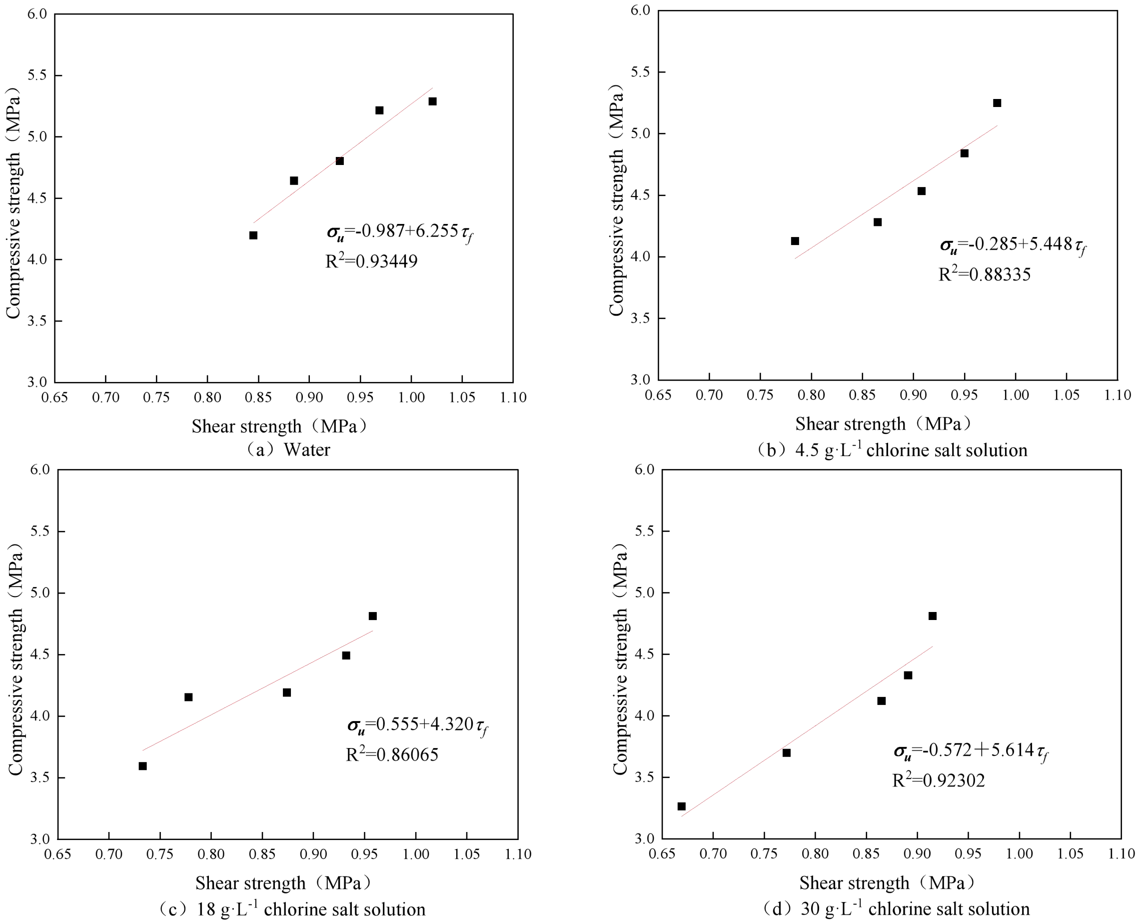


Figure 12. Unconfined Compressive-Shear Strength Correlation in MWCNTs-Reinforced Cement Soil across Varying Chloride Concentrations

Figure 12 demonstrates a consistent positive correlation between unconfined compressive strength and shear strength in MWCNTs cement soil under various environmental exposures, and a positive correlation between the two is obtained by linear fitting. These high-precision mathematical models, the correlation coefficients are all greater than 0.85, up to 0.934. Reveal two important conclusions, firstly, the unconfined compressive and shear strengths of MWCNTs cement soils in complex environments are highly correlated, and the two can be extrapolated from each other to simplify the on-site testing procedure (only a single strength index needs to be tested); and secondly, it provides reliable parameter calculations for stability calculations of road embankment slope engineering Secondly, it provides a reliable parameter for the stability calculation of embankment slope project, and the results of this study provide a reference for the engineering application of MWCNTs cement soil in harsh environments.

3.3.3 Mechanism of correlation between unconfined compressive and shear properties of MWCNTs cement soils

The improvement of mechanical properties of cement soil by MWCNTs as nano-reinforced materials showed significant positive correlation in terms of unconfined compressive and shear strength. With the increase of MWCNTs content, the unconfined compressive and shear strengths followed a rise-then-fall pattern with increasing MWCNTs content, peaking at 0.1% concentration, which can be explained from the two dimensions of material damage mechanism and reinforcement mechanism. In terms of the damage mechanism, the cement network formed by the cement hydration products breaks under the critical stress; the interface between soil particles and the cementitious matrix experiences relative sliding displacement. Both damage modes are directly dependent on the cement strength and interfacial properties of the material. In terms of the strengthening mechanism, MWCNTs promote the formation of high-density C-S-H gels and optimize the growth orientation of calcium hydroxide crystals; the bridging effect of nanofibers inhibits crack extension. However, excessive amount of MWCNTs will reduce the enhancement effect due to the agglomeration phenomenon caused by van der Waals forces, which will prevent some MWCNTs from participating in the stress transfer effectively, instead of reducing the enhancement effect.

The effect of MWCNTs on the resistance of cement soil to dry-wet cycle and chlorine salt erosion was synchronously verified in unconfined compressive and shear strength indexes, confirming the synchronization of its modification effect. This is because MWCNT can fill the pores and cracks within the samples, resulting in hindering or delaying the penetration and diffusion of destructive Na and chlorine salt ions, and MWCNT can form bridges between the cracks and impede the crack extension [15], and the direction of this impediment to crack development can be either vertically or horizontally, and therefore has the same effect on the unconfined compressive and shear strengths of cement soil sample. This multi-scale enhancement mechanism enables MWCNTs cement soil to maintain good synchronization of mechanical properties under dry-wet cycle and chlorine salt erosion, which provides a material reference for engineering applications.

4. Conclusion

Focusing on environmental degradation of cement soil's mechanical properties, it is proposed to utilize nanomaterials MWCNTs to improve the mechanical properties of cement soil. In this paper, firstly, the optimal content of MWCNTs is determined through tests, and then the unconfined compressive strength test and direct shear test are carried out on the MWCNTs cement soil under the coupling of different dry-wet cycles and chlorine salt erosion to study the unconfined compressive strength, shear strength and mass loss rate of MWCNTs cement soil with different concentrations of chlorine salt solution and different dry-wet cycles. Key findings include:

(1) For MWCNTs cement soil, unconfined compressive and shear strengths followed a rise-then-fall pattern with increasing MWCNTs content, peaking at 0.1% concentration. At this content, the unconfined compressive strength increased by 53.89%, compared to sample without MWCNTs. The shear strength increased by 40.47% under a vertical pressure of 200 kPa, compared to sample without MWCNTs.

(2) After 15 wet-dry cycles in a 30 g/L saline solution, the MWCNTs soil exhibited a 40.67% reduction in unconfined compressive strength. and the shear strength at vertical pressure 200 kPa decreased by 41.23%, and its mass loss rate was only 0.9%, which fully demonstrated that MWCNTs-modified cement soil could still maintain good strength and structural integrity under harsh environmental conditions;

(3) The unconfined compressive stress-strain curve of MWCNTs cement soil shows the characteristics of no compression-density stage and directly enters into the elastic deformation stage, which can give full play to the bearing capacity in the early stage of the stress and enhance the load response efficiency of the structure.

(4) The shear stress-displacement curves of MWCNTs cement soil show brittle damage characteristics, with a clear peak stress point, which provides an intuitive mechanical index for

structural safety warning, and facilitates the implementation of accurate pre-damage monitoring;

(5) Under varying incorporation amounts, there exists a favorable positive relationship between the unconfined compressive strength of MWCNTs cement soil and its corresponding cohesion and shear strength parameters, indicating that the reinforcing properties of MWCNTs on cement soil as well as the resistance to dry-wet cycles and chlorine salt erosion are synchronously verified in the unconfined compressive and shear strength indexes.

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